DEVELOPMENT OF A NEW LLRF SYSTEM BASED ON MicroTCA.4 FOR THE SPring-8 STORAGE RING

T. Ohshima[†,1], H. Maesaka, N. Hosoda[1], T. Fukui, M. Ishii[1],
RIKEN SPring-8 Center, Hyogo, 679-5148, Japan
[1]JASRI, Hyogo, 679-5198, Japan
H. Ego, KEK, Ibaraki, 300-3256, Japan

Abstract

The renewal of the low-level RF system for the 3rd generation synchrotron radiation facility, SPring-8, is underway. The RF system of the storage ring is composed with single-function analog modules, which are obsolete and hard to be maintained. Therefore, the system will be replaced with a modern digital system using MTCA.4 modules. The amplitude and phase of an RF signal will be detected with an under-sampling scheme because of simple composition and robustness to the ambient parameter changes. For this purpose, we are developing new MTCA.4 modules: a digitizer AMC having a sampling rate of 370 MHz and 16-bit resolution, and a signal conditioning RTM. In parallel, we have developed an amplitude and phase stabilizing software for the new RF system and built a prototype system with commercially available MTCA.4 modules with a mixer-downconverter. A motor driver controlled through EtherCAT is newly adopted to the cavity tuner control. The prototype was tested at a high-power RF test stand. The acceleration RF voltage was successfully regulated with the amplitude and phase stabilities of 0.1% and 0.1 degree in rms, respectively. Tests with the newly developed AMC and RTM will be carried out soon. The installation of the digital system to one of the four RF stations of the storage ring is planned in summer 2017.

INTRODUCTION

SPring-8 is one of the largest 3rd generation synchrotron radiation facilities [1]. It has been providing bright x-rays to users since 1997. There are four RF stations in the SPring-8 storage ring to provide enough acceleration field and to compensate the energy loss of the stored beam. Each station has a 1 MW klystron and eight accelerating cavities operated with an RF frequency of 508.58 MHz. The Low Level RF (LLRF) system stabilizes the amplitude and phase of the accelerating field of the RF cavities. The current LLRF system was built with combination of single-function analog modules [2]. Because over 20 years have been passed since the installation, it becomes difficult to maintain these modules.

In addition, an upgrade plan of SPring-8 is in progress [3]. In this plan, the beam emittance is lowered by introducing multi-bending optics and reducing the beam energy from 8 GeV to 6 GeV. The accelerating voltage is reduced from 14.3 MV to 7 MV. The synchrotron frequency is reduced from 1.8 kHz to 0.68 kHz. The required amplitude and phase stabilities of the accelerating field are better than 1E-3 and 0.1 degree, respectively, which are similar values for the present storage ring. To suppress the coherent synchrotron oscillation amplitude of the stored beam [4], we have to reduce the phase noise of the accelerating voltage near the offset frequency of 0.68kHz at the new ring. It is one of challenging tasks, because it is difficult to suppress the noise of harmonics of AC cycle caused from, such as the ripple of a klystron power supply of 720 Hz.

From the reasons described above, we decided to upgrade our LLRF system [5]. LLRF modules of the MicroTCA.4 standard [6] have been developed at DESY for EuroXFEL. We decided to use this standard for our system because it has a small form factor, high speed communication performance and flexibility which enables complicated digital control.

In this paper, the configuration of the new LLRF system is shown. Then, the result of performance test is presented.

LLRF SYSTEM WITH MTCA.4

The RF system for the SPring-8 storage ring is composed of following apparatus; a high-power klystron with a high-voltage power supply, the eight accelerating cavities, LLRF modules which stabilize the amplitude and phase of the cavity accelerating field, the cavity tuners to adjust the resonant frequency with motorized plungers, the vacuum pumps for the accelerating cavities, a cooling system of cavities.

