PULSE BY PULSE ELECTRON BEAM DISTRIBUTION FOR MULTI-BEAMLINE OPERATION AT SACLA

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Abstract

In SACLA, the second undulator beamline (BL2) is installed during the 2014 summer shutdown. The beamlines are initially switched by a DC switching magnet for the commissioning. Then the DC switching magnet will be replaced by a kicker and a DC twin-septum magnet and the pulse by pulse operation will start in January 2015. The kicker magnet is driven by a 60 Hz trapezoidal current waveform. In the pulse by pulse multi-beamline operation of XFEL, the electron beam energy should be optimized for the laser wavelengths of each beamline from bunch to bunch. To control the beam energy of the electron bunches, the multi-energy operation of the linac has been proposed and demonstrated at SACLA. The pulse by pulse operation will be also applied for the beam injection to the upgraded low-emittance ring of SPring-8 (SPring-8-II) in future. Since the SPring-8-II storage ring has a small dynamic aperture, low emittance is required for the injection beam. In addition, the use of SACLA as a low-emittance injector enables to save the running cost of the injector system during top-up operation.

INTRODUCTION

In order to meet the increasing demand for XFEL user operation, the second undulator beamline (BL2) is installed during the 2014 summer shutdown at SACLA. Different from the storage ring based synchrotron radiation facilities, the linac of XFEL can not simultaneously operate plural beamlines. However, quai-simultaneous pulse by pulse operation by distributing the electron beam to the beamlines on a bunch-to-bunch basis improves efficiency and usability of the facility.

The undulator hall of SACLA is designed to accommodate five XFEL beamlines, and a DC switching magnet located at the end of the linac currently switches the beamlines (see Fig. 1) [1]. For the pulse by pulse operation, this DC switching magnet will be replaced by a kicker magnet and a DC twin-septum magnet in January 2015. The electron beam is deflected into three directions at 60 Hz by the kicker, which is the maximum beam repetition at SACLA, and then the DC twin-septum magnet augments the deflection angles. Since the stability of the electron beam orbit is crucially important for XFEL, high stability is required, particularly, for the kicker magnet power supply.

In the XFEL operation, the electron beam energy is normally optimized for the laser wavelength requested from the user. But in case of the multi-beamline operation, the wavelengths can be different between the beamlines. Although the wavelength can be adjusted by changing the undulator gap, the tuning range is limited and small K-values result in drop of laser intensity. In order to avoid these limitations on the user experiments, it is necessary to control the beam energy from bunch to bunch in the multi-beamline operation.

The method to control the electron bunch energy in the linac has been proposed and demonstrated at SACLA by changing the repetition of a certain number of RF units [2]. In the pulse by pulse multi-beamline operation of SACLA, the multi-energy operation of the linac is planned to be used in combination with the electron bunch distribution to provide the electron beam having the optimized energy to the laser wavelength of each beamline.

ELECTRON BUNCH DISTRIBUTION

Although the maximum beam repetition of SACLA is 60 Hz, lower repetitions are sometimes used for user experiments due to the time necessary to exchanging samples. Also to save the time for preparation and removal of experimental instruments, the multi-beamline operation contributes to improve the efficiency and usability of the facility.

The schematic of SACLA is shown in Fig. 1. After the acceleration and longitudinal compression of the electron bunches in the linac, the DC switching magnet currently switches the beamlines by deflecting the beam orbit by ±3 degrees (±52 mrad). For the electron bunch distribution, this DC switching magnet will be replaced by the kicker magnet and the DC twin-septum magnet as shown in Fig. 2. In order to minimize the orbit fluctuation of the deflected beam by the kicker magnet, the deflection angle of the kicker is kept small as ±9 mrad and the rest of the angle is given by the DC twin-septum magnet (±43 mrad).

