Operation Status of a KAERI Heavy-ion Irradiation Facility (KAHIF) for nuclear fusion/fission materials

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1. Introduction

To advance the commercialization of nuclear fusion reactors, it is imperative to develop materials capable of withstanding neutron irradiation damage on the hundreds of displacements per atom (dpa) [1]. The establishment of large-scale neutron irradiation test facilities is essential for nuclear fusion materials; however, the construction and maintenance of such facilities present significant challenges is quite challenging. While using existing fission research reactors is a feasible option, this method involves longer testing periods and significant associated costs.

In response to the growing demand for advancements in nuclear fusion research, leading nations are increasingly utilizing ion beam irradiation facilities to efficiently simulate the effects of extensive neutron irradiation over shorter time scales [2]. While the final validation of materials is still conducted using neutron irradiation facilities, there is a pressing need to establish a comprehensive ion beam irradiation test facility system for nuclear fusion material research in Korea.

The Korea Atomic Energy Research Institute (KAERI) operates the KAERI Heavy Ion Irradiation Facility (KAHIF), a linear radio frequency (RF) accelerator designed to accelerate heavy ions with energies ranging from 0.172 to 1.0 MeV per nucleon [3-5]. This facility can deliver heavy ion beams, including Helium (He), Argon (Ar), and Iron (Fe), for various material research applications not only fusion but also fission materials. Since 2022, KAHIF has been supplying stable beam operations through systematic maintenance and optimization of the beam delivery processes. In 2023, a metal ion source (Metal Ions from VOlatile Compounds, MIVOC) was established to generate Fe ions, leading to successful extraction and in-house testing of Fe ion beams in 2024.

This paper outlines the significant upgrades made to KAHIF in 2024, discusses ongoing challenges, and provides a comprehensive overview of the operational statistics for general users.

2. Major Upgrades of KAHIF

2.1. Fe^{13+} ion beam irradiation

Effective simulation of neutron irradiation damage in nuclear fusion materials relies on Fe ion irradiation. Iron ions are an effective method for rapidly and precisely assessing damage to steel materials in nuclear fusion reactors. Also, it can assess damage to steel used in reactors without the interference of physical or chemical reactions from other ion beams [6]. The KAHIF facility provides Fe^{13+} ions with an atomic mass per ion charge (A/q) of 4.296. These ions are generated by vaporizing solid iron compound in MIVOC, and selectively separated using a dipole electron magnet.

The high-energy beam is accelerated to 9.68 MeV by using an RFQ (Radio-frequency Quadrupole), producing approximately 1.0 μA with a flux of 1.531 x 10^{11} ions/cm²·sec, allowing for 3 dpa simulation in 8 hours in steel alloy. To validate the iron ions acceleration, a 99.99% pure molybdenum (Mo) specimen (Nilaco® MO-293425) was irradiated with a fluence of about 1.45 x 10^{14} ions/cm² [7].

Transmission Electron Microscopy-Energy Dispersive Spectroscopy (TEM-EDS) analysis revealed that Fe ions were detectable with a peak concentration of 2.5 μm. No Fe ions were found beyond a depth of 3.5 μm. These findings were consistent with the Stopping and Range of Ions in Matter (SRIM) simulation data, confirming the successful irradiation of the beam at an energy level of 9.68 MeV [8].

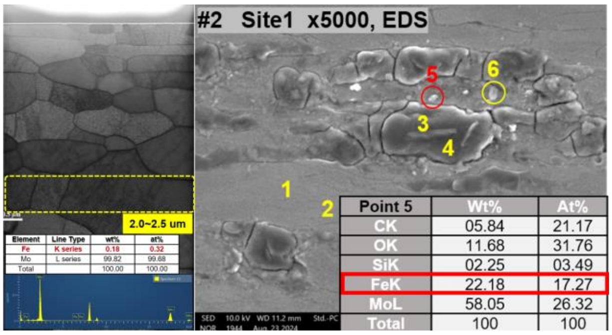

Figure 1. TEM-EDS result of Fe ion beam irradiation

2.2. Design Schematic of MEBT Beamline

To enhance the usability and reliability of the heavy-ion beam, including Fe ions, we are in the process of upgrading the Medium-Energy Beam Transport (MEBT) beamline. This beamline features a steering magnet and two quadrupole magnets, which are essential for stabilizing the ion beam. Additionally, a beam measurement system that includes a wire scanner and a Faraday cup will be incorporated into the setup. The sample chamber can heat up to 900 °C and is designed for quick sample replacements. It also provides a test report summarizing the data from beam irradiation experiments.

