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DEVELOPMENT OF A DIGITAL LLRF SYSTEM FOR SRF CAVITIES IN RAON ACCELERATOR

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Abstract

An ion accelerator, RAON is planned and under construction in Daejeon, Korea by Rare Isotope Science Project (RISP) team in Institute of Basic Science (IBS). The purpose of this accelerator is the generation of rare isotope by ISOL (Isotope Separation On-Line) and IF (In-flight Fragmentation) method. To achieve this goal RAON adopted the superconducting cavities at three different frequency (81.25 MHz, 162.5 MHz and 325 MHz) and their RF field will be controlled independently for the acceleration of ions with various A/q. A solid state power amplifier and a low level RF (LLRF) controller pairs are under development to generate and to control the RF for the cavities. Recently the development and evaluation of the digital-based LLRF have been performed. For the operation and test of SRF cavities, self-excited loop (SEL) and generator-driven-resonator (GDR) algorithm is digitally implemented and its test was performed. In this paper the status and test result of RAON LLRF controller will be described.

INTRODUCTION

Rare Isotope Science Project (RISP) project is under way and the goal of this project is to build an ion accelerator, RAON since 2009. The acceleration of the high-energy stable ion beams and rare-isotopes are planned in RAON accelerator for the research of nuclear, material, medical science and many other areas [1]. The linear accelerator part of RAON adopted a superconducting two gap cavities and normal conducting quadrupole doublet structure instead of multi gap cavities such as a multi-cell elliptical cavity for the acceleration of various ion beams. Four kinds of superconducting cavities are planned and their operation frequencies are three. There are two linear accelerator sections are under construction. In the low energy superconducting linear accelerator, a quarter wave resonator (QWR) with 81.25 MHz and a half wave resonator (HWR) with 162.5 MHz are going to be installed and two single spoke resonators (SSR) with different beta are planned for high energy superconducting linear accelerator (SCL2). The operation frequency of SSRs is 325 MHz.

As described above, there are various RF cavities in RAON accelerator and the electromagnetic field and the synchronous phase of all cavities should be controlled individually for the acceleration of various ions. Also the RF control requirement of RAON RF system is decided by the beam dynamics simulation and error study and it is shown in Table 1. A low level radio frequency (LLRF) and a solid state power amplifier (SSPA) pairs are selected for the RF system of RAON accelerator. In Fig. 1, the layout of RAON RF system is shown. Recently the manufacturing and testing of superconducting cavities and cryomodules for the construction of SCL3 are ongoing at SRF test facility at Sindong site. As a prototype of the LLRF for RAON accelerator RF system, the development of a LLRF for RAON Supercondicting Radio Frequency (SRF) test facility was performed and it is being tested during the test of the jacketed cavities and the cryomodules. In this paper, the status of the developed LLRF and its test results will be described.

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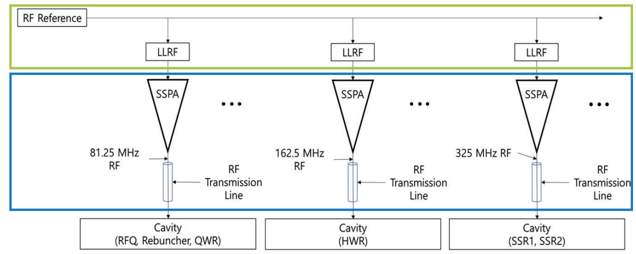

Figure 1: Schematic of RAON RF system.

Table 1: Specification of RAON RF Control System

RF Dynamic Phase Error Requirement	$\pm 1^o$ (p2p)
RF Dynamic Amplitude Error Requirement	±1% (p2p)

DEVELOPMENT OF LLRF FOR THE RAON SRF TEST FACILITY

The LLRF for RAON SRF test facility should be able not only to control the RF inside the cavities but also to provide some functions which are necessary for the testing, such as the microphponics measurement, etc. Also it is preferred to be able to operate at all operating frequency for the ease of test setup. Some strategy to decide the specification of the LLRF were as following.

1. Phase locked loop (PLL) based RF clock generation
2. Non-IQ based RF direct sampling to reduce the temperature sensitive RF components
3. FPGA-based RF digital processing for the minimization of RF components at RF frontend

For the SRF test, the information of the RF signal from the cavity, the RF reference signal, and the forward and reflected RF signals from the high power amplifier is necessary. For this purpose the AD9656, 4-channel, 16 bit, 125 MSPS, serial interfaces ADC of Analog Devices was chosen. A variable amplifier was used at the RF input to enhance the

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Figure 2: The picture of developed LLRF.

