

Remote Monitoring and Control of the KAHIF RFQ LLRF System Using EPICS-Integrated Instrumentation

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1. Introduction

The Low-Level Radio Frequency (LLRF) system of the Korea Atomic Energy Research Institute Heavy-ion Irradiation Facility (KAHIF) Radio Frequency Quadrupole (RFQ), operating at a designed resonant frequency and made fault diagnosis difficult due to the complexity of the analog circuit layout. To address these limitations, key hardware components – including a Hewlett-Packard ESG-1000 signal generator, a Tektronix DPO 4034 oscilloscope, and an Advantech ADAM-4117 data acquisition (DAQ) module – were integrated into the Experimental Physics and Industrial Control System (EPICS) framework. The newly established system enables precise remote operation with a frequency resolution of 40 Hz and an amplitude resolution of 0.04 dBm. Furthermore, real-time monitoring and archiving of RFQ amplitude and power parameters are now available during operation. This work represents a foundational step toward the development of a fully automated control system capable of autonomously adjusting the RFQ frequency and output power.

2. Methods and Results

The primary function of the LLRF system in the KAHIF RFQ is to establish and stabilize the 25.96 MHz RF field within the resonant cavity to support efficient ion beam acceleration. Stable operation requires continuous matching between the cavity resonant frequency and the RF drive frequency. In a conventional configuration, this is achieved by mechanically operational phase of KAHIF, the mechanical tuner is fixed, necessitating a source frequency tuning strategy in which the RF drive frequency from the signal generator (SG) is dynamically adjusted to track the fluctuating resonant frequency of the cavity. In addition, when a fault condition prevents the LLRF system from autonomously regulating the output field level, the SG amplitude must be manually controlled to stabilize the accelerating voltage.

2.1 Real-time monitoring and waveform analysis

A Tektronix DPO 4034 digital phosphor oscilloscope was employed to measure the reflected RF power signal

from the RFQ cavity. Because the RFQ operates in pulse mode, waveform measurements were restricted to a user-defined cursor gating interval (cursors a and b) to capture only the relevant portion of each pulse. Communication with the oscilloscope was established via the Standard Commands for Programmable Instruments (SCPI) protocol, enabling automated acquisition of amplitude, RMS, and peak-to-peak values within the gated window. The acquired waveform parameters – amplitude and RMS of the reflected signal – were published as EPICS Process Variables (PVs) to serve as real-time indicators of cavity resonance condition and to provide input signals for future closed-loop feedback control as, illustrated in Fig. 1.



Fig. 1. Snapshot of DPO 4034 display showing the gated measurement interval for reflected RF power acquisition.

In addition to the oscilloscope measurement, the analog output of the LLRF system's internal amplitude detector module was digitized using an Advantech ADAM-4117 analog input DAQ module and converted into an EPICS PV. Although the ADAM-4117 is not a standalone RF instrument, this integration allowed the cavity field amplitude – as sensed by the LLRF amplitude detector – to be continuously monitored and archived within the EPICS control environment, providing a complementary indicator of the intracavity electric field level.

2.2 Integration of Signal Generator

Three signal generator were evaluated for compatibility with the KAHIF RFQ operational requirements: The BK Precision 4055B, Hewlett-Packard ESG-1000A, and Agilent E4428C. Following comparative testing, the HP ESG-1000A was selected as the primary RF drive source due to its support for the

precise external pulse modulation required by the pulsed RFQ operation and its superior amplitude resolution.

The ESG-1000A was interfaced to the EPICS framework via SCPI, and a dedicated operator interface was developed for remote frequency and amplitude control (Fig. 2). For amplitude control, two step modes were implemented: a fine step of 0.04 dBm for precise field-level stabilization and a coarse step of 1.0 dBm for rapid response during large deviations. For frequency control, a step size of 40 Hz was adopted to enable fine tracking of cavity resonant frequency shifts while maintaining sufficient resolution to minimize the reflected power.

