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PULSE-BY-PULSE MULTI-XFEL BEAMLINE OPERATION WITH ULTRA-SHORT LASER PULSES

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Abstract

The parallel operation of multiple beamlines is an important issue to expand the opportunity of user experiments for linear accelerator based FELs. At SACLA, the parallel operation of three beamlines, BL1~3, has been open to user experiments since September 2017. BL1 is a soft x-ray beamline driven by a dedicated accelerator, which is a former SCSS test accelerator, and BL2 and BL3 are XFEL beamlines sharing the electron beam from the SACLA main accelerator. In the parallel operation, a kicker magnet with 10 ppm stability (peak-to-peak) switches the two XFEL beamlines pulse by pulse at 60 Hz. To ensure wide spectral tunability and optimize the laser performance, the beam energy and the electron bunch length are independently adjusted for the two XFEL beamlines according to user experiments. Since the electron bunch of SACLA has typically 15 fs (FWHM) in length and its peak current exceeds 10 kA, CSR effect at a dogleg beam transport to BL2 is quite significant. In order to suppress the CSR effect, an isochronous and achromatic beam optics based on two DBA structures was introduced. The parallel operation of the three FEL beamlines substantially increases user time at SACLA.

INTRODUCTION

To meet increasing demands for XFEL (X-ray Free-Electron Laser) user experiments, the parallel operation of three undulator beamlines has been provided to users since September 2017 at SACLA (SPring-8 Angstrom Compact free-electron LAser) [1, 2]. The undulator hall of SACLA can accommodate up to five undulator beamlines and three of them, BL1~3, are currently in operation.

BL1 is a soft x-ray FEL covering a spectral range of 20-150 eV for the moment [3]. To generate low energy electron beams for BL1, the former SCSS test accelerator, which had been constructed as a prototype of SACLA, was moved to the SACLA undulator hall in 2014 [4, 5]. At the same time, four C-band accelerating structures were added to increase the maximum beam energy from 250 MeV to 500 MeV. Later another four more C-band structures were installed and the current maximum beam energy is 800 MeV. This SCSS+ is a dedicated accelerator of BL1 and runs independently from the SACLA main linear accelerator.

BL2 and BL3 are XFEL undulator beamlines, whose photon energy range is 4-15 keV. For the parallel operation, these two beamlines are switched pulse by pulse at 60 Hz.

Figure 1 is a schematic layout of the SACLA facility and main parameters are listed in Table 1.

BL2 DOGLEG BEAM TRANSPORT

For the XFEL multi-beamline operation, the electron beam is deflected in three directions, 0° and ±3°, at the end of the SACLA main accelerator. The straight line (0°) corresponds to BL3, +3° to BL2, and there is a beam injection line to the SPring-8 storage ring called XSBT (XFEL to Synchrotron Beam Transport) in the direction of -3°. A bipolar kicker magnet switches among these three directions pulse by pulse at 60Hz.

Table 1: Main Parameters of SACLA

BL2 and BL3 XFEL	
Beam energy	8.5 GeV max.
Bunch charge	0.2~0.3 nC
Peak current	~10 kA
Bunch length	< 20 fs (FWHM)
Repetition	60 Hz
Undulator period	18 mm
Undulator K value	< 2.6
Photon energy	4~15 keV
FEL pulse energy	~0.6 mJ at 10 keV
BL1 soft x-ray FEL (SCSS+)	
Beam energy	800 MeV max.
Bunch charge	0.2~0.3 nC
Peak current	~0.3 kA
Bunch length	< 1 ps (FWHM)
Repetition	60 Hz
Undulator period	18 mm
Undulator K value	< 2.1
Photon energy	20~150 eV
FEL pulse energy	~0.1 mJ at 100 eV

