RF SYSTEM OF THE SPring-8 UPGRADE PROJECT

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Abstract

In the upgrade project of the SPring-8 storage ring, a beam energy is lowered from 8 to 6 GeV. The upgrade employs multi-bending optics to have a beam emittance of approximately 100 pm.rad and shortens the straight sections available for RF accelerating cavities by 30%. The total 16 bell-shaped single-cell cavities are installed in the sections and generate a needed accelerating voltage of 7 MV. The old-fashioned analogue LLRF system in use is to be replaced with a compact digital system based on the under-sampling scheme and the MTCA.4 standard. The SACLA linac is to be used as an injector of a low-emittance beam to the ring. We build a timing system to inject the beam to a target bucket-position in the ring within a time deviation of 3 ps. Since the X-ray FEL operation and the beam injection must be balanced on demand, a pulse-by-pulse control system for beam parameters of SACLA is going to be implemented to the SACLA LLRF system.

INTRODUCTION

The role of an RF acceleration system of a storage ring is to generate a sufficient beam-accelerating voltage and compensate for beam-energy loss caused by synchrotron radiation in bending magnets and insertion devices. The RF system of the SPring-8 storage ring has stably generated a voltage of 16 MV at a frequency of 508.580 MHz and accelerated an electron beam with a current of 100 mA since 1997 for synchrotron-radiation users. In operation of user experiments, an RF power of 2.8 MW is generated by klystrons in four RF stations and supplied to 32 bell-shaped single-cell cavities in straight sections of the storage ring [1]. Figure 1 shows the layout of the accelerators of SPring-8 and RF stations of the storage ring.

Figure 1: SPring-8 Accelerator complex. SR: Storage ring, Sy: 8 GeV Booster synchrotron, Li: 1 GeV Injector linac, A-D: RF stations, and SACLA: 8 GeV XFEL.

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Table 1: Parameters of the RF System of the Upgrade Ring

Beam energy [GeV]	6
Beam current [mA]	100
Operating frequency [MHz]	508.756
Radiation loss per turn	
in bending magnets [MeV]	3.0
in insertion devices [MeV]	2.0
Beam accelerating voltage [MV]	7
Over-voltage ratio	1.4
Circumference [m]	1435.45
Harmonic number	2436
Beam revolution frequency [kHz]	208.849
Natural energy spread [%]	0.0926
Synchrotron frequency [Hz]	680
Betatron function at the cavity position	
Horizontal [m]	5.50
Vertical [m]	3.00
Momentum compaction factor	3.32×10^{-5}
Bunch length [ps] rms	8
Number of RF stations	4
Number of RF cavities	16
Shunt impedance of the cavity [MΩ]	6
Total wall-loss in the cavities [kW]	510
Beam loading power [kW]	500

In the upgrade of the SPring-8, a beam energy is lowered from 8 to 6 GeV to promote the decreases in beam emittance and power consumption [2, 3]. The new storage ring employs multi-bending optics to have a beam emittance of approximately 100 pm.rad, and the straight sections are to be shortened by 30%. Therefore, the number of cavities must be reduced to half and the waveguide circuit for high-power transmission are rearranged.

Table 1 shows the parameters related to the RF system of the upgrade ring. Energy losses by radiation in bending magnets and insertion devices are 3 MeV/turn and 2 MeV/turn, respectively. An accelerating RF voltage of 7 MV is demanded so that the beam can have the sufficiently longer quantum lifetime than the dominant Touschek lifetime [2]. It is easily generated with the 16 cavities. The operating frequency is changed from 508.580 to 508.756 MHz at the request of the new optics [4]. All the RF components can be used at the changed frequency without any mechanical modification. We reuse the high-power RF components satisfying the requests in the upgrade, taking cost-effectiveness into account.

On the other hand, the analogue LLRF system in use [5] becomes out-of-dates and hard to be maintained though the system regulates the RF accelerating voltage with sufficient stabilities in Table 2. We plan to replace it with a compact digital LLRF system in the MTCA.4 standard [6] and based on the under-sampling scheme.

