PROGRESS IN SACLA OPERATION

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Abstract

In March 2012, SACLA was open to public users. Currently, 100-400 μJ laser pulses in a photon range between 5 and 15 keV are provided to the user experiments. Since SACLA employs variable-gap in-vacuum undulators, users can freely change the undulator gap to finely adjust the photon energy.

While the first lasing was achieved at 10 keV after several months of machine commissioning, the pulse energy was about 30 μJ, which was lower than a design value. In the autumn of 2011, we intensively worked on the reduction of a projected emittance, then 120 μJ was routinely obtained at 10 keV. After cathode replacement in the winter shutdown, we re-tuned the accelerator using higher energy beams with increased undulator K-values. Currently the pulse energy at 10 keV reaches 250 μJ. The stability of the accelerator, particularly the injector section, has been improved. Intensity fluctuations of 10-20 % (σ) are achieved during day-to-day operation. Since the floor of the undulator hall still moves by 50 μm in 2 months, the beam orbit at the undulator section is realigned every two weeks to maintain the FEL performance.

In this paper, we will report the recent progress of the SACLA laser performance and operation.

INTRODUCTION

Since March 2012, SACLA has provided intense X-rays to public user experiments. Fig. 1 is a schematic of the SACLA facility. 18 undulators are installed in the center beamline (BL3) as an XFEL light source in the present phase [1].

The accelerator has been operated using a basic parameter set determined from a 1-D model and 3-D simulations. However, final optimization of the parameters with observing FEL outputs is indispensable, since there are errors on RF parameters, component alignments and the limitations of simulation accuracy, like space charge and CSR effects.

In this paper, the improvement of the SACLA electron beam performance since the beginning of the beam commissioning is described.

OPTIMIZATION OF A PROJECTED EMITTANCE

The pulse energy obtained at the time of the first lasing in June 2011 was around 30 μJ at 10 keV with 7 GeV beams and K=1.8, which was lower than the expected value [2]. The main reason for this low pulse energy was supposed that only a small number of electrons contribute to the FEL amplification in the entire electron bunch.

Different from a photo-cathode based RF gun system, the injector of SACLA uses a traditional buncher-booster system with a thermionic high-voltage pulsed gun. The thermionic cathode electron gun of SACLA has advantages over an RF photo-cathode gun, such as uniform emission, a long cathode lifetime and maintenance-free operation [3]. On the other hand, the emission current is small as 1 A. In order to increase a peak current, the electron bunch is compressed in the injector by velocity bunching. For that, it is required to transport a low-energy electron bunch having a large energy chirp more than 5 m in the SACLA injector. Since the divergence of this low-energy beam due to the space charge is compensated by magnetic lenses, chromatic aberration varies a betatron phase inside the bunch resulting in the increase of a projected emittance. Although a slice emittance, which is directly connected to the FEL gain, maintains its small initial value, the increased projected emittance degrades the transverse envelope matching inside the undulator section and consequently limits the number of electrons contributing to the FEL amplification. The normalized projected emittance measured at the time of the first lasing was about 2~3 mm-mrad, which is about 5 times larger than the initial emittance of the gun.

In September 2011, the bunch charge was first augmented from 130 pC to 280 pC to increase the total number of electrons. Then the injector parameters are tuned to decrease the projected emittance.

In SACLA, the projected emittance is measured by a Q-magnet scan method using a single YAG screen. To avoid the contamination of coherent OTR, which degrades measurement reliability, a spatial mask is inserted in the focusing optics, and its shape, size and position were optimized. Also a focal length was carefully adjusted using a real beam profile. Fig. 2 is the observed beam size as a function of the CCD camera position. The CCD position was initially determined by an offline alignment using a reference plate placed at the position of the YAG screen. However the result of the online alignment using an electron beam profile revealed that the offline alignment was out of focus by a few hundreds of microns. After the improvements of the Q-magnet scan system, the measurements of the projected emittance became accurate and reliable with a reproducibility of ±10 %.