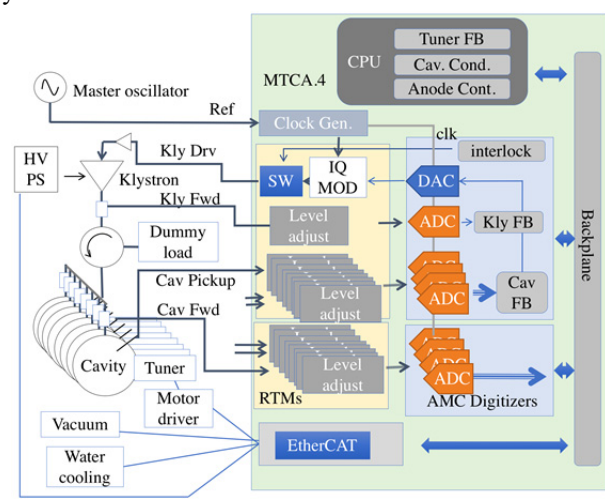

Figure 1: Block diagram of digital LLRF system.

The hardware of the new LLRF system is composed of a digitizer Advanced Mezzanine Card (AMC), a signal

† ohshima@spring8.or.jp

conditioning Rear Transition Module (RTM), a MicroTCA Carrier Hub (MCH), as shown in Fig. 1. Ethernet for Control Automation Technology (EtherCAT) [7] was selected as a field bus for a motor controller and a digitizer to monitor slowly varying analog signals, such as the vacuum pressure of the cavity. There are about 30 RF signals from RF units. So, we use multiple signal-conditioning cards to digitize these signals. To deliver the reference clock and the ADC clock to the cards, we use RF backplane so as to reduce the interconnecting cables.

An under-sampling scheme is used for the RF detection because it is more insensitive to the ambient parameter change compared to a mixer-based down conversion scheme, and the composition of the signal conditioning RTM is simple. The amplitude and phase of the rf signal are calculated from the digitized sinusoidal data by applying digital down-conversion (DDC). The variations of the amplitude and phase at the eight accelerating cavities are compensated by a numerical amplifier and a phase rotator (Aϕ). The cavity pickup signals are vector summed to form the station accelerating voltage. The phase and amplitude of the signal are stabilized to the set value with a Proportional and Integral (PI) feedback processes implemented in the Field Programmable Gate Array (FPGA). We use two feedback control loops: a cavity loop and a klystron loop. The bandwidth of the cavity loop is set to ~100Hz, because the changing speed of the perturbations, such as the temperature change of the cavity, is slow. The fast change of the amplitude and phase caused by the ripple of the klystron high voltage power supply is compensated by the klystron loop. Its bandwidth is set to ~20 kHz. Figure 2 shows the block diagram of the feedback processes.

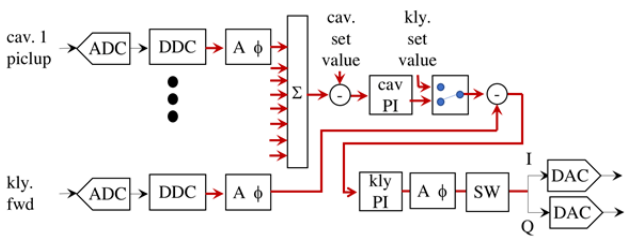

Figure 2: Block diagram of the phase and amplitude stabilization process implemented in the FPGA of the digitizer.

An interlock signal is fed into the signal conditioning RTM through the AMC to turn off the RF switch, when the system detects the abnormal states, such as an excess of the reflected power from the cavity, arcing at the input coupler of a cavity. To protect the damage from the arcing at a ceramics window or a cavity wall, the response time to turn off the RF switch should be within several micro second. This interlock procedure is implemented to the FPGA of the digitizer.

A tuner control process is implemented on a CPU module. Since the phase difference between the cavity pickup signal and the cavity forward one is almost proportional to the resonant frequency near the resonance condition, the tuner position is controlled by this phase signal.

The anode voltage control of the klystron high voltage power supply is also implemented on the CPU. Because the output power of the klystron is widely varied from 1 kW at a startup stage to 800 kW at a steady operation state, the anode voltage control is required in addition to the drive RF power control of the klystron.