The yoke of the kicker is 0.4 m long made of laminated silicon steel plates with 0.35 mm thickness and 20 mm gap, and its maximum field is 0.67 T (see Fig. 3). The power supply of the kicker is a PWM (Pulse Width Modulation) type using 8 FET units connected in parallel. The power supply generates a 60 Hz trapezoidal current waveform and its amplitude and polarity can be arbitrarily changed according to the beam energy and an electron bunch distribution pattern.

Figure 4 is an example of the distribution pattern of the electron bunches. The arrival timing of the electron

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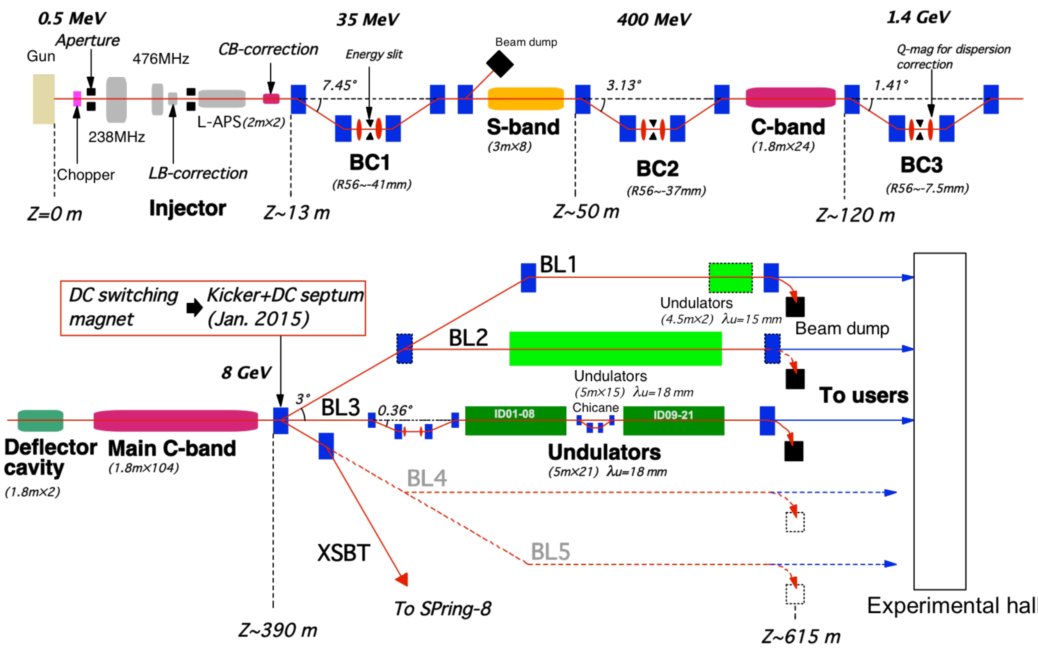

Figure 1: Schematic of SACLA.

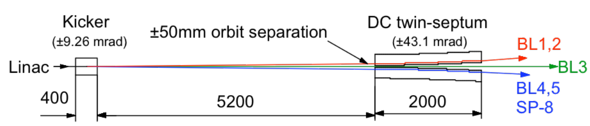

Figure 2: Configuration of a kicker magnet and a DC twin-septum magnet. The unit of the lengths is mm.

Figure 3: Kicker magnet made of 0.35 mm laminated silicon steel plates.

bunches is set at the end of the flat top of the trapezoidal waveform. When the kicker current is zero, the electron bunch goes straight through the kicker and takes the orbit to BL3. The electron bunch is deflected to BL2 for a positive current and to BL4 for a negative current. In this example, the pulse repetition of BL3 is twice higher than those of BL2 and BL4.

The DC twin-septum magnet consists of two 2 m-long septum magnets with the septum sides facing to each other. Figure 5 is the cross section of its upstream end. The electron beam orbits are horizontally separated by ±50 mm at the entrance of the twin-septum. While the electron beam for BL3 goes straight between the septums, the beam orbits for BL2 and BL4 are further deflected by ±43 mrad. The magnetic field leakage on the center straight orbit is expected to be about 0.2 G, which can be further reduced by turning on both septums owing to the cancellation of two leak fields with opposite signs.