The projected emittances were measured after the first bunch compressor (BC1) and the final bunch compressor (BC3). After the optimization of the injector parameters, the normalized emittance was reduced to around 1.5 mm-mrad, which is almost half of the previous values before optimization, with a higher bunch charge.

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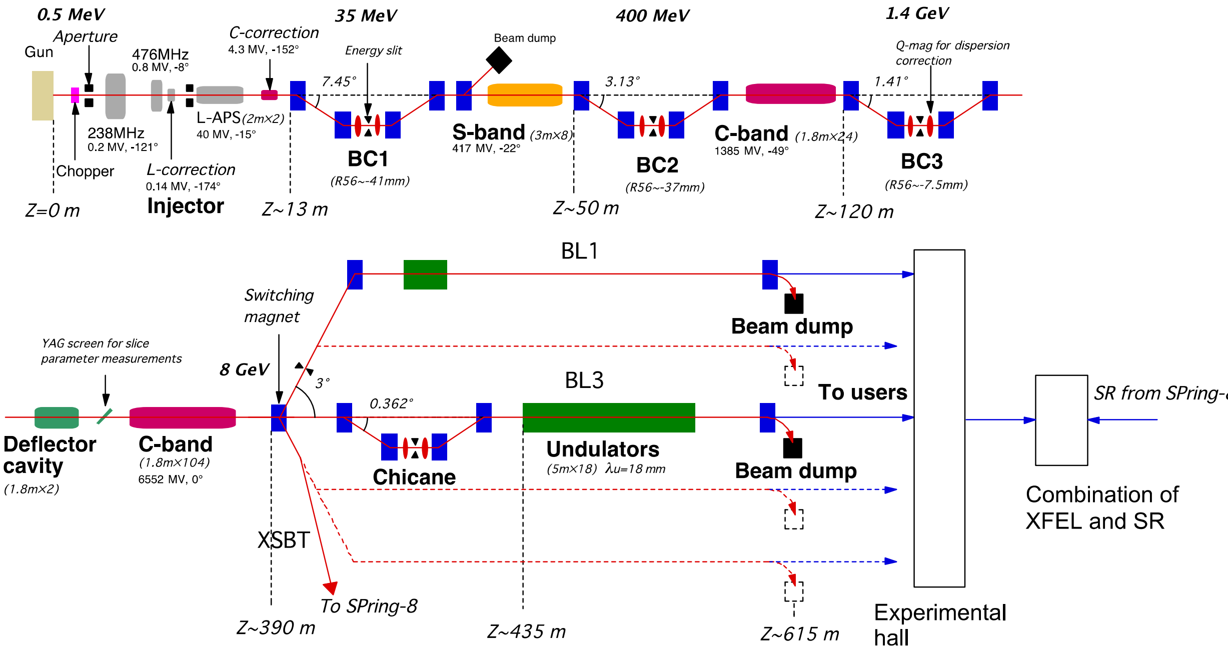

Figure 1: Layout of the SACLA facility.

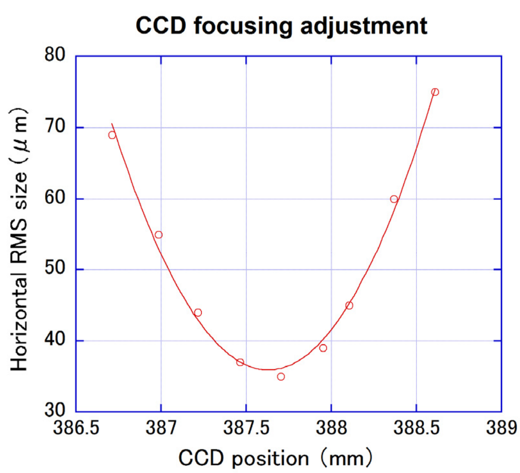

Figure 2: Measured electron beam sizes as a function of CCD position.

