DESIGN OF LLRF SYSTEM FOR RAON

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Abstract

A low-level RF (LLRF) system has been designed for the RAON superconducting linear accelerator system, which will be used for rare isotope beam research. The LLRF system is used to feed the superconducting cavities, having frequencies of 81.25 MHz, 162.5 MHz, and 325 MHz, with the controlled amplitude and phase of the RF. A prototype LLRF operating at 81.25 MHz was designed and fabricated for the superconducting quarter-wave resonator. The system uses a field programmable gate array (FPGA) to control the RF amplitude and phase within ±0.5% and ±0.4%, respectively. The resolution and working range are 0.01 dB and 15 dB in amplitude, respectively, and 0.5° and 360° in phase. The RF amplitude and the phase are designed to be controlled by a PID feedback control for keeping the voltage stability of the cavity within 1 %. This paper will describe the design in detail. Furthermore, the testing results of the LLRF prototype system will be presented.

INTRODUCTION

RAON is a superconducting linear accelerator for rare isotope beams to be built at the Institute for Basic Science in Daejeon, Korea. For the construction of RAON, the Rare Isotope Science Project (RISP) was approved in 2011 [1, 2].

For the production of the rare isotope beam, two methods are used for RAON. One is in-flight fragmentation method with a superconducting linear accelerator. The other method is Isotope Separation On-Line (ISOL) which uses a 70-MeV proton cyclotron. Both methods need for the superconducting linac as the driver. The superconducting cavities of RAON have three kinds of cavities, a quarter wave resonator (QWR), a half wave resonator (HWR), and two types of single spoke resonator (SSR1 and SSR2).

The operation frequencies are 81.25 MHz, 162.5 MHz, and 325 MHz for the QWR, the HWR, and the SSR1 and SSR2, respectively. Highly-charged heavy ion beams which are accelerated by an injector and an RFQ are injected into the superconducting linac. The injector and RFQ are needed to feed relatively high RF power because of high levels of dissipated power. The normal conducting cavity of the RFQ is supplied with RF power operating at a frequency of 81.25 MHz.

An RF system is not only used to feed RF to the injector and the superconducting linac, but also to control RF. The RF system is composed of a low-level RF (LLRF) and a high-power RF (HPRF). For the high-power RF, solid state power amplifiers (SSPA), which are also controlled by the LLRF system, are used for RAON [3].

In this paper, some details of the design and the test results of the prototype LLRF system are presented. In Section 2, the design of the prototype of the 81.25 MHz LLRF is described. In Section 3, the setup for the test process and the test results of the proportional-integral-derivative (PID) feedback control of the prototype LLRF are provided. In Section 4, a summary is provided and future work is described.

DESIGN OF LLRF SYSTEM

One purpose of a LLRF system is the controlling of the RF amplitude and phase of the accelerating RF field in the cavities. The LLRF should perform:

- RF signal generation and distribution
- Feedback and feedforward control for the stability of the accelerating field in the cavity
- Interlock for the protection of the SSPA (high-power RF system)

Some of the major obstacles of the LLRF system are to perturbations such as SSPA drop and ripple, temperature variations, beam loading, multipacting, field emission, and quenching [4, 5]. The LLRF system for RAON uses the PID feedback control and a feedforward control to suppress the perturbations. Table 1 shows the technical specifications of LLRF system for the RAON.

A prototype LLRF system operating at 81.25 MHz was developed and fabricated to deliver the RF to the QWR. A block diagram of the prototype LLRF system is shown in Figure 1.

Table 1: Technical specifications of the LLRF system

Factor	Specifics
Frequency	QWR: 81.25 MHz
	HWR: 162.5 MHz
	SSR: 325 MHz
Cavity bandwidth	± 20 Hz
Gradient	> 10 MV/m
Amplitude stability	0.4 %
Phase stability	0.5 degree
Stability of mechanical tuner	± 20 Hz

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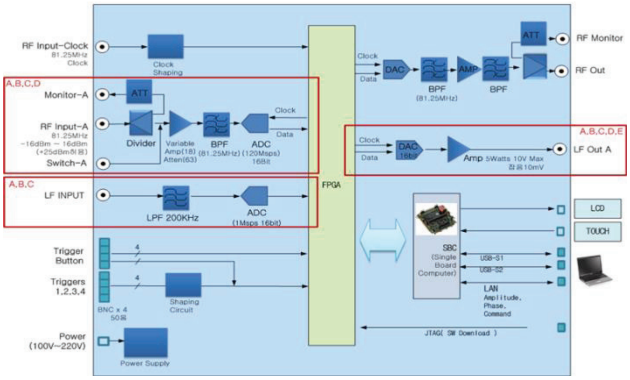

Figure 1: Block diagram of the prototype LLRF.