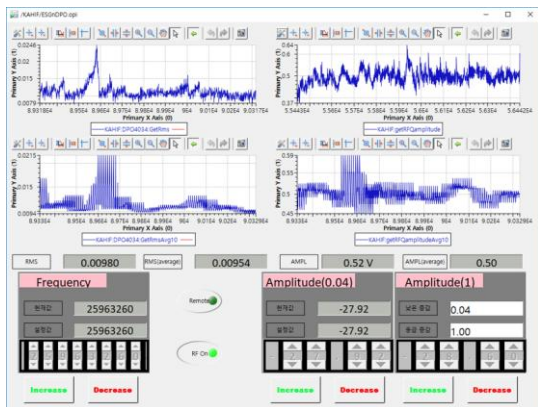


Fig. 2. The Operator Interface panel for remote control of RF drive frequency and amplitude via the signal generator.

2.3 Real-time monitoring and Archived data Analysis

Figure 3 presents representative trends of the reflected RF power signal (amplitude and RMS) and the LLRF amplitude detector output recorded during RFQ operation using the EPICS Data Browser. The archived data confirm that all three parameters are continuously acquired and stored with sufficient time resolution for post-operation analysis. The figure also shows the result of applying a digital filtering algorithm to the raw reflected power signal in preparation for future closed-loop feedback implementation.

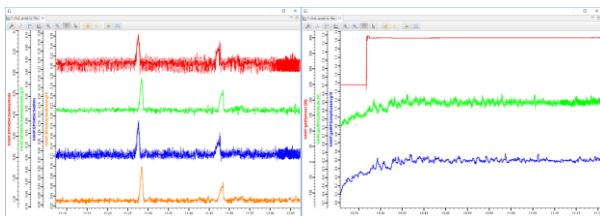


Fig.3. Data plot of the reflected RF power amplitude, RMS, and LLRF amplitude detector output.

Figure 4(A) shows the frequency tuning operation over approximately 400 minutes. The SG drive frequency (red trace) was varied within a range of

roughly 25.9500–25.9775 MHz, while the reflected signal (blue trace) fluctuated correspondingly, with reflection minimized when the drive frequency closely tracked the cavity resonant frequency. Figure 4(B) illustrates the amplitude stabilization performance over the same period. Following an initial transient settling phase of approximately 50 minutes, the SG amplitude (green trace) was incrementally adjusted, maintaining the RFQ pickup voltage (black trace) at a stable level of approximately 0.4–0.5 V. Both plots confirm that the EPICS-based remote tuning interface achieved effective operational control of the KAHIF RFQ under the degraded LLRF condition.

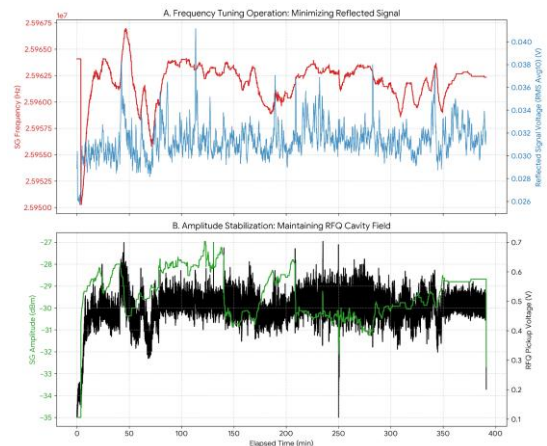


Fig. 4. Operation trends of KAHIF RFQ LLRF System.

3. Conclusions

The LLRF system of the KAHIF RFQ, originally based on an unmodifiable analog circuit architecture, required manual RF frequency and amplitude control due to operational constraints. By integrating the substitute instrumentation into an EPICS-based control framework, precise remote operation and real-time parameter monitoring were successfully achieved. The established EPICS PV infrastructure lays the groundwork for future autonomous closed-loop control of cavity resonant frequency tracking and field level stabilization..

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