Figure 3 (a) and (b) are the gain curves measured at 10 keV with 7 GeV and K=1.8 before and after the projected emittance optimization. The saturation is clearly observed around the 10th undulator after the emittance optimization, and the final pulse energy is increased from 30 μJ to 120 μJ.

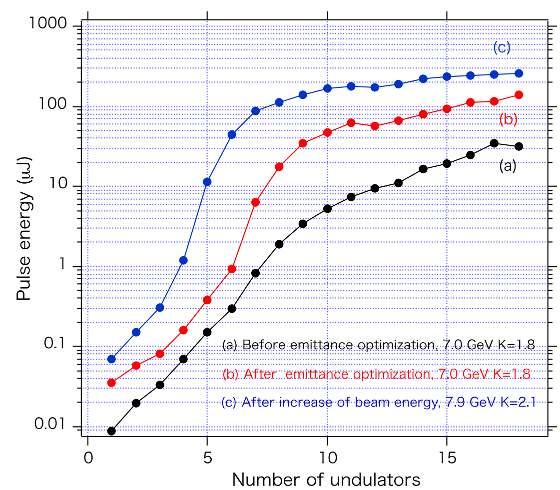

Figure 3: Measured gain curves at 10 keV, (a) at the time of the first lasing (7.0 GeV, K=1.8), (b) after projected emittance optimization (7.0 GeV, K=1.8), and (c) after increase of the beam energy (7.9 GeV, K=2.1).

CATHODE REPLACEMENT AND PULSE ENERGY IMPROVEMENT

During the winter shutdown of December 2011, a CeB_6 single crystal cathode of the electron gun was replaced considering the public user operation starting from March 2012. This cathode had been used for about one year since February 2011. It was still usable and there was no clear effect on the lasing.

From the experiences of the SCSS test accelerator, the beam divergence is normally changed for a new cathode. Therefore the FEL had been recovered by tuning mainly the injector focusing at SCSS. However, only 60 % of the pulse energy could be obtained by the same procedure at SACLA. Finally the circular aperture of a collimator installed downstream of a fast beam chopper, which slices out a 1 ns bunch from μs beam emission from the gun, was reduced from ϕ5 mm to ϕ4 mm. Although the bunch charge is decreased, a slice emittance is expected to be smaller for this reduced aperture size. Although a clear explanation can not be given yet, the FEL output recovered to the previous value.

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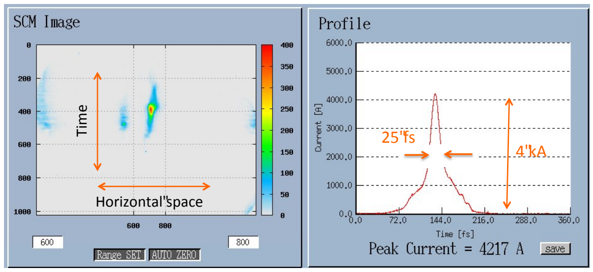

Figure 4: Longitudinal electron bunch profile measured by an RF deflector, (left) screen image and (right) temporal profile including the vertical beam size. The electron beam profile is the pattern with a red spot in center and two other dilute patterns on the left are contamination of coherent OTR in the left figure.

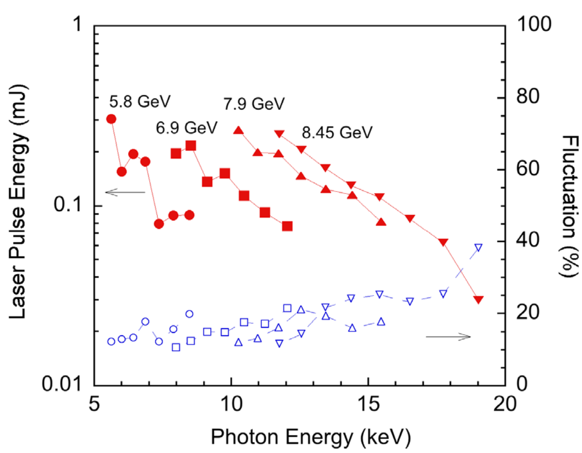

Figure 5: Photon energy range and FEL outputs currently available at SACLA. Pulse energies are measured at four different beam energies. At each beam energy, the undulator K-value is changed from 1.5 to 2.1. Dashed lines show relative intensity fluctuations.