A cavity conditioning process is implemented on the CPU module. It gradually increases the klystron power to an aimed value, keeping the vacuum pressure of the cavity to be sufficiently low. If the pressure exceeds the threshold value, it stops increasing the power until the recovery of the pressure.

NEW MTCA.4 MODULES

We searched for suitable MTCA.4 modules for under sampling at 508.58 MHz input signal. DESY group has developed the signal conditioning RTMs at an operating frequency of 1.3 GHz, 700 MHz with down conversion type. But we could not find suitable modules for our purpose. Therefore, we decided to develop a new digitizer AMC and a signal conditioning RTM. The new digitizer AMC has a fast sampling rate of 370 Ms/s with 16-bit resolution. The module has 10 channel digitizer input and 2 channel DAC output. Our new signal conditioning RTM has a nine channel RF inputs, one baseband input and one vector modulation output. The nine single ended inputs are converted to differential signals with baluns. Its bandwidth is 400 MHz to 600 MHz. Figure 3 shows a photo of the signal conditioning RTM and the fast digitizer AMC.

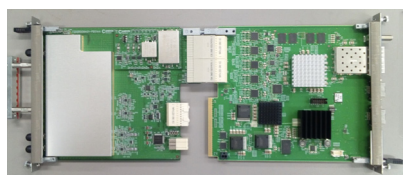

Figure 3: Photo of a new digitizer AMC and a signal conditioning RTM.

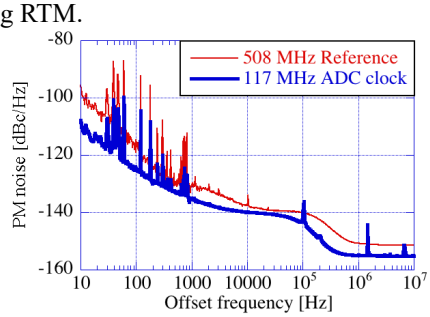

Figure 4: Phase noise of a 508 MHz reference input signal (thin line) and a 117 MHz output signal (thick line) from the clock eRTM as a function of the offset frequency.

We also fabricated an extended Rear-Transition-Module (eRTM) to deliver the reference 508.58 MHz signal and the ADC clock to the signal conditioning RTMs through the RF backplane. It generates nine RF outputs and eleven clock outputs to the RF backplane. Figure 4 shows an example of the phase noise of the ADC clock signal generated from the eRTM. The reference

ISBN 978-3-95450-182-3

input frequency is 508.58 MHz and its phase noise is shown with a red line. The phase noise of the output frequency of 117 MHz, which is 3/13 multiple of the input reference frequency, is also shown with a blue line. The integrated phase noise of the input and the output signals were 65 fs and 140 fs in rms, respectively. The value of 140 fs corresponds to the phase variation of 0.025 degree at 508.58 MHz signal, and is sufficient for our purpose.

SOFTWARE TEST WITH COMMERCIALLY AVAILABLE MTCA.4 MODULES

Because of our tight schedule, we must develop software programs for the MTCA.4 system in parallel with production of the new hardware. So, the programs were developed with the commercially available modules; a SIS8300L2 digitizer AMC [8] and a DWC8VM1 down conversion and vector modulation RTM [8]. Most part of the programs developed with the mixer-based down conversion scheme can be reused for that with the under-sampling scheme. A high-power test of the programs was carried out at an RF test stand of SPring-8. The configuration is similar to that shown in Fig. 1. The major differences were a mixer type down conversion was adopted, the number of cavity was one instead of eight, the anode voltage control was done by an old analog module, the interlock signals were handled by the old modules and the summed interlock signal was fed to the RTM module.

We measured the dependence of the cavity reflection power as a function of the tuner position with a constant klystron output power. Figure 5 shows the result. The tuner position was successfully controlled through the EtherCAT motor controller. The RF signal amplitude and phase as a function of the tuner position were measured. The target value of the tuner control process was set to the phase angle at the minimum reflection condition in order to maintain the resonant frequency.

