DEVELOPMENT AND CHARACTERIZATION OF A FEBIAD ION SOURCE FOR RI BEAM PRODUCTION AT THE RAON ISOL SYSTEM

Je Hwan Han[1,2*], Yeong Heum Yeon[1†], Hyung Joo Woo[1], Kyounghun Yoo[1], Wonjoo Hwang[1], Hee Joong Yim[1], Ha-Na Kim[1], Dong Joon Park[1], Jae-Won Jeong[1], Jae Hong Kim[1], JunYoung Moon[1], SeongJin Heo[1], Takashi Hasimoto[1], Hyoun Woo Jung[1], Young Jae Lee[1], Jin Ho Lee[1], Moses Chung[3‡]

[1]Institute for Rare Isotope Science, Daejeon, Korea

[2]Department of Physics, Ulsan National Institute of Science and Technology, Ulsan, Korea

[3]Pohang University of Science and Technology, Pohang, Gyeongbuk, Korea

Abstract

RAON is a heavy-ion accelerator facility in Korea that uniquely combines Isotope Separation On-Line (ISOL) and In-Flight (IF) techniques to produce a wide range of Rare Isotope (RI) beams. In the ISOL system, ion sources are continuously being developed to expand RI beam production capabilities. Among them, the Forced Electron Beam Induced Arc Discharge (FEBIAD) ion source is a promising candidate for efficient RI beam generation.

A prototype FEBIAD ion source was evaluated at the offline facility, where successful Ar, Kr, and Xe isotope beam extraction demonstrated its operational feasibility. Since the FEBIAD ion source operates at elevated temperatures, structural deformation due to thermal expansion can occur. In particular, bending and variations in the gap between the anode grid and cathode have been identified as critical issues.

To mitigate these effects, a new FEBIAD ion source design was developed and fabricated to ensure structural stability under high-temperature conditions by adding a heating strap and allowing the body to slide. The Sliding-type FEBIAD successfully achieved Kr isotope beam separation in offline tests. Subsequent online experiments confirmed stable operation of the source under ISOL conditions, demonstrating its suitability for reliable RI beam production. Future work will involve RI beam extraction experiments using various targets within the RAON ISOL system.

INTRODUCTION

The ISOL (Isotope Separation On-Line) system at RAON consists of a cyclotron, Target Ion Source (TIS) module, pre-mass separator, radio-frequency quadrupole (RFQ) cooler-buncher, electron beam ion source (EBIS) charge breeder, and A/Q separator [1]. Three types of ion sources — surface, laser, and plasma — are planned for operation. Currently, the surface and laser ion sources are in operation, while the plasma ion source is under development and testing. An offline test facility has been established at RAON for the development and performance evaluation of ion sources. The facility consists of a TIS chamber, X–Y steerers, electrostatic quadrupole triplet (EQT), dipole magnet, and beam diagnostics. The layout of the RAON offline test facility is shown in Fig. 1.

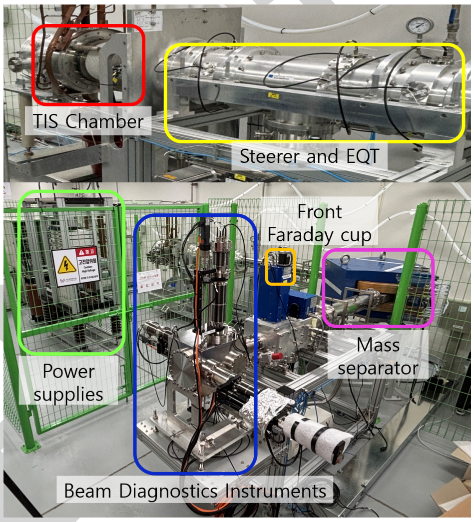

Figure 1: RAON ISOL Offline Test Facility

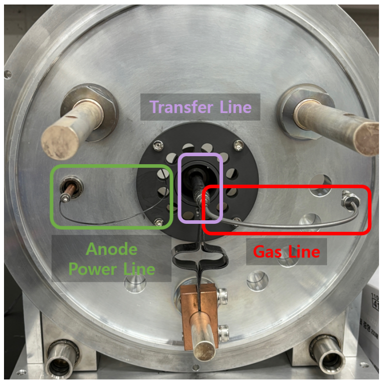

Figure 2: Prototype FEBIAD ion source installed in the TIS chamber.

