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ON-DEMAND BEAM ROUTE AND RF PARAMETER SWITCHING SYSTEM FOR TIME-SHARING OF A LINAC FOR X-RAY FREE-ELECTRON LASER AS AN INJECTOR TO A 4TH-GENERATION SYNCHROTRON RADIATION SOURCE

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Abstract

We have an upgrade plan to dramatically reduce the natural emittance of the current SPring-8 storage ring, and we will use the linac of the x-ray free-electron laser (XFEL), SACLA, as an injector. To share the SACLA linac for both XFEL beamlines and the storage ring, the beam route and parameters must be switched on-demand basis. We have, therefore, developed an on-demand beam route and parameter switching system with sufficient speed, precision and reliability. Beam route data are transmitted to each accelerator unit by a reflective memory network, and rf parameters of each unit are changed by special software shot-to-shot according to the received data. We tested the on-demand switching system at a test bench and the SACLA linac. The beam route and parameters were appropriately controlled with a negligible failure rate of less than $2.5 \times 10^{-8}/\mathrm{shot/unit}$. The time-sharing operation of the SACLA linac will be started in the next year.

INTRODUCTION

For a fourth-generation ring-based synchrotron radiation light source (4GLS) using a multi-bend achromat lattice, a low-emittance injector is necessary for effectively injecting the beam to the ring with a narrow dynamic aperture. Some of the 4GLS projects, mainly 3 GeV class machines, are designed with linac-based full-energy injectors, which has a possibility to drive a (soft) x-ray free-electron laser (XFEL). Therefore, time-sharing of a high-quality linac is a key issue of a 4GLS project combined with an XFEL.

We have an upgrade plan of SPring-8 to reduce the ring emittance from 3 nm rad to 0.1 nm rad, SPring-8-II [1], which is a typical 6 GeV class 4GLS project using a linac-based injector. Electron beams from the XFEL facility, SACLA [2], will be shared for the beam injection together with the XFEL operation. The beam injection from SACLA is also planned for the present SPring-8 storage ring in advance [3] to reduce the electric power consumption and the maintenance cost by shutting down the current injector.

To provide electron beams from the SACLA linac to both XFEL beamlines and the SPring-8(-II) injection in parallel, we need to switch some beam parameters for each shot. Although the beam energy of SPring-8(-II) is fixed, that of an XFEL beamline is often changed according to the desired XFEL photon energy. The bunch length for an XFEL beamline is required to be as short as 10 fs, while the SPring-8-II prefers a longer-bunch beam to reduce an emittance growth due to coherent synchrotron radiation (CSR) in bending magnets distributed over the beam transport line. The beam injection frequency of SPring-8-II is 10 Hz for an initial injection and once a few minutes for top-up operations, while the repetition rate of the SACLA linac is 60 Hz. In order to utilize the remaining beam shots for XFEL beamlines, a flexible beam route and parameter switching system is necessary for the SACLA linac.

To satisfy the requirements above, we have developed an on-demand beam route and parameter switching system for SACLA. This system is designed to change the beam energy, bunch length and beam route for each shot of a machine with a 60 Hz repetition rate on-demand basis. We describe the design of the system and the results from a test setup and a test experiment of SACLA in this article.

ON-DEMAND BEAM ROUTE AND PARAMETER SWITCHING SYSTEM

Overview of SACLA

A schematic layout of SACLA is shown in Fig. 1. The SACLA linac consists of a low-emittance thermionic electron gun [4], sub-harmonic accelerators [5], and C-band main accelerators [6]. SACLA has three XFEL beamlines (BL1–3) and a beam transport to the storage ring (XSBT): the main linac provides electron beams to BL2, BL3 and XSBT, and a dedicated small linac is used for BL1. The beam route of the main linac is switched by a kicker magnet for BL2, BL3 and XSBT [7, 8]. The maximum beam energy is 8 GeV and the maximum repetition rate is 60 Hz.

Current Beam Route and Parameter Switching Scheme

Since SACLA has been operated with two XFEL beamlines driven by the main linac since 2016, we already developed a beam route and parameter switching system with minimal functions [9]. The requirements for the current system are the beam energy and bunch length control for each beamline and the beam route switching in an equal rate one after another.

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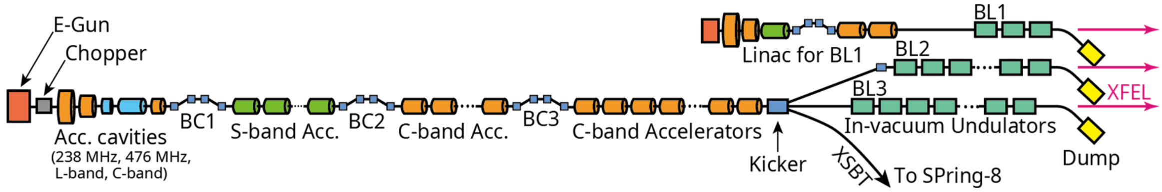

Figure 1: Schematic layout of SACLA.