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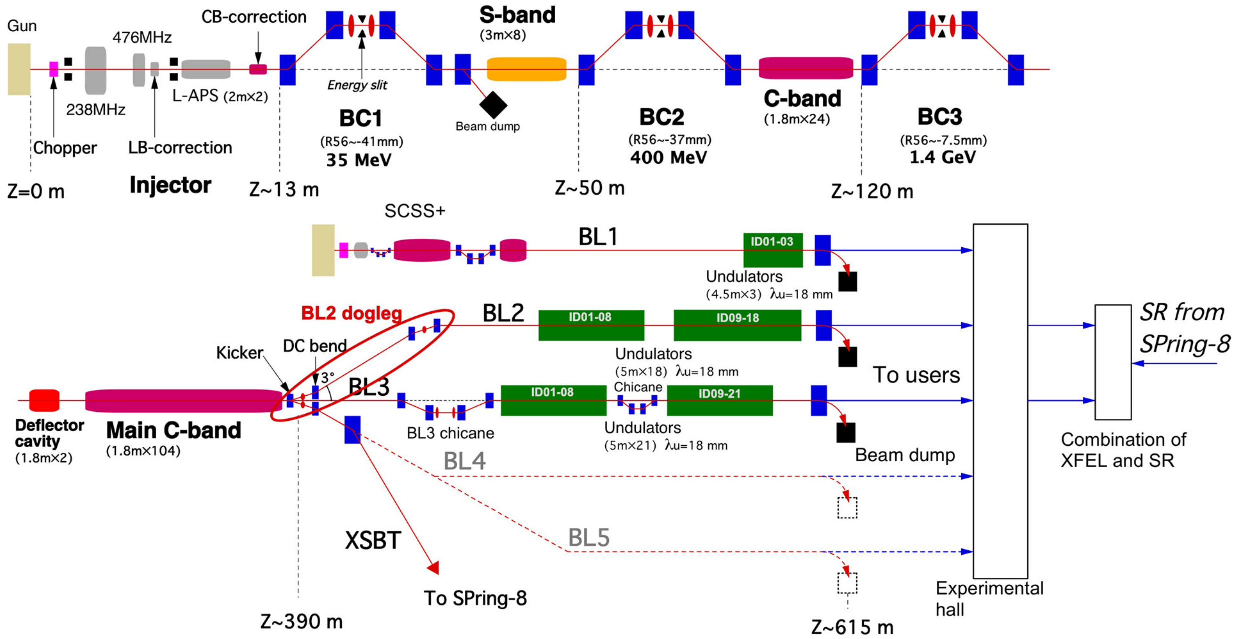

Figure 1: Schematic layout of SACLA.

The XFEL multi-beamline operation was first tested in 2015 using a kicker magnet and a DC septum magnet [6]. For BL2, the electron beam is transported through a 3° dogleg beam transport. Since the stability of the electron beam orbit at undulators is crucially important for XFELs, the deflection angle of the kicker magnet was made as small as possible to ease stability specification of a pulsed power supply of the kicker magnet. The deflection angles of the kicker magnet and the DC septum magnet were designed as 0.5° and 2.5° respectively. Consequently, the electron beam optics of the BL2 dogleg became asymmetry as shown in Figure 2 (a).

The electron bunches of SACLA used for daily XFEL operation have a peak current of 10 kA and a bunch length of around 15 fs (FWHM). Although simultaneous lasing was obtained at both BL2 and BL3 beamlines, the electron beam became unstable with a high peak current of 10 kA due to CSR (Coherent Synchrotron Radiation) effect. Thus it was necessary to reduce the peak current down to less than 3 kA to obtain stable lasing.

In order to mitigate the degradation of the electron beam quality, a new beam optics was introduced to the BL2 dogleg beam transport in 2017 [2]. The new beam optics is composed of two DBA (Double Bend Achromat) structures. All bending magnets have the same deflection angle of 1.5° including the kicker magnet and the beam optics retrieves symmetry as shown in Figure 2 (b).

One technical challenge of the new optics was the development of a pulsed power supply of the kicker magnet [7]. Since the deflection angle of the kicker was increased by a factor of three, the maximum output power reaches 300 A-1 kV. The developed power supply employs SiC MOSFETs as switching elements and regulates the output current using PWM (Pulse Width Modulation) control.