The SACLA accelerator had been mainly operated at 7 GeV (maximum 8 GeV) since the beam commissioning to reduce an RF fault rate. After more than one year of operation, the stability of RF components was improved, and the beam energy has been increased to 8 GeV (maximum 8.4 GeV) in 2012. Consequently, the pulse energy at 10 keV goes up to 250 μJ using 8 GeV electron beams with an increased K-value. Fig. 3 (c) is a measured gain curve at 10 keV with 8 GeV and K=2.1. Not only the increase of the final pulse energy, but also the reduction of the gain length are achieved.

Since SACLA employs in-vacuum undulators, resistive wake fields are not negligible. In order to cancel out the average beam energy loss due to the wake fields, gap tapering is applied to 18 undulators, in which the undulator gaps become linearly larger towards downstream [4]. Typical tapering ratio is the order of $\Delta K = 1 \times 10^{-3}$ corresponding to an undulator gap change of ~20 μm between two consecutive undulators. The gap tapering is optimized depending on the conditions of the electron beam and the undulator gap to maximize the FEL output.

USER OPERATION

Since March 2012, SACLA has been operated as a public user facility. 7000 operating hours are planned in a 2012 fiscal year and 50 % is used for the facility tuning and developments. The C-band accelerators are stably operated at 35~40 MV/m gradients, and the maximum beam energy is currently 8.5 GeV. During the user time, the availability of the photon beam is 90~95 %, which depends on the beam energy. Most of the time loss is due to RF faults, either high voltage discharges or thyratron misfires. The fluctuation of SASE is typically 10~20 % (σ) and the stability of the center wavelength is about 3×10^{-4} (σ).

Figure 4 is the longitudinal electron beam distribution measure by an RF deflector after the final bunch compression at BC3. A typical electron bunch length is around 25 fs (FWHM) with a peak current of 4 kA. The photon pulse length deduced from a single-shot measurement of SASE spectral spike widths is about 10~15 fs (FWHM) [5].

The divergences of the photon beam including the fluctuations of the electron beam orbit are about 1.5 μrad horizontal and 1 μrad vertical at 10 keV, which are larger than the inherent divergence of SASE. This is supposed to be due to the orbit fluctuations, which come mainly from the injector [6]. Since it is already found that the orbit fluctuations have a correlation with the switching frequency of injector heaters used for the temperature control of RF cooling water, the heater system will be replaced to a DC regulation system in order to suppress the beam orbit fluctuations [7].

Different from LCLS or FLASH, SACLA is equipped with variable-gap in-vacuum undulators, that is one of the unique features of SACLA. In order to fully utilize this, feed-forward correction tables of steering magnets are prepared [8]. There are 18 undulators installed in the SACLA BL3 and a pair of steering magnets is attached at both extremities of each undulator. The electron beam orbit deviation is measured by RF cavity BPMs as a function of the undulator gap, and then the orbit is corrected by using a pair of steering magnets [9]. The feed-forward tables are made for each undulator.

In order to accurately extract beam orbit deviation excited by the gap movement, initial fluctuation of the injection orbit to the undulators is measured for each electron bunch using two RF cavity BPMs installed upstream of the undulator section. During the orbit deviation measurements, the fluctuation of the injection orbit is transferred by linear matrices and subtracted from the measured BPM data to extract net orbit deviation. With this subtraction, the beam orbit measurements attain sub-micron accuracy. The orbit deviation due to the undulator gap change is suppressed within ±10 μm by the feed-forward correction scheme [8].