We have completed the design of the MEBT beamline, which contains electromagnets and a target chamber including a sample holder chamber and a diagnostic chamber with a measurement system. The target chamber can hold samples of up to 30x30 cm^2 and can rotate and move to create various ion irradiation environments. Furthermore, the beam shape can be controlled using electromagnets, and real-time monitoring of the beam irradiation environment will be recorded by the diagnostic system. With this design process is finished, the fabrication and construction of the beamline are scheduled to begin in the second half of 2025.

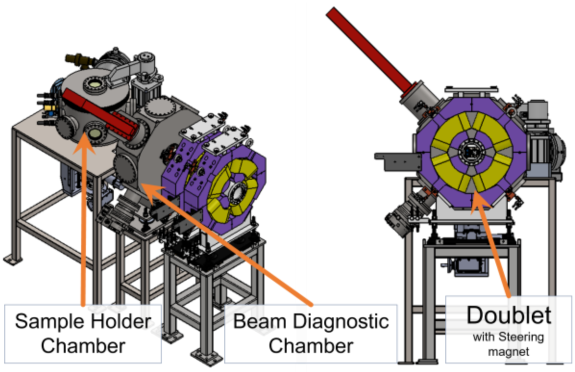

Figure 2. Design Schematic of MEBT Beamline

3. Operation Summary of KAHIF in 2024

KAHIF began providing beam irradiation services in 2022 and has since collaborated with 30 research teams, including universities and institutes. The facility has accumulated 450 hours of beam irradiation, achieving an 87% utilization rate, and has secured funding for three research projects. Currently, KAHIF has a plan to supply a Fe ion beam service in 2024 due to rising demand.

Research in nuclear materials accounts for 65% of ion irradiation, with 56% focused on nuclear fuel materials. In nuclear fusion, studies have primarily targeted the Advanced Reduced-Activation Alloy (ARAA) steel for a Korean fusion structural material. While steel alloys have been the focus, research has also included gadolinium (Gd) sintered bodies and aluminum alloys. Moving forward, a wider range of nuclear and fusion material research is expected, including increased demand for iron ion irradiation.

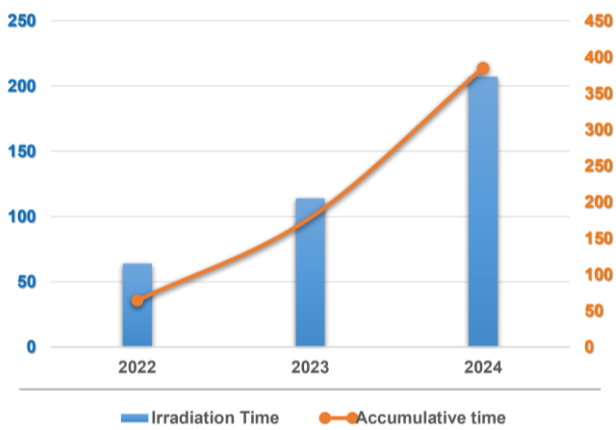

Figure 3. Beamtime statistics of a KAHIF

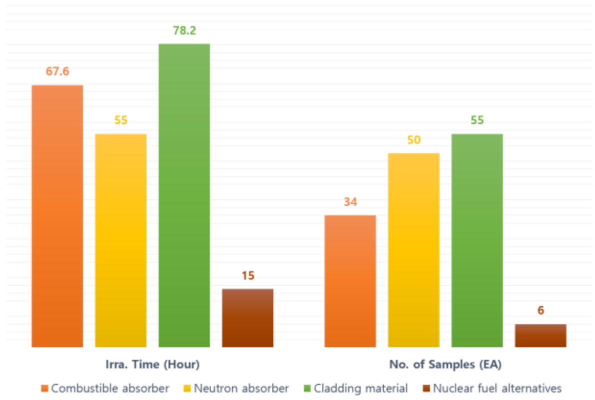

Figure 4. Summary of a KAHIF ion irradiation samples

4. Conclusion

The KAHIF facility has acquired the Fe ion irradiation capability of 3 dpa/8 hrs, thereby achieving a cumulative operating time of 450 hours by 2024. It makes broaden its research scope not only studies on neutron irradiation damage but also investigations into corrosion and neutron absorption. It has enhanced dual ion beam irradiation capabilities and intends to conduct evaluations of nuclear fuel for Small Modular Reactors (SMR) as well as assessments of corrosion impacts related to nickel beam-based Molten Salt Reactors (MSR). This expansion aims to address the requirements of researchers who currently depend on foreign facilities, thereby promoting the advancement of domestic material technology.

Acknowledgement

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