Transactions of the Korean Nuclear Society Spring Meeting
Jeju, Korea, May 22-23, 2025

Optimal Charge State Selection of Fe ions for beam acceleration in the KAHIF ECR Ion Source

Kihyun Lee *, Seunghyun Lee, Sangbeen Lee, Dae-Sik Chang, and Dong Won Lee
Korea Atomic Energy Research Institute, Daejeon, Republic of Korea
Corresponding author: khlee08@kaeri.re.kr

Keywords : Fe ion beam, Mass spectroscopy, heavy ion beam, accelerator, KAHIF

1. Introduction

The Korea Atomic Energy Research Institute (KAERI) has been upgrading the KAERI Heavy Ion Irradiation Facility (KAHIF) to support metal ion beam capabilities for irradiation damage evaluation in nuclear materials. [1-5] Ion irradiation testing is often used an alternative to neutron irradiation due to its ability to simulate radiation damage more rapidly and cost-effectively. Unlike neutron irradiation, which requires access to nuclear reactors and poses activation concerns, ion irradiation offers better control over irradiation conditions, shorter experiment duration, and reduced radioactive waste generation

A major candidate of structural material for fusion reactors in Korea is advanced reduced activation alloy (ARAA) steel, which is primarily Fe-based. [2] Utilizing Fe ion beams for irradiation enables high-displacements per atom (dpa) damage induction while avoiding contamination from extraneous elements, thereby preserving the material's intrinsic composition. To ensure the efficient delivery of high-purity Fe ion beams at KAHIF, this study investigates the charge state distribution of Fe ions in ferrocene plasma generated by the Electron Cyclotron Resonance (ECR) ion source. The goal is to determine the most suitable Fe charge state for acceleration, ensuring optimal beam performance for irradiation applications.

2. Charge State Analysis of KHAIF ECR Ion Source

ECR ion sources generate plasma containing various ion species, including Fe, C, and H from the ferrocene introduced through the Metal Ions from Volatile Compounds (MIVOC) system. Additionally, residual gases such as O and N present in the vacuum environment contribute to the ion composition. To ensure the extraction of pure Fe ions, unwanted species must be filtered out. For this purpose, mass spectroscopy or charge state analysis is necessary.

2.1 Analysis method

A mass analysis method using a bending magnet was employed to determine the charge state distribution of Fe ions in the ECR ion source. The different elements within the ion source exhibit distinct atomic numbers and masses and can exist in multiple charge states depending on the applied Radio Frequency (RF) power and magnetic confinement strength. Consequently, each ion species possesses a unique charge-to-mass ratio (A/q). By utilizing a bending magnet along the ion beam path, the ions can be separated based on their A/q values. Analyzing the current detected by a Faraday cup at different bending magnet current settings allows precise identification of ion species and their charge states.

The ion bending radius is determined by its A/q and the strength of the bending magnet. In theory, the required magnetic field strength to obtain a desired ion species can be calculated. However, in actual experiments, even if the magnetic field strength of the bending magnet is linearly related to the applied current, an offset error exists between the measured and actual current values. This offset error varies slightly in each experiment, necessitating a correction method for bending magnet scans. To address this issue, the following approach was applied in this study, based on three key assumptions for charge state identification during bending magnet scanning experiments.

- The first detected peak corresponds to A/q=1
- The second peak corresponds to A/q=2
- The offset value in the bending magnet current remains constant throughout a single scan

By applying these assumptions, the offset current I_{offset} is calculated as follows:

(1) $I_{offset} = I_{Bm,n,m} - I_{Bm,n,r}$

where $I_{Bm,n,m}$ and $I_{Bm,n,r}$ represent the measured and actual bending magnet currents for an ion species with charge-to-mass ratio A/q=n. Since the square of the bending magnet current is proportional to A/q value, the relationship can be expressed as:

(2) $I^2_{BM,n,r} = \mathrm{n} \times I^2_{BM,1,r}$

Substituting the offset current correction, the real bending magnet current for any A/q=n can be derived as:

(3) $(I_{Bm,n,m} - I_{offset})^2 = \mathrm{n} \times (I_{Bm,1,m} - I_{offset})^2$

(4) $I_{Bm,n,m} = \sqrt{n} \times \left(I_{Bm,1,m} - I_{offset}\right) + I_{offset}$

The measured bending magnet current at A/q = 1,2 can be obtained experimentally due to the assumptions.

Therefore, the offset current I_{offset} can be obtained as follows :

$$(5)\ I_{Bm,2,m} = \sqrt{2} \times \left(I_{Bm,1,m} - I_{offset}\right) + I_{offset}$$

$$(6)\ I_{offset} = (I_{Bm,2,m} - \sqrt{2} \times I_{Bm,1,m})/(1 - \sqrt{2})$$

By applying the offset current correction, the A/q values corresponding to each peak position can be calculated based on the bending magnet current for A/q = 1.

Charge state analysis is completed after identifying ion species from the A/q values obtained for each peak. Since considering all possible elements would lead to an excessive number of possibilities, only elements typically present in high-vacuum accelerator systems, as shown in Fig. 1, were considered in this study.