The fabrication of the kicker magnet and its power supply have been already completed. The stability and reproducibility are checked with a DCCT and a gated NMR. The gated NMR is specially designed to measure pulsed magnetic fields developed by ECHO DENSHI Co., Ltd. As shown in Fig. 6, the resonant frequency is scanned during the gate opened for 0.6 ms. From the results of the magnetic field measurements, we confirmed that the stability of the kicker fields is better than 30 ppm (p-p). The DC twin-septum and its power supply are under fabrication.

MULTI-BEAMLINE OPERATION AT SACLA

The beam orbit to the BL2 undulators passes through a dogleg after the end of the linac. The electron beam is deflected by 3 degrees (52 mrad) by the kicker and the DC twin septum magnets, and then deflected back to parallel with BL3 (see Fig.1) by a DC bending magnet. In order to cancel R_{56} and keep achromatic and isochronous conditions, two small inversed bending magnets will be introduced in the dogleg. This is necessary to avoid unwanted bunch length change at the dogleg and keep the accelerator operation conditions the same for BL2 and BL3.

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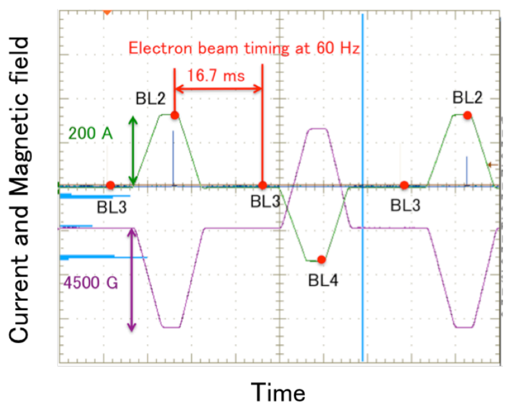

Figure 4: Measured current waveform (green line) and magnetic fields (purple line) of the kicker magnet. Red circles on the green line correspond to the beam arrival timing at 60 Hz.

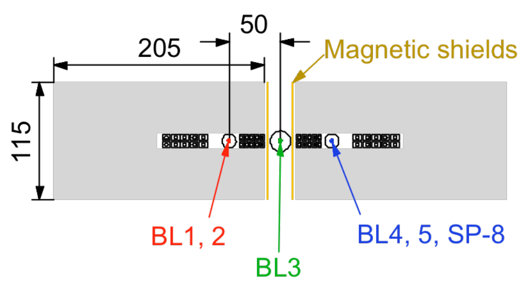

Figure 5: Cross sectional view of the DC twin-septum magnet (upstream end). The unit of the lengths is mm.

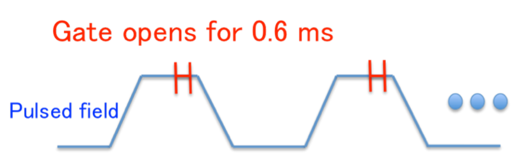

Figure 6: Gated NMR scans the resonant frequency and measures the magnetic fields for 0.6 ms-long gate duration shown in red.

There are three bending magnets on the electron beam orbit to BL2, which are the kicker, the DC twin-septum and the DC bending magnet. The expected stabilities of these magnets are 30 ppm (p-p) for the kicker, 10 ppm (p-p) for the twin-septum and 3 ppm (p-p) for the DC bending magnet. Compared to the current electron beam orbit stability of SACLA, which is about 1 μrad (p-p), the electron bunch distribution will increase the beam orbit fluctuation by 10-20 %, but it will not cause serious degradation of the pointing stability or the performance of the laser currently achieved at SACLA.

