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Performance and Operational Experience of SCRFQ in KAHIF

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1. Introduction

KAERI Heavy ion Irradiation Facility (KAHIF), an RF(Radio Frequency)-based linear accelerator at the Korea Atomic Energy Research Institute (KAERI) in Daejeon, is utilizing for nuclear fusion and fission materials science research [1]. Heavy ion beam irradiation facilities, such as KAHIF, are essential tools for evaluating material performance under neutron exposure conditions and investigating radiation damage mechanisms. KAHIF is dedicated to materials research, and it is projected to significantly advance fusion and fission energy technologies.

The facility is primarily utilized for structural material investigations, including neutron irradiation damage assessment. Commercial nuclear reactor realization requires extensive material research and databases, for which ion beam irradiation offers an efficient and economical approach [2,3]. Furthermore, KAHIF supports broader nuclear materials research, enhancing radiation, temperature, and corrosion resistance through controlled ion beam studies.

The facility comprises a linear accelerator capable of accelerating ions up to approximately 1.0 MeV/u [1,4]. Ions from an 18 GHz Electron Cyclotron Resonance (ECR) source are isotopically separated by dipole magnets. A 25.96 MHz Radio Frequency Quadrupole (RFQ) then accelerates these ions to approximately 178 keV/u. While capable of further acceleration to 1.0 MeV/u via a re-buncher and Interdigital H-type Drift Tube Linac (IH-DTL), current operation emphasizes stable, high-flux beam delivery post-RFQ. Consequently, subsequent acceleration stages are presently off-line. Although the design and fabrication of key accelerator components, including the Split Coaxial RFQ (SCRFQ), were primarily led by High Energy Accelerator Research Organization in Japan (KEK), the originating institution, performance validation and operational expertise have been acquired at KAHIF through extensive long-term operation following its relocation to Korea. In particular, KAHIF has its own distinctiveness because it is the only facility among the research institutes utilizing accelerators in Korea that utilizes SCRFQ as a major accelerator components. This paper details the performance and operational experience of the 25.96 MHz RFQ at KAHIF.

2. Features of SCRFQ

2.1. Role of RFQ

Figure 1 shows the beam line and the main accelerator components of KAHIF. The LEBT (low energy beam transport) section is designed to match the ion beam between the ion source and the RFQ. In order to obtain a good matching, the Einzel lenses are placed to make a focus point at the upstream of the RFQ.

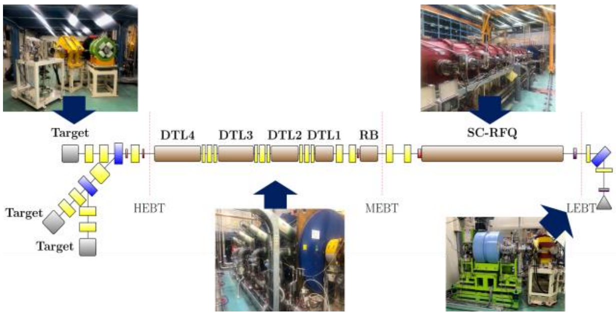

Figure 1. Schematic view and main components of KAHIF

Ion beams originating from ion sources typically possess very low energies, ranges from a few keV to tens of keV. General linear accelerator structures (e.g., DTL) are designed to accelerate particles efficiently only after they have reached a certain velocity threshold. Attempting to accelerate very slow ion beams directly using structures like DTL leads to reduced acceleration efficiency and substantial beam loss. The RFQ is specifically designed for efficient acceleration of low-velocity ion beams. It is designed to effectively accelerate even the slow ion beams emitted from the ion source to an energy range suitable for subsequent acceleration stages.

The DTL placed downstream of the RFQ as shown in Figure 1 is a highly efficient linear accelerator for boosting ion beams from 178 keV/u to 1.0 MeV/u. The efficient acceleration within a DTL necessitates high-quality input beams (beam focusing, energy spread, and beam stability). The RFQ not only accelerates ion beams but also focuses improving beam quality. The RFQ employs a quadrupole electrode structure to effectively focus the beam and reduce energy spread during acceleration. Furthermore, the RFQ enhances the longitudinal beam quality through bunching (grouping particles according to RF phase). The quadrupole electrode structure within the RFQ strongly focuses the beam, suppressing beam expansion due to space charge and minimizing beam quality degradation. The design features of SCRFQ are described in section 2.2.