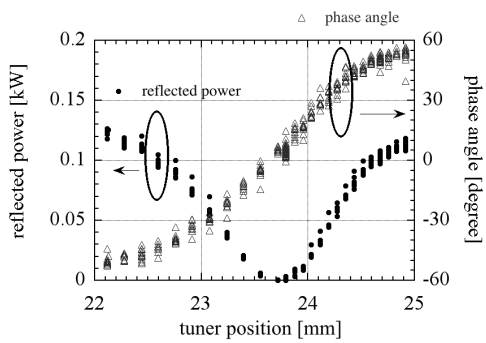

Figure 5: Reflected power from the cavity (filled circle) and the phase angle between the forward and the pickup signals (open triangle) as a function of the tuner positon.

After the tuner process was set up, the performance of the cavity conditioning process was checked. Figure 6 shows an example of conditioning status. The cavity forward power was gradually increased with watching the cavity pressure not to exceed the threshold value of 1.45E-6 Pa.

The stabilities of the amplitude and phase of the pickup signal of the cavity at a steady condition were 2.9E-4 and 0.10 degree in rms, respectively. While these results satisfy the requirements, the stabilities can be further improved by tuning the PI parameters of the feedback control loops and by replacing the ADC clock generator with the new clock eRTM which can provide a low phase noise clock.

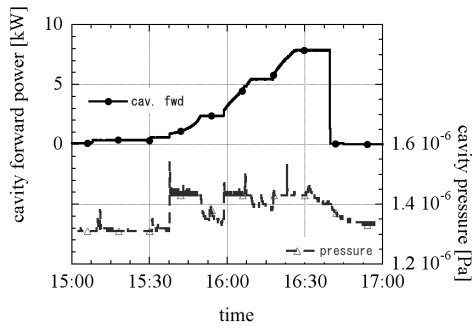

Figure 6: Trend graph of the cavity forward power and vacuum pressure of the cavity.

SUMMARY

The current analog LLRF system of the SPring-8 storage ring will be replaced to digital one. We have developed a AMC and a RTM modules for the under-sampling scheme. These modules were fabricated and wait for performance test after small modifications. Software programs for MTCA.4 modules were prepared using commercially available modules. Tuner control process through EtherCAT field bus was successfully operated. Cavity conditioning process also worked as expected. The phase and amplitude stability of the cavity at the high-power test was 2.9E-4 rms and 0.10 degree rms, respectively, which already satisfy the requirements. Further tests, such as optimization of feedback parameters, adoption of the new AMC and RTM, will be carried out at the test stand soon. Replacement of one of the four RF stations will be carried out in FY 2018.

ACKNOWLEDGEMENT

The authors thank H. Schlarb, L. Frank, and R. Kay for their help in handling the MTCA modules. They also thank the operators at SPring-8 for their help during the high-power test and coding the programs for MTCA.4 modules.

REFERENCES

[1] http://www.spring8.or.jp

[2] M. Hara et al., “RF Stations of the SPring-8 Storage Ring”, in Proc. PAC’97, Vancouver, Canada, May 1997, paper 4P028, pp. 2971-2973.

[3] H. Tanaka, et al., “SPring-8 Upgrade Project”, in Proc. IPAC2016, Busan, Korea, May 2016, paper WEPO019, pp. 2867-2870

[4] T. Ohshima, N. Kumagai, “Suppression of Coherent Synchrotron Oscillation of the SPring-8 Storage Ring”, in Proc.

PAC'01, Chicago, U.S.A., June 2001, paper TPPH132, pp. 1975-1977.

[5] H. Ego et. al., "RF System of the SPring-8 Upgrade Project", Proc. Of IPAC2016, Busan, Korea, May 2016, paper MOPW009, pp. 414-416

[6] http://mtca.desy.de

[7] http://ethercat.org

[8] http://www.struck.de

ISBN 978-3-95450-182-3