The in-vacuum undulators installed in BL2 are the same as those of BL3, whose periodicity is 18 mm. The user experiments will be allocated to these two beamlines not by the wavelength range, but by the type of the experiments. So in order to perform two user experiments in parallel, the laser wavelengths should be independently adjusted for these two beamlines. Since the tuning range of the undulator is limited within 30 % at SACLA, a large difference in wavelengths between the beamlines should be covered by changing the beam energy from bunch to bunch.

By operating some RF units at subharmonics of the bunch repetition, the number of accelerating structures effectively used for acceleration can be adjusted from bunch to bunch. Figure 7 is an example of accelerator setup for the multi-energy operation. All electron bunches are accelerated to 6.8 GeV at 60 Hz in the upstream part of the linac. By operating 4 RF units at 30 Hz and another 2 units at 15 Hz in the last part of the linac, half of the electron bunches pass through these 6 RF units without being accelerated, so the beam energy stays at 6.8 GeV. A quarter of the electron bunches are accelerated to 7.6 GeV by the 4 RF units working at 30 Hz. The last quarter of the bunches are further accelerated by the 2 RF units working at 15 Hz, thus the final beam energy reaches 8.0 GeV. By properly choosing the combination of the number and repetition of the RF units, the electron beam energy can be controlled from bunch to bunch.

Figure 8 shows an example of the multi-energy operation demonstrated at SACLA. The repetition of the electron bunch was 10 Hz and 8 RF units were operated at 5 Hz. The beam energy of the electron bunches were measured at a chicane located upstream of the BL3 undulators. Since the beam energy gain of one RF unit is about 130 MeV, the beam energy is alternately changed from bunch to bunch between 8.0 GeV and 6.9 GeV as expected.

Figure 9 is the SASE spectrum obtained from three-energy bunches measured by a monochromator. The repetition of the electron beam was 10 Hz, and 2 RF units were operated at 5 Hz and one RF unit at 1 Hz in Fig. 9. Consequently the SASE pulses were observed at 10 keV, 9.35 keV and 8.7 keV at the repetitions of 1 Hz, 4 Hz and 5 Hz respectively.

In the multi-beamline operation of SACLA, the beam energy of the electron bunches will be accelerated to the optimum energies for the laser wavelength of each beamline. Then the electron bunches are distributed to the beamlines pulse by pulse using the kicker and the DC twin-septum magnets located at the end of the linac.

ELECTRON BEAM INJECTION TO SPRING-8-II

SPring-8-II is the upgrade plan of the SPring-8 storage ring aiming at low emittance, which is currently scheduled around 2020 [3]. In this upgrade plan, SACLA is considered to be used as a low emittance injector for achieving good injection efficiency, low operation cost and minimum energy consumption. The SPring-8-II storage ring requires a low-emittance injection beam due to its small dynamic aperture. Since the emittance of a synchrotron booster is determined from its equilibrium state of the circulating electron beam, it is hard to obtain a low-emittance beam with the existing SPring-8 injector system composed of a linac and a FODO synchrotron

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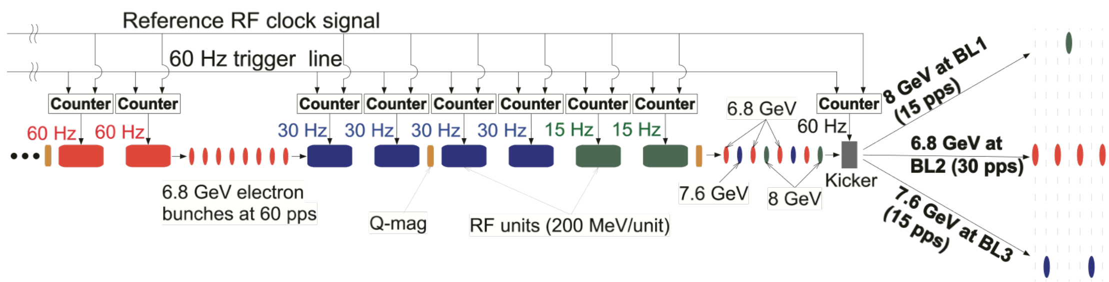

Figure 7: Example of the RF setup for the multi-energy operation.