The prototype LLRF consists of a clock module, a phase-amplitude detector (PAD), a phase-amplitude controller (PAC), a main board (FPGA) and a host system. The clock module is used for synchronized operation of the RF system. A local frequency (81.25 MHz) and a sampling frequency of 108.33 MHz i.e., four-thirds of local frequency are generated by the clock module.

The PAD, which combines the RF input and the local frequency given by the clock module, provides a converted a low frequency (IF) signal to the FPGA.

The PAC, which mixes the IQ signal given by the FPGA and the local frequency with IQ modulator, generates an output RF signal.

The FPGA, which performs a computation such as an averaging, a standard deviation, the captured analogue-digital converted data and converting the dB and degree using the IQ values, provides the PID feedback control. The FPGA is connected to temperature sensors to measure the temperature. For the temperature monitoring, the measured temperatures are provided to the host system.

A configuration of the LLRF is displayed by the host system. For the target phase and amplitude, the PID is controlled by the host system. And the phase and amplitude are calculated and calibrated using IQ data. The calculated data is saved in an archive. The data can be also monitored in real time.

The PAD and the PAC are fast analogue parts and the FPGA is a digital control part. An analogue-digital convertor (ADC) and a digital-analogue convertor (DAC) are used to communicate between the fast analogue parts and the digital control part.

The operation ranges of amplitude and phase are from -15 to 10 dBm and from 0 to 360 degrees, respectively. The target resolutions are 0.05 dB for amplitude and 0.1 degrees for phase.

TEST RESULTS

A sweep signal generator was used as a clock signal for the prototype LLRF. The clock signal has a power amplitude of 0 dBm with a frequency of 81.25 MHz. Self-consistent tests for the PAD and the PAC were completed.

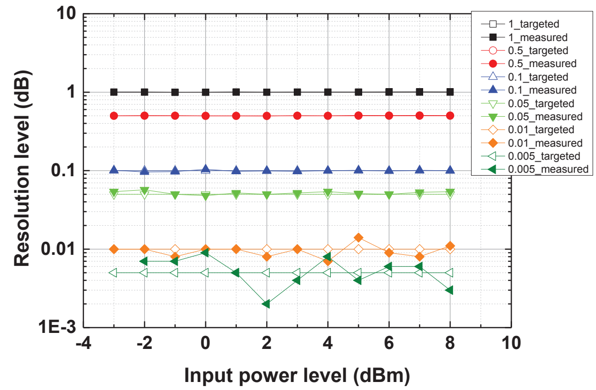

Figure 2: Power resolution of the prototype LLRF.

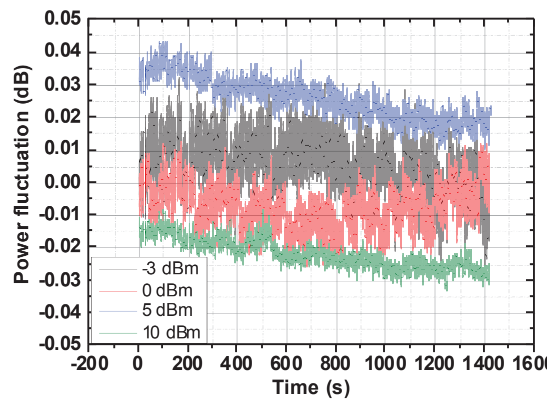

Figure 3: Amplitude stability of the prototype LLRF without feedback control.

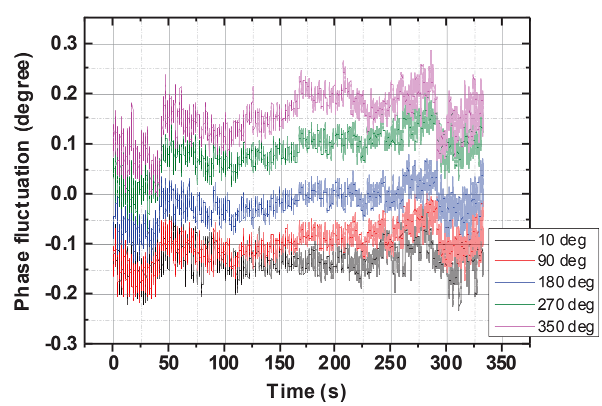

Figure 4: Phase stability of the prototype LLRF without feedback control .

The detected power amplitude was compared using a spectrum analyzer and a power meter.