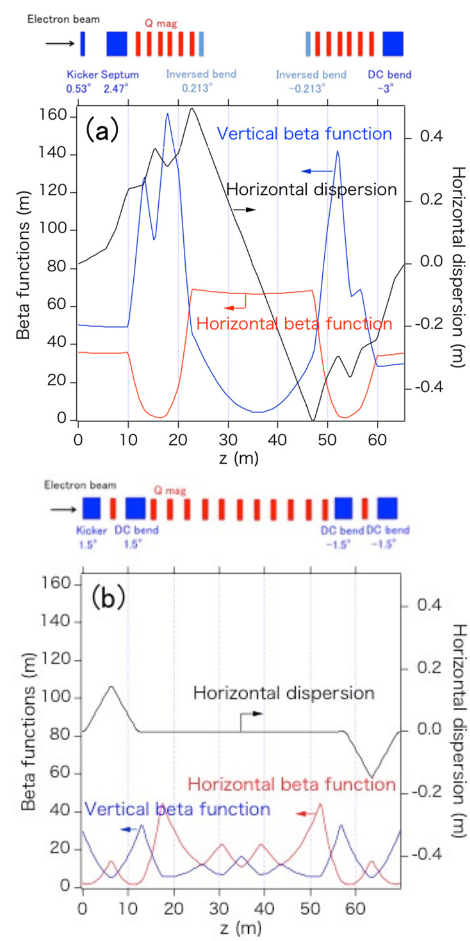

Figure 2: Optics functions of the BL2 dogleg beam transport, (a) old beam optics and (b) new beam optics. Magnet configurations are shown on top of each plot.

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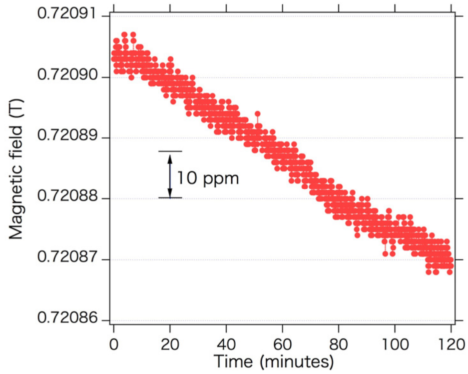

Figure 3: Stability of the kicker magnetic fields measured by a gated NMR detector.

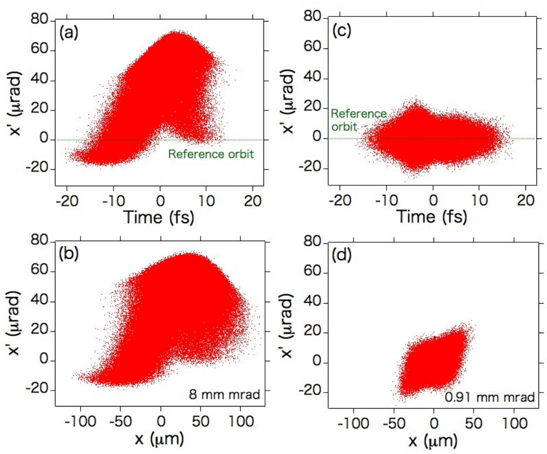

Figure 4: Phase space distributions of the electron bunch after the BL2 dogleg calculated for (a, b) the old beam optics and (c, d) the new beam optics.

The pulsed power supply generates bipolar trapezoidal current waveforms at 60 Hz, which is the maximum beam repetition of the SACLA main accelerator. The amplitude and polarity of the trapezoidal waveform can be arbitrarily changed pulse by pulse according to the beam energy and the direction of the beam deflection.

The stability of the kicker magnetic fields is measured and confirmed by a gated NMR (Nuclear Magnetic Resonance) detector [8]. As shown in Figure 3, pulse-to-pulse stability of about 10 ppm (0.26 μrad) is attained, which is reasonably small compared with the intrinsic electron beam orbit stability of SACLA (about 1 μrad).

SUPPRESSION OF CSR EFFECT

The degradation of the electron beam quality caused by the CSR effect is mainly due to the electron energy change inside bending magnets [9]. The radiation emitted from back electrons catches head electrons and changes their energy. Once the electron energy changes inside a bending magnet, the deflection angle also changes. As the result, the electron bunch is transversely kinked in the deflecting plane and its center of gravity deviates from a reference orbit.

