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EXPERIMENTAL TEST OF THE PROTOTYPE LLRF SYSTEMS FOR PAL-XFEL*

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Abstract

Two prototype LLRF systems were developed in collaboration with Pohang Accelerator Laboratory(PAL) and domestic companies. They are focused on the control of single klystron system to obtain mainly analogue performance. The low power test of the developed LLRF showed good performance previously. We experimentally tested LLRF in the klystron systems to see performance in the high power situation. They showed performance around the prototype specification for short time and relatively long time. During test some bugs are discovered and fixed..

INTRODUCTION

PAL-XFEL project is underway at Pohang Accelerator Laboratory(PAL). The first lasing of PAL-XFEL is expected in 2016. PAL-XFEL machine is mainly composed of S-band normal conducting accelerating columns to achieve 10 GeV electron beams for hard X-ray radiation.

The updated requirement of RF field stability of PAL-XFEL is below 0.02 % in amplitude and below 0.03 ° in phase [1]. The targets of RF stability in rms for the prototype LLRF system is 0.05 % in power and 0.05 ° in phase.

To satisfy the requirement of PAL-XFEL, Various development projects in RF system started several years ago. The developed LLRF system is comprised with LLRF system itself and Solid-State Amplifier(SSA). For convenience, we call the former as LLRF, and the latter as SSA. LLRF generates RF pulses with a few mW, and detects RF pulses with similar power levels. SSA receives RF pulses from LLRF, and amplifies to RF pulses with 800 W peak power to drive klystron.

Two LLRFs are independently developed in cooperation with two local companies (Fig. 1). These have common features. Each LLRF receives 2.856 GHz reference RF and trigger. It internally has a module generating local frequency and clock frequency. Each LLRF has a module generating RF pulses, which we call PAC(Phase Amplitude Controller). PAC generates RF pulses with the length 0.5~7 μs, and the rate of repetition 1~60 Hz. It also has the function of 180 ° PSK(Phase Shift Keying) to operate SLED(SLAC Energy Doubler). It uses FPGA, 16 bit DAC, and IQ modulation to generate RF pulses.

Each LLRF has a module detecting RF pulses, which we call PAD(Phase Amplitude Detector). PAD detects 10 RF pulses. It uses IQ demodulation to analyse RF pulses. It can measure phase, amplitude, waveform, and the pulse-to-pulse rms stability of RF pulses. FPGA and 16bit ADCs are used to process signals.

Each LLRF has local feedback function using PI method within FPGA.

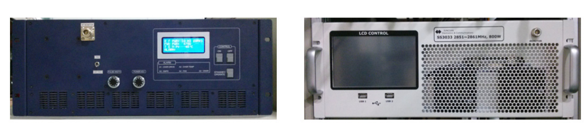
These two LLRFs have differences. LLRF-A uses two mixers for IQ modulation and demodulation, but LLRF-B uses one mixer for the same functions. LLRF-A uses IF frequency of 29.75 MHz and clock frequency of 238 MHz (x8 of IF) for IQ processing, but LLRF-B uses IF frequency of 22.3125 MHz and clock frequency of 89.25 MHz (x4 of IF) for IQ processing.

Two SSAs are independently developed in cooperation with two local companies (Fig. 2). Each SSA receives RF pulses with about 0 dBm, and amplifies RF pulses with 800 W peak power. It uses RF power transistors, and cascading of these chips to make target RF power.

These two LLRFs and SSAs were tested and satisfied the required specification. The rms RF stability requirements <0.05 % in power and <0.05 ° in phase were also satisfied at the output of SSAs [2,3].

(a) LLRF-A (b) LLRF-B

Figure 1: Two LLRFs developed.



(a) SSA-A (b) SSA-B

Figure 2: Two SSAs developed.

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Evaluation of LLRF systems connected to the actual klystron system is important. Connection of LLRF and SSA with klystron and modulator can reduce the stability performance. The noisy field of modulator can damage LLRF and SSA to work incorrectly. In addition to the performance, the applicability of LLRF system must be checked. So, we tested after installation of LLRF system to high power RF system(klystron and modulator). In the following, we present the results of test.

HIGH POWER TEST

The stability performance was verified at ITF(Injector Test Facility) within PAL configured as Fig. 3. LLRF receives a reference 2.856 GHz CW signal and a synchronized trigger signal. ITF synch. generator makes the synchronized trigger with 0.992 MHz divided from 2.856 GHz and 120 Hz from AC 60Hz. LLRF PAC generates 2.856 GHz RF pulses, which enter to SSA. SSA amplifies to 800 W RF pulses, which enter to klystron. Klystron amplifies to a few 10 MW RF pulses, which are propagated by waveguide network. Klystron is E3712 from TOSHIBA and can generate up to 80 MW pulses.