The prototype FEBIAD ion source was fabricated based on the MK5 structure developed at CERN ISOLDE [2], as shown in Fig. 2. Its operational characteristics were evaluated at the RAON offline test facility. The FEBIAD adopts an electron impact ionization scheme in which electrons

* jwksmin@ibs.re.kr
† Corresponding author: yhyeon@ibs.re.kr
‡ Corresponding author: moses@postech.ac.kr

emitted from a heated cathode are accelerated by the potential difference between the cathode and anode, and then collide with neutral atoms to induce ionization. This method is applicable to a wide range of elements and is known to be effective for ionizing elements with high ionization energies that are difficult to ionize by surface ionization.

The FEBIAD ion source is susceptible to structural deformation due to thermal expansion under high-temperature operating conditions. Such deformation can alter discharge behavior and ion extraction characteristics, necessitating further design consideration. In this study, a Sliding-type FEBIAD ion source was designed and fabricated to mitigate these issues, and its operational characteristics were evaluated through offline experiments, followed by verification of its applicability in an online environment.

PROTOTYPE FEBIAD CHARACTERIZATION

The anode drain current as a function of cathode heating current is shown in Fig. 3. The discharge formation and electron emission behavior were evaluated by measuring the anode drain current characteristics as a function of cathode current, with an applied magnetic field of 300 G and an extraction voltage of 20 kV. As the cathode current increased, thermionic emission increased, and the anode drain current showed an overall increasing trend. This is interpreted as a result of an increased electron current collected at the anode, driven by the greater supply of thermionic emitted electrons. The increased electron density also promotes electron impact ionization in the plasma, influencing beam extraction characteristics. Meanwhile, at higher anode voltages, a higher anode drain current was measured under the same cathode current conditions, which is attributed to improved electron collection efficiency resulting from the increased energy of accelerated electrons.

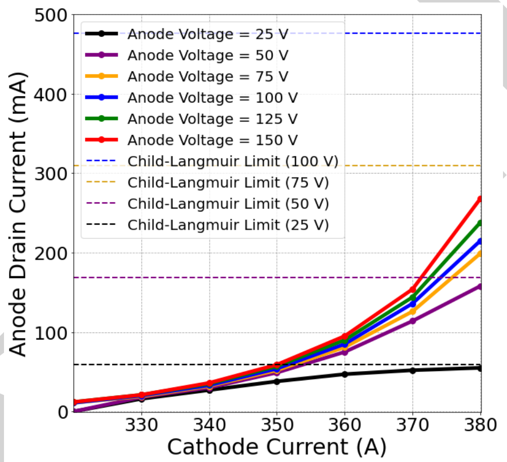

Figure 3: Anode drain current versus cathode heating current for different anode voltages. Child–Langmuir space-charge limited current thresholds are shown for comparison.

When the measured anode current was compared with the space-charge limited current calculated from the Child–Langmuir law, the current at low anode voltage (25 V) conditions was observed to approach the limit [3,4]. This indicates that the prototype FEBIAD ion source operates within the space-charge limited regime under these conditions, while at higher anode voltages it operates below the space-charge limited current.

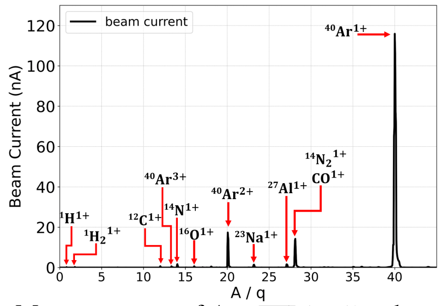

Figure 4: Mass spectrum of Ar gas injection showing residual gas and Ar isotope peaks.