To mitigate the CSR effect, it is necessary to cancel it out at the end of the BL2 dogleg. The simplest solution is making the betatron phase advance equal to π between the four identical bending magnets of the dogleg [10, 11]. Since the horizontal phase advance of the DBA structure is naturally π and only the phase advance between the two DBA structures is adjusted to π. To keep the same bunch length at the four bending magnets, R_{56} of the dogleg is set to zero by making the beam orbit horizontally off-centered at two quadrupole magnets of the DBA structures.

Figure 4 shows the electron bunch distribution in the horizontal phase space after the BL2 dogleg calculated by ELEGANT [12]. Figure 4 (a, b) and (c, d) are simulated for the old beam optics and the new beam optics respectively. The initial conditions assumed in Figure 4 are a gaussian distribution with a 10 kA peak current, a 10 fs bunch length (FWHM) and normalized emittance of 0.8 mm-mrad. The electron bunch is kinked and the bunch center largely deviates from a reference orbit with the old optics, in which the cancellation of the CSR effect is not considered. Although there is a slight increase of the projected emittance, the CSR effect is clearly cancelled out with the new optics.

The suppression of the CSR effect is experimentally confirmed. Figure 5 compares the electron beam profile observed at the BL2 undulator section before and after the replacement of the beam optics. The electron beam energy is 7.8 GeV and the peak current is about 10 kA. As shown in Figure 5, the electron bunch spread horizontally due to the CSR effect with the old optics, while it keeps a round shape with the new optics.

Figure 6 is the electron beam orbit stability measured in front of the BL2 undulator section using a pair of BPMs (Beam Position Monitors). With the old beam optics, the beam position scattered over an area of 16 pm-rad in the horizontal phase space, but the stability is improved by an order of magnitude with the new beam optics.

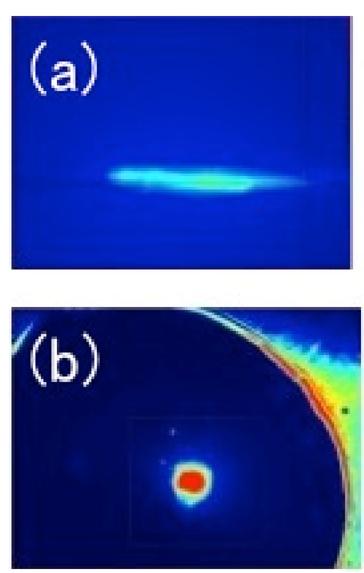

Figure 5: Transverse electron bunch profiles observed by a YAG screen at the BL2 undulator section, (a) old optics and (b) new optics.

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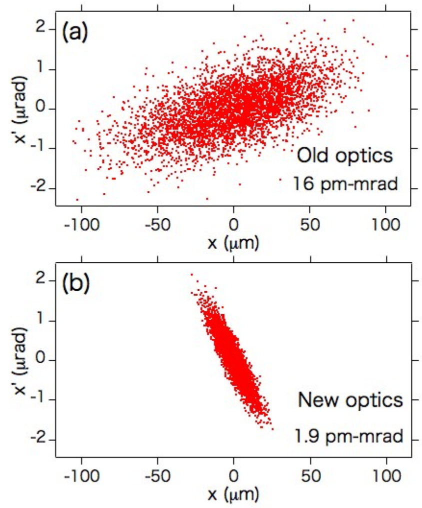

Figure 6: Stability of the horizontal electron beam orbit measured in front of the BL2 undulators, (a) old beam optics and (b) new beam optics.

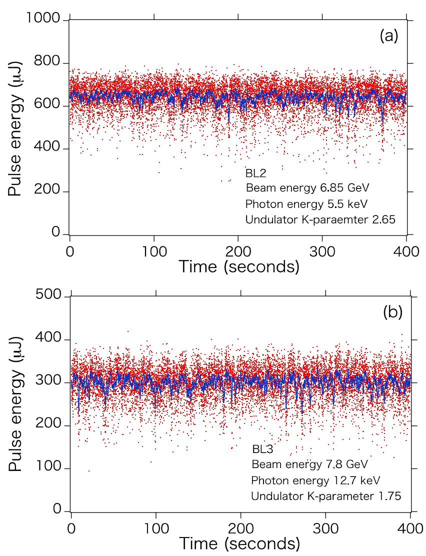

Figure 7: XFEL pulse energies measured in the multi-beamline operation, (a) BL2 and (b) BL3. The photon energies are 5.5 keV at BL2 and 12.7 keV at BL3. The red dots represents single-shot data and the blue line is averaged values over one second.