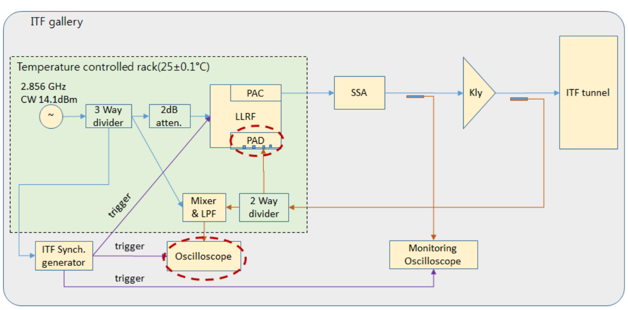

Figure 3: Stability measurement setup.

The modulator supplying DC to the klystron is developed at PAL. It has the rms stability slightly not meeting PAL-XFEL requirement(50 ppm for modulator). The newly developed modulator for PAL-XFEL satisfies the requirement.

The forward power of the klystron is picked up and divided into two. One of the two is sent to PAD. The other is sent to Mixer measurement device.

Some temperature sensitive parts are installed within the temperature controlled rack which maintains 25±0.1 °C.

First, LLRF internally calculates stability from the PAD input as follows. The signals sent to PAD are AD converted by 16 bit ADC. The amplitude and phase are calculated for each RF pulse. The rms stabilities in amplitude and phase are calculated for 100 pulses. The calculated values are used for the verification.

Second, The phase stability is measured using mixer and LPF (Low Pass Filter) as follows [4]. Mixer receives the 2.856 GHz reference signal and the 2.856 GHz RF pulse picked up from klystron forward power. The mixer followed by LPF then generates the phase as DC voltage. We measure the phase stability using this voltage sequence with oscilloscope.

Because two LLRFs and two SSAs are developed, the test is done for all the 4 possible combinations of. The test is done for the cases for short-term(3 min) and relatively long-term(2 hours), and with Feedback ON and OFF.

The operation conditions for the test are as follows. The voltage of modulator is 35 kV. RF pulse width is 1.5 µs. The rate of repetition is 10 Hz.

Figure 4 and 5 show LLRF PAD measurement results of klystron forward power. It is seen that SSA-A and SSA-B show very similar result and the difference comes mainly from LLRFs for all cases.

From 3 min short-term measurement (feedback off), the stability performance of LLRF-SSA-klystron connection is shown. LLRF-A connections show the rms stabilities of 0.025 % in power(0.0125 % in voltage) and 0.037 ° in phase and LLRF-B connections show the rms stabilities of 0.038 % in power(0.019 % in voltage) and 0.027 % in phase. All the connections satisfy the targets 0.05 % in power and 0.05 ° in phase. The updated targets 0.02 % in voltage and 0.03 ° in phase for PAL-XFEL are nearly satisfied.

From relatively long-term measurement for 2 hours (feedback on), the feedback performance is verified. LLRF-A connections and LLRF-B connections all show that the stabilities are slightly worse than those cases of feedback off, but remain within the target 0.05 % in power and 0.05 ° in phase, and target amplitude and phase are well tracked by feedback. To satisfy the updated targets for PAL-XFEL(0.02 % in voltage and 0.03 ° in phase), LLRF systems should be improved in stabilities and feedback algorithms.

To crosscheck the results of PAD measurement, the analogue phase measurement using mixer and LPF are performed. The results are shown in Fig. 6. It is shown from Fig. 6 that LLRF-A connections show slightly bigger value in phase stabilities than LLRF-B connections, and both connections satisfy the target 0.05 ° in phase, which confirm the PAD measurements.

DEBUGGING

Several system bugs during the test were discovered and fixed.

Impedance mismatching of trigger was discovered. LLRFs were designed to receive 1 MΩ TTL as usual, but in accelerator environment 50 Ω was the impedance of trigger. This mismatching of trigger caused wrong action of LLRFs. By changing the impedance of LLRFs to 50 Ω, the problem was solved.

The developed LLRFs missed the important relation between IF and trigger. The generated RF pulses of LLRFs showed periodic trembling around triggered time. It was a critical problem because it can cause trembling of electron beams. It was verified through an experiment that the signals used for the generation of synchronized trigger should be synchronized with IF of IQ modulation and

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demodulation as well as reference RF signal. The above result was applied to the current prototype LLRFs and will be to the systems for PAL-XFEL.