The beam route is equally switched by setting the kicker magnet to repeat the current pattern for two consecutive shots. The beam energy is changed by turning on and off the trigger signals of some of the accelerator units shot-to-shot [10]. Since the trigger module has a function to set the trigger rate to $60/n$ Hz, where n is an integer, the beam energy can be easily controlled in case of equal rate switching.

For the bunch length control, we developed special software to switch the rf phases of the accelerator units upstream the third bunch compressor (BC3). We execute a parameter switching process on the VME-CPU of the low-level rf control system. This process monitors the trigger number of a trigger module, takes rf data from ADC and sets rf parameters to DAC according to the trigger number.

The current beam route and parameter switching scheme has worked well and the beam energy and bunch length have been appropriately optimized for both BL2 and BL3 [7, 9].

On-Demand Beam Route and Parameter Switching System

Since the software-based scheme worked well for the current switching system, we decided to use similar software also for the on-demand switching system. A schematic diagram of the on-demand switching system is shown in Fig. 2. To distribute a beam route information to each accelerator unit for on-demand switching, we constructed a reflective memory (RFM) network for the beam route distribution in addition to the existing Ethernet network, since Ethernet is not reliable to transfer data with a sufficiently small latency at all times.

The master unit was originally developed with a VME system and was recently replaced with a MicroTCA.4 (MTCA.4) system to implement a synchronization function with SPring-8 [3]. The master unit has a CPU board with a RFM module and an interrupt register board. In the MTCA.4 case, a digitizer board for synchronization is added. Whereas the VME or MTCA.4 modules are usually controlled by an equipment manager (EM) process on the CPU, we additionally execute an EM agent (EMA) process for real-time processing [11]. The EMA master process takes the trigger number counted by the VME interrupt register or the MTCA.4 digitizer, composes beam route data, consisting of previous, current and next route numbers, according to the trigger number, and sends the route data through the RFM network.

Each slave VME receives the route data from the RFM and sets rf parameters etc. to the modules. A slave accelerator unit has a trigger delay unit (TDU) to generate timing signals, such as a charging start for a high-voltage power supply, etc., an in-phase and quadrature modulator (IQ-MOD) driven by a VME-DAC to generate an acceleration rf signal, and IQ detectors (IQ-DET) with VME-ADCs to monitor the rf signals from high power rf components. We additionally execute some EMA processes, EMA-SW, EMA-PID1 and EMA-PID2, for parameter switching. EMA-SW takes the trigger number and ADC data, sort the data according to the trigger number and sets the next rf parameters to the DAC. EMA-PID1 and -PID2 regulate the phase of each beam route by proportional-integrate-differential (PID) control. The VME system for the kicker magnet has a CPU, a RFM, and an interrupt register. The EMA-SW process takes the trigger number from the interrupt register and sets the excitation current to the kicker magnet.

The route data, the rf parameters and the trigger number are recorded by an event-synchronized data-acquisition (Sync-DAQ) system [11, 12] shot-to-shot in order to check whether the beam parameter was switched appropriately or not.

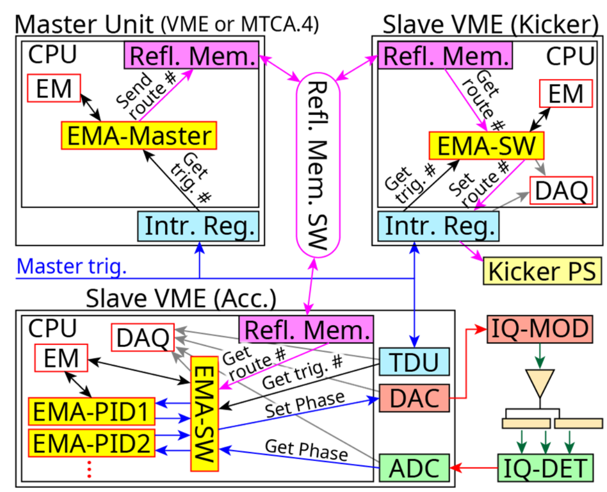

Figure 2: Schematic diagram of the on-demand beam route and parameter switching system.

TEST RESULTS

We developed and tested the on-demand switching system in a test bench and in the linac for BL1. The system was then installed to the SACLA linac and tested with actual electron beams.