RF measurement at low RF input power. The sampling frequency was 104.9 MHz for non-IQ sampling. The brief specification of the developed LLRF are summarized in Table 2 and its picture is shown in Fig. 2. This LLRF can work with three different operating frequency of RAON accelerator cavities by selecting the frequency mode.

For the control of LLRF, Experimental Physics and Industrial Control System (EPICS) input/output controller (IOC) has been implemented. All parameters such as measured RF data, field setpoint, PID constant, etc. can be monitored and controlled with the EPICS Operator Interface (OPI) based on the Control System Studio (CSS).

Xilinx Zynq system on chip (SoC) was selected for the compatibility with RAON standard architecture. This Zynq SoC is a SoC which has the conventional FPGA for the hardware programmability and an ARM-based processor in one chip [2]. This ARM processor with 1GB DDR3 SDRAM and 64 GB eMMC memory are used for the operating system to run the EPICS IOC.

The generator driven resonator (GDR) algorithm and the self-excited loop (SEL) algorithm were implemented. The GDR algorithm is to control the amplitude and the phase of the cavity with integrated Proportional-Integral-Differential (PID) controller in amplitude-phase domain or I-Q domain [3]. In this project, the control is performed in amplitude-phase domain. The measured RF data is originally in I and Q domain, we transformed it to amplitude and phase domain with the Coordinate Rotation Digital Computer (CORDIC) algorithm. With this RF data the RF output is adjusted by the calculated results from the negative feedback loop with PID controller [4]. The SEL algorithm is

Table 2: Important Parameters of Developed LLRF

Item	Specification
RF Input	4
RF Output	1
Storage	Micro SD card + eMMC
RF ADC	AD9656 (16 bit, 4ch, serial)
SoC	Xilinx Zynq Ultrascale ZU9EG
Clock Generator	HMC7044 PLL
Operating System	Embedded Linux
EPICS IOC	In Arm core of Zynq SoC

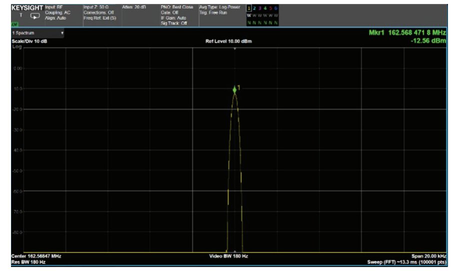

Figure 3: Cavity resonance frequency tracking and excitation test result with HWR cavity.

to measure and to track the resonance frequency of the superconducting cavities. A SEL is in essence an unstable positive feedback loop where the limit cycle of amplitude of the oscillations is set by the nonlinear element in the loop (limiter) and the loop gain is greater than 1 [5]. This SEL algorithm was digitally implemented in FPGA [6]. The measured amplitude data is used for the regulation of the cavity field with PID controller for amplitude. The phase data is directly passed through to the RF output, while we can add a constant phase to simulate the loop phase shift. By setting an amplitude and adjusting the loop phase shift, we can excite the cavity. With this algorithm, the resonance frequency of the superconducting cavity can be tracked easily and the cavity field can be sustained at any resonance frequency. This function is necessary for the cavity vertical test because it is performed without the tuner.

TESTS RESULTS OF DEVELOPED LLRF

In RISP SRF test facility, the integrated test of LLRF with superconducting cavities has been performed. As a first step, the frequency tracking and cavity excitation test with HWR cavity was performed during the vertical test. In Fig. 3 the test results are shown. The operation frequency is 162.5 MHz, but its real resonance frequency is about 162.568 MHz. With SEL mode operation, the developed LLRF could find the resonance frequency and excite the cavity to operation amplitude level while the resonance fre-

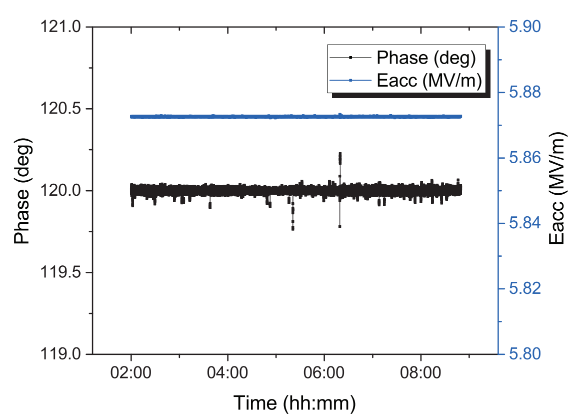

Figure 4: Amplitude and phase control experimental result with QWR cavity.