XFEL MULTI-BEAMLINE OPERATION

After the replacement of the beam optics, high peak current bunches of 10 kA are now stably transported through the BL2 dogleg. As the result, the XFEL pulse energy is considerably augmented by a factor of 2-3.

Figure 7 shows the XFEL output obtained in the multi-beamline operation of BL2 and BL3. The repetition of the electron beam is 60 Hz and the peak current is about 10 kA. In order to obtain a broad spectral tunability, which is one of the most important features of FELs, the electron beam is accelerated to different beam energies for BL2 and BL3 [13]. By running fourteen C-band accelerating structures at 30 Hz, which is half the beam repetition, the electron bunches are alternately accelerated to 6.85 GeV and 7.8 GeV. Then the kicker magnet deflects lower energy bunches to BL2 and higher energy bunches to BL3. Thus a wide spectral tuning range is achieved even in the multi-beamline operation by adjusting the beam energy independently for each beamline.

For XFEL, the electron bunches are not only accelerated but also longitudinally compressed in the linear accelerator. At SACLA, the electron bunch is compressed by velocity bunching in the injector section and a three-stage bunch compressor (BC1-3) downstream (Figure 1). However the optimum conditions of the bunch compression are slightly different between BL2 and BL3. This is mainly due to the different R_{56} of the two beamlines. After the end of the SACLA accelerator, there is the dogleg beam transport at BL2, whose R_{56} is zero, while a chicane is installed at BL3 to remove dark currents, whose R_{56} is -750 μm. Therefore it is necessary to independently adjust the bunch compression parameters, namely RF phases, to operate the both beamlines under the optimum condition. Figure 8 plots the XFEL pulse energies of BL2 and BL3 as a function of CSR intensity measured at BC3, which relates with the electron bunch length. Figure 8 illustrates that the two beamlines are operated with the electron bunches of different lengths in order to obtain the maximum XFEL output.

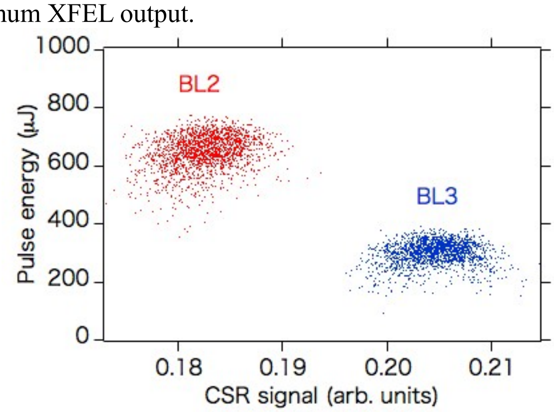

Figure 8: XFEL pulse energies plotted as a function of the CSR signal of BC3. The photon energies are 5.5 keV at BL2 and 12.7 keV keV at BL3. The red and blue dots represent the pulses of BL2 and BL3 respectively.

SUMMARY

The CSR effect is successfully cancelled out at the dogleg beam transport using the beam optics based on two DBA structures with π phase advance between bending magnets. Suppression of the CSR effect enables the multi-beamline operation with high peak current bunches and higher XFEL output is now available at SACLA. The parallel operation of three beamlines substantially expands the opportunity of user experiments. The total user time of more than 6000 hours is foreseen for FY2018.

The developed method of pulse by pulse control of the beam energy and bunch length is applied for the beam injection to the SPring-8 storage ring. In the upgrade plan of SPring-8, SACLA will be used as a low emittance

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injector. For the beam injection, the electron beam is accelerated to a fixed beam energy, such as 6 or 8 GeV, with low peak currents. In the top-up operation, one electron bunch is injected to the storage ring every few minutes upon request, while keeping XFEL multi-beamline operation.

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