After establishing stable discharge conditions through anode drain current characterization, beam extraction experiments were performed using argon (Ar), krypton (Kr), and xenon (Xe) gases, all under an anode potential of 150 V, magnetic field of 300 G, and extraction voltage of 20 kV. The Ar beam was extracted with a cathode current of 365 A, anode drain current of 110 mA, and gas pressure of 1.2×10^{-6} mbar. The mass spectrum measured during Ar gas injection is shown in Fig. 4. For Kr and Xe, the cathode currents were 350 A and 345 A, anode drain currents were 28 mA and 30 mA, and gas pressures were 1.4×10^{-6} mbar and 2.2×10^{-6} mbar, respectively. The Kr and Xe isotope beam extraction results are shown in Fig. 5. Stable discharge and continuous ion beam extraction were achieved under all gas conditions. Furthermore, isotope beam separation for each gas was demonstrated using the dipole magnet.

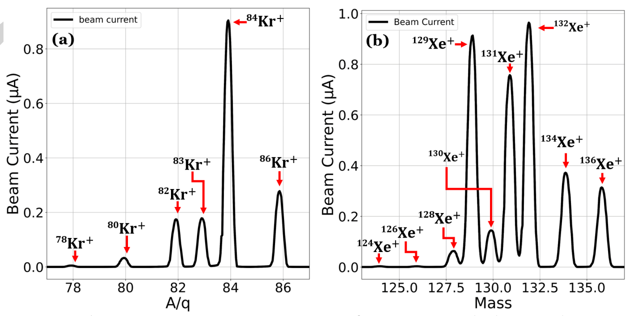

Figure 5: Isotope mass spectra of (a) Kr and (b) Xe beams extracted from the prototype FEBIAD.

These results demonstrate that the prototype FEBIAD ion source can stably perform ionization and beam production for various noble gases. However, thermal expansion-induced structural deformation was identified as a critical challenge, motivating the development of an improved design.

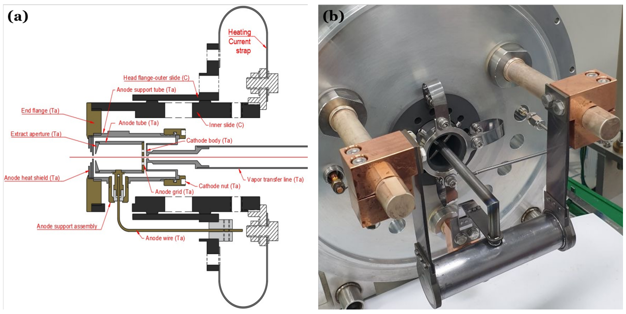

Figure 6: Sliding-type FEBIAD ion source: (a) cross-section drawing and (b) photograph of the fabricated ion source.

SLIDING-TYPE FEBIAD DESIGN AND EVALUATION

In the conventional FEBIAD ion source, the transfer line, anode, outer tube, and head flange are rigidly connected. The transfer line is connected to the target container, while the graphite outer tube and head flange are fixed to the TIS chamber. During high-temperature operation, thermal expansion occurs predominantly toward the cavity, causing the deformation to concentrate in the transfer line. This leads to changes in the cathode-anode gap, which directly affects the electron emission and discharge conditions. In extreme cases, inter-electrode contact may occur, causing discharge instability or device damage [5]. In addition, tilting of the heated transfer line due to thermal expansion can induce misalignment between the ion source and the extraction electrode, altering the electric field distribution for ion extraction, and affecting beam extraction conditions. The cross-sectional drawing and photograph of the fabricated Sliding-type FEBIAD ion source are shown in Fig. 6.

To mitigate these problems, a Sliding-type FEBIAD ion source was designed and fabricated in this study. In this design, an inner slide that can move axially within the graphite outer tube was introduced. The inner slide is connected to the TIS chamber via a loop-shaped heating current strap, which maintains electrical continuity while simultaneously acting as a spring to enable the sliding motion. This design absorbs thermal expansion-induced deformation while maintaining the cathode-anode gap and the alignment between the ion source and extraction electrode. As a result, discharge stability and beam extraction reproducibility are preserved even under high-temperature operating conditions.

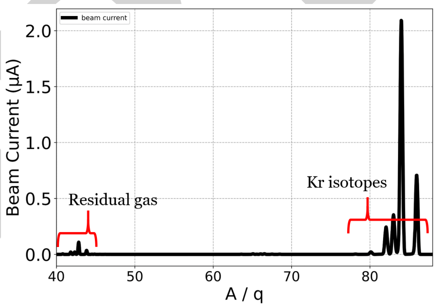

Figure 7: Mass spectrum of Kr isotope beams extracted from the Sliding-type FEBIAD with a target container.