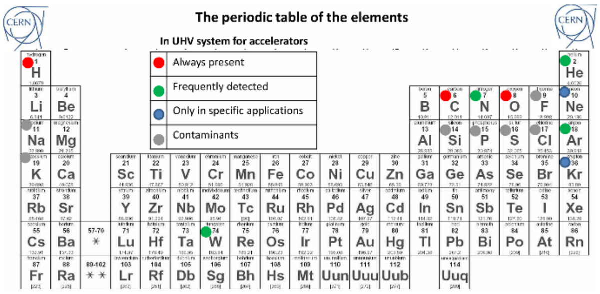

Fig. 1. The elements that are commonly present in accelerator vacuum systems,

2.2 Analysis results and selection of Fe charge state

In order to use a pure Fe ion beam in KAHIF, it is necessary to determine the A/q value and the corresponding bending magnet current value for Fe alone, without other impurities, by charge distribution analysis. The charge state distribution of Fe ions in the ECR ion source is influenced by factors such as RF power, neutral gas pressure, and magnetic field configuration. To determine the optimal ion species for acceleration, experiments were conducted to analyze the charge state distribution of ions in ferrocene plasma.

Table 1 shows the charge distribution analysis of a ferrocene plasma injected with 100 W of RF power. The peak bending magnet currents, which represent Faraday cup current above the noise level, are listed, and an offset current correction was applied to match the A/q. Candidate ion species were limited to those with a/q differences of 0.05 or less from the theoretical value, and are listed in order of smaller error.

Table 1 Observed peaks of ferrocene plasma

Observed Peak [A]	A/q	Candidates
11.07	1.00	H^{+}
15.24	2.00	H^{2+}, He^{2+}, C^{6+}, N^{7+}, O^{8+}, Ar^{20+}
16.35	2.32	N^{6+}, Ar^{17+}, Fe^{24+}, O^{7+}
17.39	2.65	O^{6+}, Ar^{15+}, Fe^{21+}
17.84	2.80	N^{5+}, Ar^{14+}, Fe^{20+}
18.43	3.00	C^{4+}
19.02	3.20	O^{5+}
19.84	3.50	N^{4+}, Fe^{16+}
21.13	4.00	Fe^{14+}, Ar^{10+}, O^{4+}, C^{3+}, He^{+}
21.95	4.33	Fe^{13+}
22.19	4.43	Ar^{9+}
22.76	4.67	N^{3+}, Fe^{12+}
23.53	5.01	Ar^{8+}

Based on these results, the ion species with the smallest error at each peak position can be identified, as shown in Figure 2. The figure illustrates the ion species obtained in the accelerator as a function of the bending magnet current, along with the corresponding beam current measured by the Faraday cup.

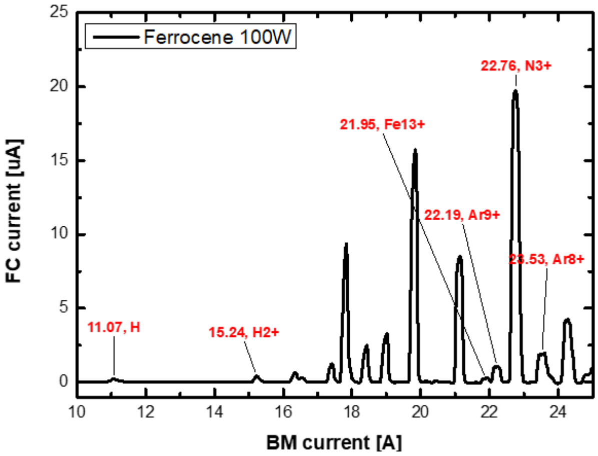

Fig. 2. Charge state analysis results of ferrocene plasma

According to the analysis results, Fe ions are present at seven different A/q values, including 4.33. However, in other cases, additional candidate ions may exist, indicating the possibility of impurity extraction. Therefore, at KAHIF, Fe^{13+} with A/q = 4.33 was selected as the ion species for Fe ion beam services, using a bending magnet current of 21.95 A.

3. Conclusions

In this study, we investigated the charge state distribution of Fe ions in the KAHIF ECR ion source and selected the optimal charge state for acceleration and irradiation applications. To achieve this, a mass analysis method using a bending magnet was employed to determine the A/q of ion species generated from ferrocene plasma. Through charge state distribution analysis, Fe^{13+} (A/q = 4.33) was identified as the most suitable charge state for acceleration in the KAHIF facility.

Acknowledgement

This work was supported by National R&D Program through the National Research Foundation of Korea (NRF) funded by the Korea government (Ministry of Science and ICT) (RS-2025-00156272)

REFERENCES

[1] S. R. Huh, et al., Present Status of the Daejeon Ion Accelerator Complex at KAERI, Proceedings of the 16 International Conference on Accelerator and Large Experimental Control Systems, 2017

[2] S. R. Huh, et al., Current Status and future plans of the Korea atomic energy research institute heavy ion irradiation facility, Transactions of the Korean Nuclear Society Spring Meeting, 2023

[3] S. Lee, et al., A KAHIF-upgrade project for fusion/fission material irradiation evaluation, Transactions of the Korean Nuclear Society Spring Meeting, 2023

[4] K. Lee, et al., DPA Calculation for Helium and Iron Beams on ARAA using SRIM code in KAHIF Accelerator, Transactions of the Korean Nuclear Society Spring Meeting, 2023

[5] S. Lee, et al., Beam Optics Study of KAHIF MEBT Beam Line, Transactions of the Korean Nuclear Society Spring Meeting, 2023

[6] S. Lee, et al., Preliminary Study for Beam Transport Line Upgrade in KAHIF, Transactions of the Korean Nuclear Society Spring Meeting, 2024

[7] Y.B. Chun, et al., Development of Zr-containing advanced reduced-activation alloy(ARAA) as structural material for fusion reactors, Fusion Engineering and Design, 109-111, 629-633, 2016