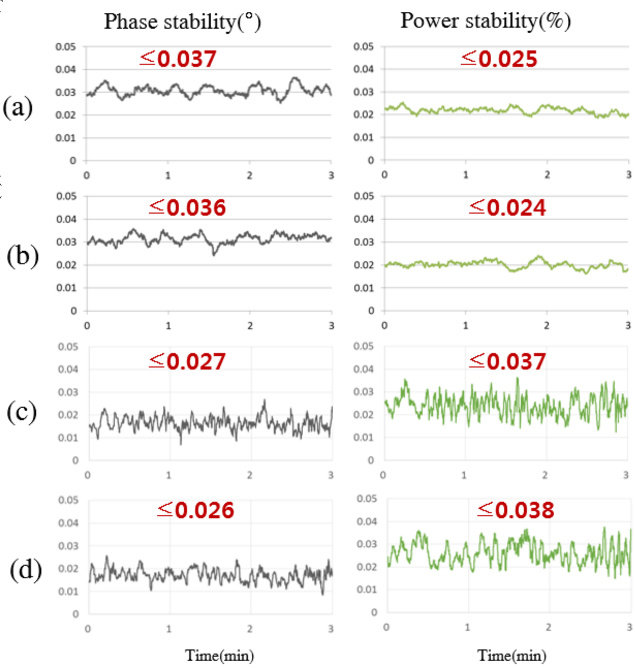

Figure 4: Short-term stability results. (a) LLRF-A and SSA-A connection, (b) LLRF-A and SSA-B connection, (c) LLRF-B and SSA-A connection, (d) LLRF-B and SSA-B connection.

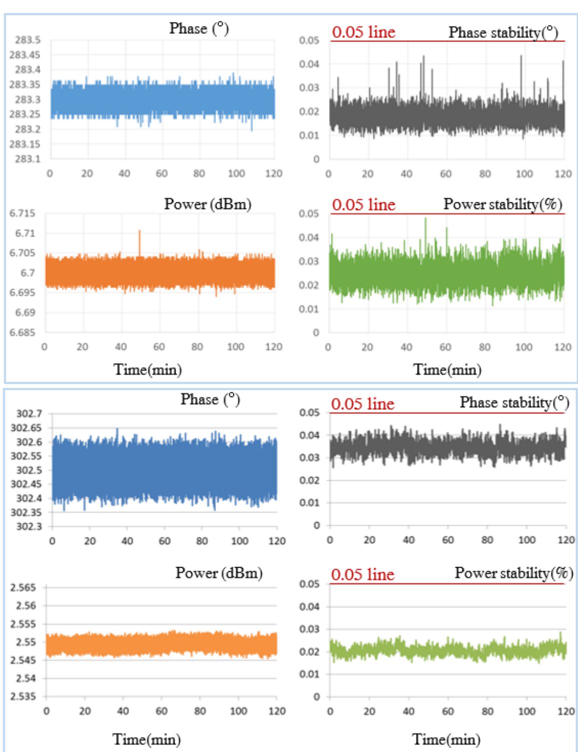

Figure 5: long-term stability results. (a) LLRF-B and SSA-B connection, (b) LLRF-A and SSA-B connection.

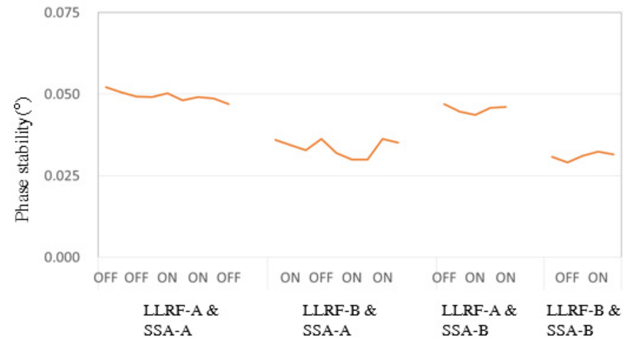

Figure 6: Results of analogue mixer measurement. ON/OFF means feedback ON/OFF.

CONCLUSION

Two prototype LLRF systems are developed in cooperation with local companies. To evaluate LLRF systems in the actual situation, high power test connected with klystron system was executed showing the satisfaction of the stability targets 0.05 % in power and 0.05 ° in phase set for the prototypes, and the slight lack for the PAL-XFEL targets(0.02 % in voltage and 0.03 ° in phase).

Through the test, some important bugs are found and fixed. These are synchronization issue, trigger impedance matching.

Currently an upgraded LLRF system for PAL-XFEL is on development, which include beam synchronous acquisition, and beam-based feedback functions.

ACKNOWLEDGMENT

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