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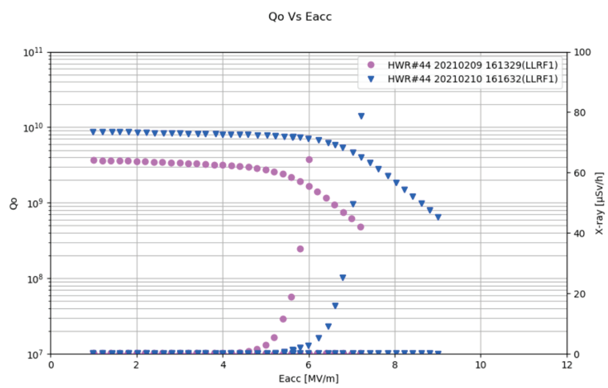


Figure 5: Q_0 Measurement result of HWR cavity VT.

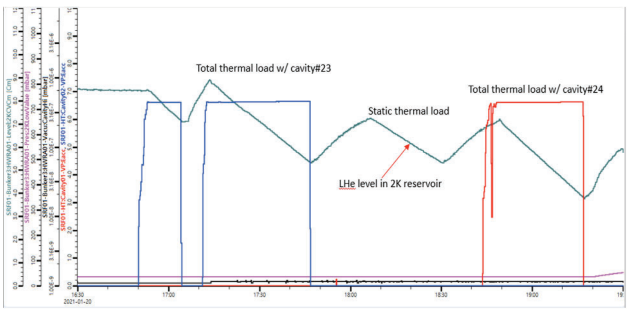


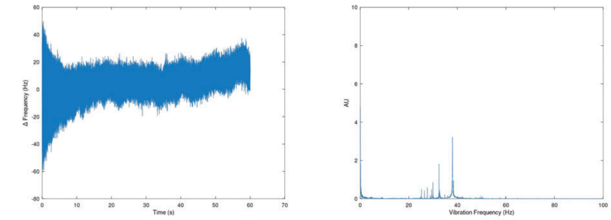
Figure 6: Measurement of heat load during HWR cryomodule test.

quency of the cavity was about 68 kHz off from the operation frequency as shown in Fig. 3.

As a next step, the RF amplitude/phase control test was performed. This test was performed with the QWR cryomodule. In Fig. 4, the test result is shown. The amplitude fluctuation was 5.87±0.1% and the phase fluctuation was 120±0.24 degree. This result satisfied the RF control requirement. From the test result, we could find that the developed LLRF can be used for the vertical test and cryomodule test and it is being used for the acceptance test of the cavities and cryomodule at SRF TF. Figures 5 and 6 show some test results which are performed with the developed LLRF.

During the SRF testing and installing the cryomodule, the investigation and suppression of the microphonics are generally performed [7]. For the investigation of the microphonics, the measurement of the cavities resonance frequency fluctuation is widely used. For this purpose the frequency fluctuation measurement function is developed and implemented. The measured SEL frequency is processed at 1 kHz or 10 kHz sampling rates and this result can be stored and exported from LLRF.

The measurement of microphonics at SRF test facility with QWR cavity was performed. Selected measurement result is shown in Fig. 7. The measured frequency fluctuation is useful for the microphonics suppression. For the successful operation of cryomodule, this experiment will be continued at SRF test facilities and tunnel to find and to suppress the microphonics perturbation.



(a) Frequency fluctuation according vs time (b) FFT result of measured frequency fluctuation

Figure 7: Frequency fluctuation measurement test result at RISP SRF Test Facility with QWR cavity.

CONCLUSION

The design of the developed LLRF for RAON SRF TF and its test results were described. It adopted the RF direct sampling, digital-based RF processing technology and the GDR and SEL RF control algorithms were implemented. It was tested during the vertical test and the cryomodule test at SRF TF and it could track the resonance frequency, lock the amplitude and the phase of the cavity. We could verify that it can satisfy the requirements for the SRF cavity testing and operation. Nowadays the test of the cavities and cryomodules for the construction of SCL3 are ongoing and the the accelerator commissioning at the accelerator tunnel will be conducted in the near future.

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