2.2. SCRFQ Design Features

SCRFQ utilizes a coaxial resonator, split along its inner conductor. The cross-section view of SCRFQ one unit is shown in Figure 2. The split inner conductor, with its modulated gap, forms the electrodes and simultaneously is integral to the resonant structure. The electromagnetic field is highly concentrated within the gap region between the split inner conductors. This coaxial configuration offers a high quality-factor (Q-factor) and efficient energy storage, leading to improved power efficiency compared to 4-rod structures, and in some scenarios, comparable to or approaching 4-vane structures, particularly at lower to medium frequencies. The larger inductance compared with another structure with same cavity radius is the most advantage of the split coaxial type. This is very suitable for a low frequency RFQ. The main specifications of SCRFQ in KAHIF are summarized in Table 1.

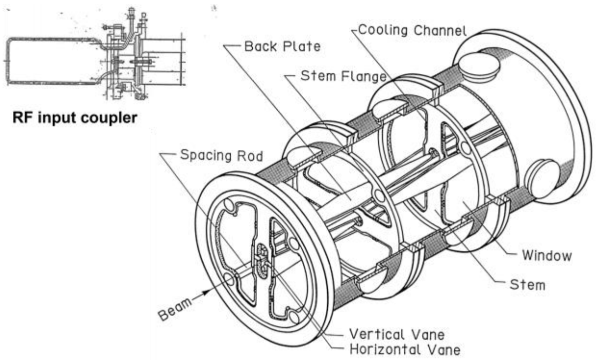

Figure 2. Drawing of SCRFQ cavity unit tank. The loop type RF input coupler is used.

Table 1: The main specifications of SCRFQ

Frequency	25.96 MHz
Charge-to-mass ratio (q/a)	>1/28
Input energy	2.0 keV/u
Output energy	178 keV/u
Normalized emittance	0.6 π mm·mrad
Cavity length	8.6 m
Cavity inner diameter	0.9 m
Number of unit tank	4
Number of module-cavity (per unit tank)	3
Mean aperture radius	0.9846 cm
Minimum aperture radius	0.5388 cm
Final synchronous phase	-30°

The RFQ accelerates ions with a charge-to-mass ratio greater than 1/28 from 2.0 to 178 keV/u. The cavity comprises four unit-cavities with 3 module-cavity. The material of the tank is mild steel, whose inner wall is plated with copper with a thickness of 100 um. And the inner structure except the vanes and spacing rods is oxygen-free copper. The vanes are made of chromium-copper alloy containing Cr of 1 % and the spacing rods are copper plated stainless steel. The electrodes comprising the vanes and the spear-shaped back plates are supported by stems. The stem-flanges are arranged at equal distance by spacing-rods. It is possible to align the vanes with an accuracy better than ±40 um by using the spacing-rods. In the low-energy part, the first unit cavity, the radius of curvature of the vane-tip is variable. The curvature of vane-tip is constant in the high-energy part.

The RFQ consists of 3 units, each unit having 4 cavity modules, for a total of 12 acceleration modules. As shown in Figure 3, one RF power coupler for applying RF power to the RFQ and one RF pickup loop coupler for measuring acceleration voltage are assembled. Plug-type tuners for frequency tuning are assembled in each of the 12 modules, and four TMPs (turbomolecular pump), 500 l/s, are assembled to maintain the high vacuum state (<1.0 x 10^{-5} Pa). Two cryopumps for spare are also assembled at the upper port of RFQ.

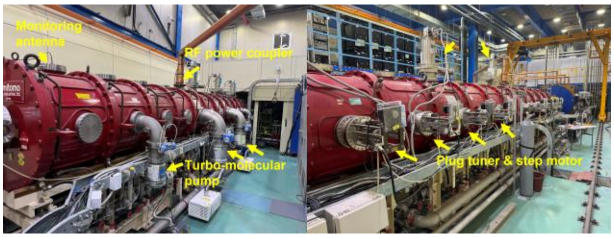

Figure 3. Picture of SCRFQ in the beam line.

3. Operation Experience

3.1. RF performance

The RF power is transmitted to the cavity through a loop type RF input coupler (Figure 2) with WD-120D coaxial line. The loop is rotatable for the impedance matching to 50 Ω. The voltage standing wave ratio (VSWR) of 1.01 was obtained by rotating the loop by 19° to the magnetic flux. Based on the measured VSWR, the coupling coefficient can be obtained as 0.99, which means the under coupling state. The RF input coupler is installed at 8th module cavity.