The linac of SACLA, an 8 GeV XFEL, is going to be shared as an injector instead of the 8 GeV booster synchrotron and 1 GeV linac of SPring-8 [2, 7, 8]. A new system precisely synchronizing SACLA with the storage ring is under development since a low-emittance and ultra-short pulse-width beam must be conveyed from SACLA to the upgrade ring with a small dynamic aperture. We must control a beam of SACLA pulse-by-pulse and on demand to balance the injection and the X-ray laser operation.

Table 2: Requirements for Stability of RF Acceleration

Amplitude noise integrated from DC to 200 kHz	$< 1 \times 10^{-3}$
Phase noise integrated from DC to 200 kHz [degree]	< 0.1
Phase and AM noises at the offset frequency near the synchrotron frequency [dBc/Hz]	< -100
Operating frequency	$< 3 \times 10^{-9}$

HIGH-POWER RF SYSTEM

An energy loss by radiation is up to 5 MeV/turn and the maximal power to beam loading is 500 kW at a beam current of 100 mA. The 16 cavities consume a total RF power of 510 kW to generate the accelerating voltage of 7 MV. An RF power of the four stations is so redundant that the beam acceleration can be kept by raising RF power of the three stations by 55% even though one station fails by an interlock.

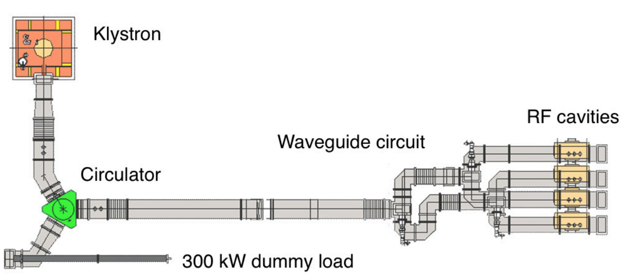

Figure 2: Configuration of the high-power components.

Figure 2 shows the rearranged high-power RF components. Each station has the klystron with an output of 1 MW, an efficiency of more than 60% and a gain of more than 50 dB. The klystron is driven by a 90 kV DC power-supply with a voltage ripple of less than 0.5% p-p. The WR-1500 waveguide circuit from the klystron to the four cavities is shown in Fig. 2. The existing rectangular waveguides, magic Ts, a circulator and dummy loads are available and rearranged. An RF power of 253 kW is transmitted from the klystron to the cavities through the circuit. The bell-shaped single-cell cavity has a shunt impedance of 6 MΩ and a Q-value of approximately 40,000. We have suppressed coupled-bunch instabilities arising from the impedances of parasitic higher-order modes (HOMs) in the cavities by using a tuner for changing the frequencies of the HOMs and powerful bunch-by-bunch feedback system [9-11]. These countermeasures are taken in the upgrade ring.

LOW-LEVEL RF SYSTEM

Figure 3 shows a schematic diagram of the digital LLRF system under development. The AMC digitizer with an FPGA and an RTM for under-sampling is the core part for stabilizing the RF fields in the cavities. The functions of signal detection, level adjustment and feedback control are integrated in the FPGA. The EtherCAT is going to be used as the field-network for non-RF instruments such as the tuner controller and the anode-voltage controller of the klystron.

Perturbations on the accelerating voltage are suppressed by two-fold feedback loops in the FPGA. The first one is against the change in the klystron output-power by ripples of the power-supply, and the phase shift up to approximately 60º by modulation of the anode voltage. The modulation is indispensable for efficient operation of the klystron according as the amount of the output power. The bandwidth of this klystron loop is approximately 100 kHz. The second one is against the perturbations to cavities such as temperature drift. The bandwidth of the cavity loop is approximately 100 Hz.

In 2016, we started on fabricating prototypes of an AMC digitizer and an RTM for under-sampling. The digitizer consists of an FPGA, 10-ch 16-bit ADCs of more than 300 MSPS, and 2-ch 16-bit DACs of more than 500 MSPS. In order to have the phase stabilities in Table 2, ADC clock-jitters must be suppressed to less than 100 fs. This performance can be achieved by the techniques utilized in SACLA [12]. The digitizer, furthermore, can be used for the beam diagnosis [2].