To evaluate the performance of the Sliding-type FEBIAD ion source under actual ISOL operating conditions, ionization and beam extraction experiments were conducted with Kr gas injection and a TiC target installed on the target container. The Kr beam was extracted under the following conditions: cathode current of 420 A, anode potential of 150 V, magnetic field of 300 G, anode drain current of 110 mA, and Kr gas pressure of 2.0×10^{-6} mbar, with an extraction voltage of 20 kV. The experimental results are shown in Fig. 7. These conditions represented a target-coupled environment more closely resembling actual ISOL operating conditions.

Stable discharge was established and continuous Kr ion beam extraction was confirmed. Isotope beam separation of Kr was also demonstrated using the dipole magnet, showing that the Sliding-type FEBIAD ion source operates normally under target-coupled conditions.

To quantitatively evaluate the ionization efficiency, a preliminary experiment using a calibrated leak was performed with Ar gas. An initial ionization efficiency of 11.4% was measured. As this was a preliminary result, further verification through precise condition control and repeated experiments is needed [6, 7].

Following offline experiments, the Sliding-type FEBIAD ion source was installed in the online system, where high-voltage and high-current tests were successfully performed, confirming stable operation under actual ISOL conditions.

CONCLUSION

In this study, a FEBIAD ion source for the RAON ISOL system was developed and characterized. A prototype FEBIAD ion source based on the MK5 structure demonstrated stable discharge formation and successful isotope beam extraction for Ar, Kr, and Xe, validating its operational feasibility.

A Sliding-type FEBIAD ion source was designed and fabricated to mitigate thermal expansion-induced structural deformation issues identified during prototype operation. Beam extraction experiments with a TiC target confirmed stable operation under target-coupled conditions, and an initial ionization efficiency of 11.4% was obtained through a calibrated leak experiment. Following offline experiments, the ion source was successfully installed in the online system, where high-voltage and high-current tests confirmed stable operation under actual ISOL conditions.

Future work will include a full performance evaluation of the Sliding-type FEBIAD ion source under various operating conditions. In particular, systematic optimization of parameters such as anode voltage, cathode current, and magnetic field will be performed to measure ionization efficiencies for various noble gases and compare with results from other ISOL facilities. Furthermore, radioactive isotope beam extraction experiments using various targets will be conducted in the online ISOL environment, with the ultimate goal of supporting stable RI beam production at the RAON facility.

REFERENCES

[1] J. Lee *et al.*, "Recent progress of ISOL facility at RAON," *Nucl. Instrum. Methods Phys. Res. B*, vol. 542, pp. 17–21, 2023. doi:10.1016/j.nimb.2023.05.045

[2] S. Sundell, H. Ravn, and the ISOLDE Collaboration, "Ion source with combined cathode and transfer line heating," *Nucl. Instrum. Methods Phys. Res. B*, vol. 70, pp. 160–164, 1992. doi:10.1016/0168-583X(92)95926-I

[3] C. D. Child, "Discharge from hot CaO," *Phys. Rev.*, vol. 32, pp. 492–511, 1911. doi:10.1103/PhysRevSeriesI.32.492

[4] I. Langmuir and K. T. Compton, "Electrical discharges in gases, Part II. Fundamental phenomena in electrical discharges," *Rev. Mod. Phys.*, vol. 3, pp. 191–257, 1931. doi:10.1103/RevModPhys.3.191

[5] M. Manzolaro *et al.*, "Electrical-thermal-structural finite element simulation and experimental study of a plasma ion source for the production of radioactive ion beams," *Rev. Sci. Instrum.*, vol. 87, p. 033303, 2016. doi:10.1063/1.4943209

[6] M. Manzolaro *et al.*, "Ongoing characterization of the forced electron beam induced arc discharge ion source for the selective production of exotic species facility," *Rev. Sci. Instrum.*, vol. 85, p. 02B918, 2014. doi:10.1063/1.4857175

[7] A. Monetti *et al.*, "Performance evaluation of the SPES FEBIAD ion source," *Nucl. Instrum. Methods Phys. Res. B*, vol. 563, p. 165688, 2025. doi:10.1016/j.nimb.2025.165688