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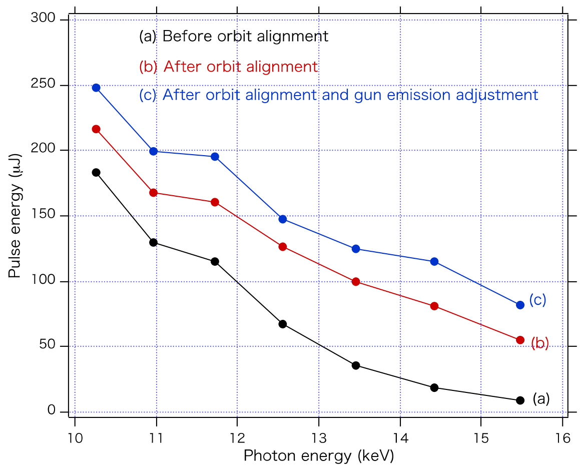

Figure 6: FEL outputs as a function of the photon energy. The electron beam energy is 7.9 GeV and the undulator K-value is changed from 1.5 to 2.1. (a) Before beam orbit alignment, (b) after orbit alignment at the undulator section, (c) after orbit alignment and gun emission adjustment.

Figure 5 shows the photon energy range and FEL outputs currently obtained at SACLA. The pulse energies more than 100 µJ are routinely available at photon energies between 5~15 keV. By using the feed-forward correction, the users can freely set and adjust the FEL wavelength by themselves within several seconds. Phase shifters and undulator tapering are automatically optimized at the same time as the undulator gap change.

Since the floor of the SACLA undulator hall is still moving by roughly 50 µm per two months, the electron beam orbit of the undulator section is realigned every two weeks by making the axes of synchrotron radiation from each undulator in a straight line [4]. To maintain the emission from a gun cathode at 1 A, the cathode temperature is also readjusted every one month, because the emission current slowly drops as its operation time. Fig. 6 shows a recovery of the FEL pulse energy through these routine readjustments. In Fig. 6, the pulse energies are measured at 7.9 GeV by changing the undulator K-value from 1.5 to 2.1. The gun emission is increased from 0.87 A to 1 A in Fig. 6 (c).

FUTURE DEVELOPMENTS

To avoid demagnetization of the undulator magnets due to dark currents from high-gradient C-band accelerators, a chicane had been installed in the middle of the C-band main accelerators located downstream of BC3, where the beam energy was 3 GeV. Since the dark currents had decreased to a negligible level after more than one-year operation, this chicane was removed in April 2012. Instead of the chicane, the installation of additional C-band accelerators is planned to raise the maximum beam energy to 9 GeV. At the same time, the minimum undulator gap, which is currently 3.5 mm, corresponding to K=2.15, is planned to reduce to 3 mm. Mechanically, the gap of the SACLA BL3 undulators can be closed to 2 mm, at which a electron beam halo is confirmed to be still negligible from the measurements of a beam halo monitor. Increase of the K-value together with the beam energy will enhances the FEL output over a wider photon energy range.

After the success of the self-seeded FEL experiment at LCLS, the installation of a single crystal is considered at the SACLA BL3 to operate it in a self-seeded mode [10]. During the summer shutdown of August 2012, the 9th undulator is moved to the end of the present 18 undulators and a small chicane is installed. The set up of a single crystal is planned in 2013.

The pulse repetition rate of SACLA is currently 10 Hz. In order to improve the efficiency of user experiments, the repetition rate will be increased to 20 or 30 Hz in the autumn 2012, and 60 Hz in 2013.

Since the SACLA undulator hall can accommodate five beamlines, the development of a fast beam distribution system to plural beamlines has been started for future installation of additional beamlines. The beam distribution system consists of a pulsed kicker and a DC septum magnet and its operation frequency is 60 Hz.

The SCSS test accelerator, which has been operated since 2006 as a VUV FEL source, will be shut down in June 2013 and moved to the SACLA undulator hall. The SCSS test accelerator will be reassembled in a 100 meter-long vacant space upstream of SACLA BL1. With additional C-band accelerators, it will operate as a soft x-ray FEL, which is independent from SACLA, with a maximum beam energy of 1.4 GeV in 2015.

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