The PAD was tested for dynamic range stability. The clock signal is divided by 3dB divider. The divided signals are inputted to a reference channel and an input channel, channel A or B. The signal of the input channel A or B is compared with the reference signal. The deviations are less than 0.03% for the amplitude and 0.02 degrees for the phase.

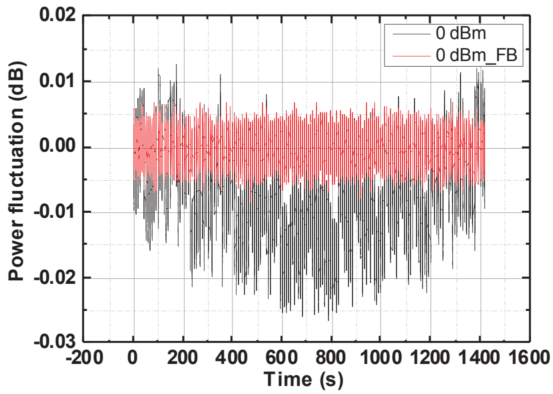

Figure 5: Amplitude stability of the prototype LLRF: compared with no feedback control and PID feedback control.

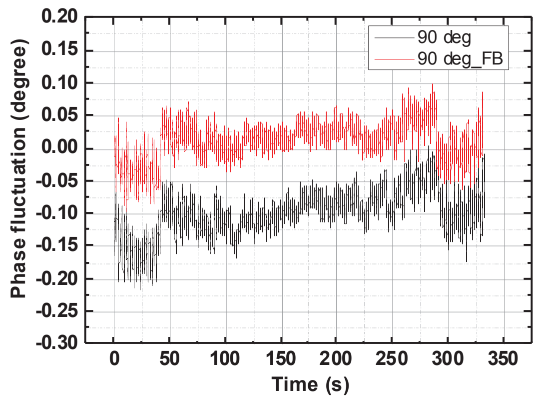

Figure 6: Phase stability of the prototype LLRF: compared with no feedback control and PID feedback control.

The PAC resolution test of the prototype LLRF system was conducted to evaluate the power resolution. Except for the RF output channel (PA controlled channel), input channels (channel A and B) are terminated by a 50 ohm termination for the resolution test. When the target power varied at the host system, the PA controlled power from the PAC was measured by the power-meter. The variation steps are 1, 0.5, 0.1, 0.05 and 0.01 dB. Figure 2 shows the power resolution result. The LLRF is operated with a power resolution less than 0.05 dB for the whole range of the input power.

The power amplitude stability has been measured. When the power amplitude was fixed (-3, 0, 5, and 10 dBm), the phase was swept from 0 to 360 degrees and vice versa from 360 to 0 degrees with 0.5 degree steps. During the phase sweep, the power amplitude was measured. The maximum amplitude fluctuation is 0.9% at fixed amplitude of 5 dBm without feedback control (Figure 3).

The phase stability has been measured in the same way. When the phase was fixed (10, 90, 180, 270, and 350 degree), the amplitude was varied from -3 to 10 dBm and 10 to -3 dBm with a step size of 0.05 dB. The maximum phase fluctuation is measured to be 0.24 degrees for 90 degrees without feedback control (Figure 4).

The power amplitude drifts as time goes on. When the PID feedback control was performed, this amplitude fluctuation was reduced to 0.1% and the amplitude drift vanished (Figure 5).

Figure 6 shows that the phase fluctuation is reduced to 0.17 degrees by the PID feedback control. The phase difference between the measured phase and the targeted phase is also reduced when the PID feedback control is performed.

The power amplitude and phase are less than the target stabilities of the amplitude and phase i.e., 0.4 % and 0.5 degrees for the QWR voltage stability of 1% (Table 1).

SUMMARY AND FUTURE WORK

A prototype 81.25 MHz LLRF for the QWR of RAON was designed and tested successfully. The stabilities of the PAD are less than 0.03% for amplitude and 0.02 degrees for phase. The LLRF is operated with power resolution less than 0.05 dB for the whole range of input power. Maximum fluctuations are 0.9% for amplitude and 0.08 degrees for phase without the feedback control. With the PID feedback control, the targeted stabilities are achieved for whole range of the input power. The test results are in good agreement with the specifications of the LLRF.

In 2013, the integrated test will be carried out employing the SSPA, and later, the superconducting cavities. For the coupled test, an interlock will be developed to protect the SSPA and the superconducting cavities under abnormal conditions. The feedforward control is more effective than the PID feedback control for repetitive perturbation, therefore the feedforward control will be added to improve the operating stability.

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