To verify whether the acceleration voltage is applied inside the RFQ, a monitoring antenna is assembled at 12th module cavity. The voltage applied inside the RFQ can be obtained from the voltage measured by this antenna, and for this, calibration between the voltage between the internal vanes (V_{vv}) and the voltage of the monitoring antenna (V_{ML}) is necessary. This was performed during the RFQ assembly process, and the calibration constant was obtained V_{vv}/V_{ML}=10,388. This kind of the calibration was conducted at the assemble step of the RFQ [4,5]. The high power RF operation could be possible based on these calibration data.

The Table 2 includes the monitoring voltage in cases of He, Ar, and Fe ion beam acceleration. Because the required RF power is proportional to the $(a/q)^2$, the RF pickup voltage also has the dependence of the charge-to-mass ratio. The operation mode of the RFQ is in the pulse mode, 3.0 ms of the pulse width, 122.8 Hz of the repetition rate, therefore the duty factor is about 98 %. The shape of the RF signals are shown in Figure 4. The resonance frequency of RFQ is shifted from 25.950 MHz to 25.965 ~ 25.968 MHz in stable state (which means the reflection RF power is minimized).

Table 2: The monitoring voltage of SCRFQ

Ion beam	Monitoring voltage
He^{+} (a/q=4)	0.36 ~ 0.37
Ar^{9+} (a/q=4.44)	0.54 ~ 0.55
Fe^{13+} (a/q=4.31)	0.49 ~ 0.50

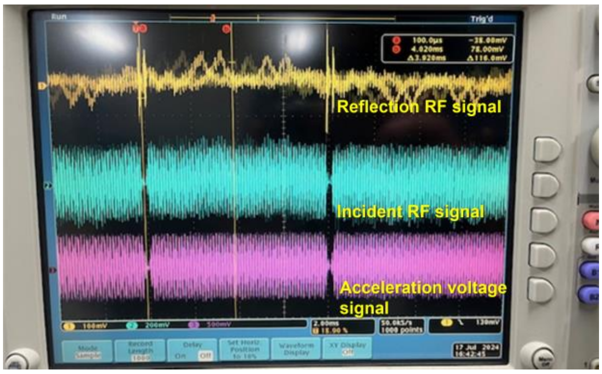

Figure 4. The operation mode of RFQ. The incident, reflected RF signal and the acceleration voltage are measured by the oscilloscope. (duty = 98%)

Currently, the RF system for RFQ is operating independently based on the analog system. The digitalization of the RF system is undergoing to integrate in the KAHIF main control system which is based on EPICS.

3.2. Beam transport

To ensure a reliable beam delivery for subsequent ion beam irradiation experiments, the beam transmission efficiency of the RFQ is presently under evaluation. Following the application of RF power and the attainment of a stable operational regime, the incident beam current is measured utilizing a Faraday cup positioned upstream of the RFQ (FC1). Concurrently, the accelerated beam current is monitored via a Faraday cup located downstream of the RFQ (FC2). The result beam transmission rates, determined for various ion beam species, are presented in Table 3.

As indicated by the results in Table 3, the beam transmission rate is currently achieving below 100%. This means that there are still parts that need to be optimized for the RFQ. To enhance the beam transmission rate through the RFQ, inspections of both the high power and low-level RF systems are underway. This is attributed to the fact that the currently utilized high power RF system, constructed two decades prior and relocated with the accelerator facilities, may exhibit issues related to the durability of its internal components. Furthermore, to improve beam transmission, the reactivation of plug tuners, presently inactive, may be necessary, thus necessitating the maintenance of the low-level RF system as well.

Table 3: The measurement beam currents

Ion beam	FC1 (uA)	FC2 (uA)	Transmission rate
He^{+}	26	22.5	86 %
Ar^{9+}	22	15.4	70 %
Fe^{13+}	1.5	1.0	66 %

4. Conclusion and Plans

KAHIF serves as an ion beam irradiation facility primarily dedicated to supporting research in the fields of domestic nuclear fusion and fission materials. It is currently providing stable ion beam and irradiation using helium, argon, iron, and other ion species. To achieve its target beam specifications of 178 keV per nucleon acceleration and an ion beam flux exceeding 10^{15} ions/cm^2/s, KAHIF has been operating an SCRFQ as its main accelerator. In order to increase the beam transmission rate, RF system, which is including the high power RF and the low-level RF, is under the optimization. To further enhance the stability and reliability of irradiation experiments, plans are underway to integrate the RF signals of the RFQ with the central control system.

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