Bench Test Results

We set a certain beam route pattern with multiple beam destinations and checked the correctness of the beam route and parameters in a VME test bench and the linac for BL1. Point data of rf parameters etc. for each shot were recorded by Sync-DAQ to confirm the beam route and parameters for every shot. Some waveforms of the ADC modules were

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also acquired once a second to impose a certain load to the VME bus.

The setup of the test bench consists of two VMEs: one master VME and one slave VME. We executed an on-demand parameter switching software for more than 100 hours. We found a few delays of Sync-DAQ from the obtained data, but no error on parameter switching was observed. Figure 3 shows typical histograms of some important timestamps. The data for parameter switching is taken just after the previous beam and the rf parameters are set to the modules about 7 ms after the beam. All the tasks are completed within the time frame of the 60 Hz period.

For the evaluation in the linac for BL1, we used one master unit and four slave units. The test data were taken for more than 40 hours and no failures in the parameter switching were found. Although one DAQ delay was found, the rate of this delay is less than 1×10^{-7}/shot /unit, which is significantly smaller than the other failures, such as a misfire of a thyratron in a klystron power supply.

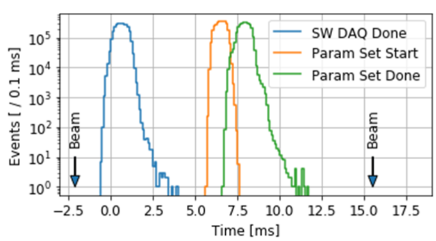

Figure 3: Histograms of timestamps of the switching process. The blue line shows the finish time of the DAQ for switching. The orange and green lines show the start and finish times of the parameter setting, respectively. The beam timing is also indicated by the arrows.

Test Results at SACLA

We installed RFM modules and the on-demand switching software to 40 accelerator units out of 76: all the accelerator units upstream of BC3 and 10 units downstream of BC3. We tested the on-demand switching system several times with actual electron beams. In the most recent experiment, we did not observe any failure shots of the beam route and parameter switching system for 5 hours. The number of total beam shots was more than 10^6 and the failure rate was less than 2.5×10^{-8}/shot /unit, which is significantly smaller than other failure causes.

Trend graphs of the XFEL intensities of BL2 and BL3 in this experiment are plotted in Fig. 4. Beam energy, photon energy and undulator K-value were 7.8 GeV, 10 keV and 2.1, respectively, for both beamlines. Electron beams with 60 Hz repetition rate were equally distributed to the two beamlines (30 Hz each)The acceleration rf parameters for each beamline were individually optimized to maximize the XFEL intensity. Some intensity drops during the experiment were due to another machine tuning performed in parallel. Thus, high-quality electron beams for XFEL operation were appropriately distributed to multiple beamlines.

In another experiment, we set different beam energy to each beamline. The XFEL performance was confirmed to be optimized for both beamlines even for different beam energies. We also tested a beam energy control function without stopping the other beamline. The beam energy was appropriately changed without any deterioration of the XFEL performance at the other beamline. This function is necessary for the user service of the time-sharing operation of both the XFEL beamlines and the SPring-8 injection, since the beam energy is necessary to be changed for each XFEL user.

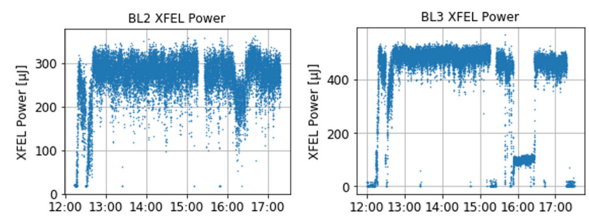

Figure 4: XFEL intensity trend graphs of BL2 (left) and BL3 (right) during the test experiment of the on-demand beam route and parameter switching system.

SUMMARY AND OUTLOOK

We developed an on-demand beam route and rf parameter switching system to share the SACLA linac for the XFEL beamlines and the injection to SPring-8(-II). We designed and constructed a software-based switching system with a RFM network for the distribution of beam route information. This system was tested in a test bench, the linac for BL1 and the SACLA main linac. We did not observe any failure shots in a 5-hour experiment at the SACLA linac. This result corresponds to the failure rate of less than 2.5×10^{-8}/shot /unit, which is negligible compared to other failure causes, such as faults of high-voltage power supplies.

At this moment, the on-demand switching system is installed to about half of the accelerator units. We have a plan to extend this system to all the accelerator units in this year. Beam injection experiments from SACLA to SPring-8 have also been performed since last year, where the beam route is fixed to XSBT during the injection experiment. The synchronization system between SACLA and SPring-8 [3] with the on-demand switching system will be ready in this year. The first user service of the time-sharing operation of the SACLA linac with the on-demand switching system is scheduled in the next year.

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