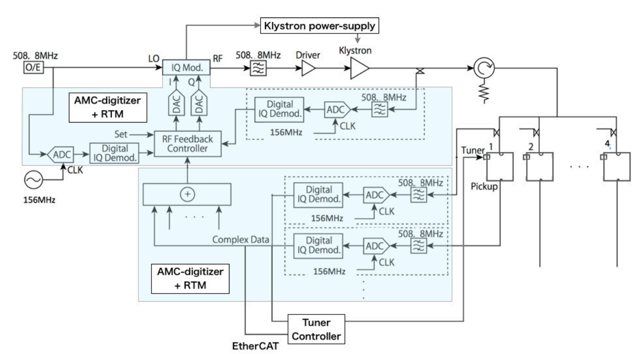

Figure 3: Schematic diagram of the digital LLRF system.

TIMING SYSTEM

In order to inject an electron beam from SACLA to the storage ring, the beam timing of SACLA must be syn-

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chronized with a target bucket of the storage ring. Furthermore, the injection must be done in parallel with the SACLA user operation. Since the injection and the X-ray FEL operation demand different beam energy and bunch length, we must develop a pulse-by-pulse control system for changing a beam route and RF fields of the SACLA linac on demand. The timing and synchronizing instruments also consist of boards with the digitizer.

Synchronization Scheme

A synchronizer is a module conditioning the beam timing of the SACLA linac for injection. The scheme of the synchronizer is shown in Fig. 4. The synchronizer is to be installed in SACLA and receive an injection request, a target bucket-number, a storage-ring (SR) reference signal of 508.756 MHz and a beam-revolution signal of 208.849 kHz from the SR master oscillator through a phase-stabilized optical fiber. The synchronizer estimates the phase difference between the SACLA reference signal of 79.3 MHz and the SR reference signal, and modulates a phase of 10 MHz clock for the SACLA master oscillator to make an adequate RF signal and a trigger pulse for the SACLA linac. A model was fabricated with an ADC-AMC on the market and feasibility studies were done. A precision of 8 ps p-p on the phase modulation was obtained and nearly the rated value of 3 ps rms.

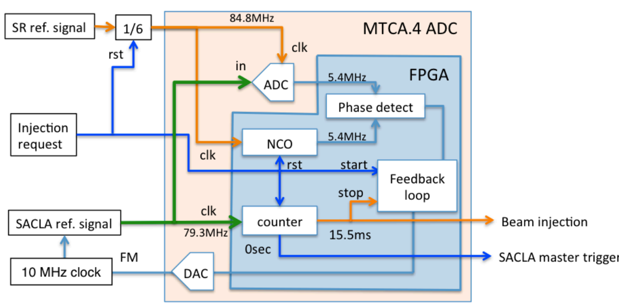

Figure 4: Scheme of synchronization between SR and SACLA.

Pulse-by-pulse Beam Formation in SACLA

Event information on beam-forming in SACLA must be delivered to the accelerator units to switch their RF parameters. We are examining two types of delivering methods: one through the existing Ethernet network and the other on the trigger pulse. No additional hardware is needed for both methods. The first method is done by software on CPUs of the units and costs low, but the latency strongly depends on network traffic and CPU loads. The delivery is not real-time. Although the second method needs the firmware modification of the trigger-delay-unit, DAC and ADC boards of the accelerator units [13] and costs more, the event information is firmly transmitted to and received by the units.

By using the first method as a feasibility study, we demonstrated beam-formation of bunch lengths of 100 fs and 20 fs alternately at 30 pps. The electron beam quality was stable during the pulse-by-pulse RF control.

SUMMARY

In the upgrade project of the SPring-8 storage ring, the high-power RF components can be reused and rearranged to generate a beam-accelerating voltage of 7 MV although the operating frequency is changed from 508.580 to 508.756 MHz and the spaces for RF cavities are reduced.

We are developing a compact digital LLRF system based on the under-sampling scheme and the MTCA.4 standard in order to replace the infirm analogue LLRF system. The SACLA linac is to be used as an injector to the ring. Precisely synchronized timing and pulse-by-pulse beam-control systems were designed for the injection compatible with the X-FEL operation of SACLA. We have set up some tests on the schemes and verified them.

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