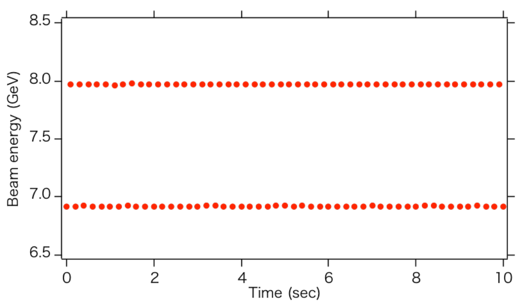

Figure 8: Electron bunch energies measured at the chicane in front of the BL3 undulators during the multi-energy operation.

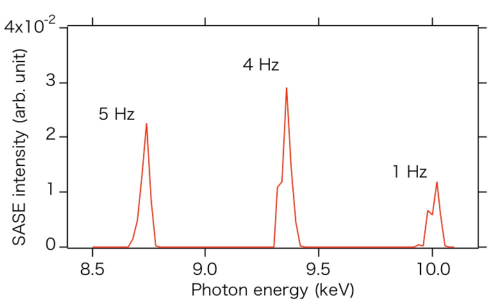

Figure 9: Spectra of SASE measured by a monochromator. The electron bunch repetition was 10 Hz and the beam energies of the electron bunches were changed between 7.3, 7.55 and 7.8 GeV.

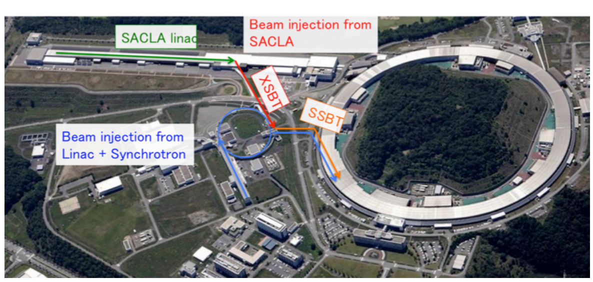

Figure 10: Beam transport line from SACLA to SPring-8 (XSBT and SSBT).

booster. In addition, despite of a low injection frequency during top-up operation, it is necessary to maintain the injector system in a warmed-up condition. Consequently it results in an increase of operation cost and energy consumption. On the other hand, SACLA is an independent user facility from SPring-8-II and its linac is always running. Therefore the beam injection from SACLA will enable to save the energy consumption and operation cost necessary for idling the accelerator.

The nominal beam energy of SPring-8-II is expected to be 6 GeV, while the beam energies used for the XFEL operation are around 5~8.5 GeV depending on the laser wavelength. The electron bunches are highly compressed and its peak current reaches several kA for the XFEL operation, but such high peak current is not necessary or even harmful for the beam injection due to the emittance degradation at a beam transport line. To achieve the parallel operation of XFEL and the beam injection to SPring-8-II, not only the beam energy but also the peak current should be controlled from bunch to bunch.

The beam transport line from SACLA to the exit of the existing synchrotron booster, which is called XSBT (XFEL to Synchrotron Beam Transport) in Fig. 10, had been constructed together with the SACLA facility. The electron beam of SACLA has already been successfully transported to the exit of XSBT. Further beam transport to the storage ring and the evaluation of the beam emittance are planned before the construction of SPring-8-II.

SUMMARY

Following the installation of the BL2 undulators, the pulse by pulse operation of multi-beamline will start in January 2015 at SACLA. For the beam injection to SPring-8-II, it is necessary to elongate the bunch length, which is possible by controlling the RF phase to reduce the energy chirp at the bunch compressors. Also since the electron beam is injected to the storage ring on-demand during top-up operation, the parameter of the RF units should be changed at arbitrary timing. For those features, a new timing and low-level RF systems are planned to be developed by 2020.

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