A SOFT X-RAY FREE-ELECTRON LASER BEAMLINE OF SACLA

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Abstract

At the Japanese x-ray free-electron laser (FEL) facility, SACLA, the beamline-1 (BL1) has been upgraded from a "spontaneous radiation" to a "soft x-ray FEL" beamline, which generates FEL lights over a wide wavelength range from the extreme-ultraviolet (EUV) to the soft x-ray regions. We started operation for users in July 2016. A dedicated accelerator, which is a refinement of the SCSS test accelerator operated in 2005-2013, was installed beside the XFEL beamlines in the SACLA undulator hall. The SCSS concept to make an FEL facility compact was continuously adopted. In the 2016 summer shutdown period, the beam energy was upgraded from 500 MeV to 800 MeV by adding two C-band rf units. The maximum K-value of the undulator magnet is 2.1. The available wavelengths of the FEL lights were extended to the range from 8 to 60 nm with pulse energies between several to one hundred microjoules at a pulse repetition rate of 60 Hz. In this paper, we report an overview of the upgraded SACLA-BL1 and characteristics of the FEL light pulse.

INTRODUCTION

In the past ten years, short-wavelength free-electron lasers (FELs) ranging from extreme-ultraviolet to x-ray wavelength regions have become indispensable tools for a wide range of sciences, e.g., fundamental physics, atomic, molecular, and optical physics, chemistry, biology, and material science. After the successful operation of FLASH at DESY [1], the SCSS test accelerator at SPring-8 [2], and LCLS at SLAC [3], various FEL facilities have been built or are under construction in the world [4-10].

In the SPring-8 campus, the x-ray FEL (XFEL) facility, SACLA, was constructed and started user operation in the beginning of 2012 [4]. The undulator hall was designed to operate five beamlines that cover the wide wavelength range from soft to hard x-ray regions. The accelerator of SACLA can deriver 5- to 8-GeV electron beams for the central three beamlines to generate 4- to 15-keV hard XFEL lights. Presently, two hard XFEL beamlines are running simultaneously by the pulse-by-pulse switching system [11, 12]. Although it is necessary to reduce the beam energy down to a few GeV or less to generate soft XFEL lights at the outer two beamlines, the operation together with the hard XFEL beamlines becomes difficult and the pulse repetition rates of hard XFEL beamlines are restricted. Therefore, one of the outer beamlines (BL1) was upgraded as an independent FEL light source equipped with a dedicated accelerator machine.

The accelerator of BL1, many of whose components are reused of the SCSS test accelerator, was installed in the SACLA undulator hall in 2014 [13]. At first, the electron beam of 500 MeV emitted an extreme-ultraviolet FEL light with a photon energy of 40 eV [14] then the beam energy was increased to 800 MeV to cover a soft x-ray region beyond 100 eV. The facility has been open to public users since the summer in 2016.

OVERVIEW OF SACLA-BL1

The schematic layout of the soft XFEL beamline, SACLA-BL1, is shown in Figure 1.

The injector system is the same as that of the original SCSS test accelerator. The CeB_6 thermionic gun launches a microsecond pulsed beam with a 1-A peak current at a repetition rate of 60 Hz [15]. The beam chopper cuts out a 1-ns short bunch from the long pulse then it is injected to the plural buncher cavities to longitudinally-compress it to ~10 ps. The S-band structures accelerate the bunch to 49 MeV and provide an energy chirp to further-compress it down to ~2 ps at the first bunch compressor chicane (BC1) [16].

Five C-band accelerator units are used as a main accelerator system [17, 18]. The first three units accelerate the bunch to 500 MeV and make an energy chirp to compress it to sub-ps by the second bunch compressor (BC2). The rest two units accelerate it at on-crest phase to the final beam energy of 800 MeV.

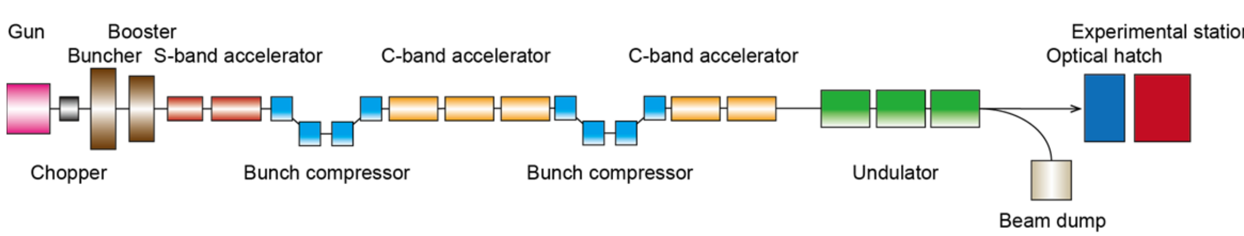

Figure 1: Layout of the soft XFEL beamline of SACLA.

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Three in-vacuum undulator units are used to generate soft XFEL light beams [19]. The usable gap range is from 3.8 mm to 20 mm. The maximum deflection parameter (K-value) is 2.1. The periodic length of the magnet and total number of periods are 18 mm and 777, respectively. The photon energy of FEL pulse can be varied from 20 eV to 150 eV by tuning the electron beam energy and/or the undulator K-value.

The properties of the soft XFEL beam are monitored in the optical hatch located between the undulator hall and the experimental station. The beam profile and the wavelength are measured by a Ce:YAG screen and a spectrometer, respectively. The laser pulse energy is constantly monitored using an argon gas monitor. A nitrogen gas attenuator can be used when it is necessary to adjust the laser intensity for experiments.

ELECTRON BEAM PERFORMANCES

In order to confirm whether the electron beam is compressed in the injector properly or not, the emittance and the longitudinal current profile have been measured at the exit of the BC1.

The projected emittance has been measured by means of the quadrupole-magnet-scan method. The squared beam sizes were well fit to a quadratic curve as a function of the magnetic field strength. Both of the horizontal and vertical emittances were analysed to be 3 mm mrad (normalized, root-mean-squared, projected), which is consistent with a particle tracking simulation.

The longitudinal current profile has been also measured by means of the rf zero-phasing method [20]. The known linear energy chirp was provided along the bunch by the third C-band unit then the energy profile, which corresponded to the temporal profile, was analysed by the bending magnet of the BC2. The result is shown in Figure 2. It was confirmed that the bunch was compressed to 0.8 ps (full width of half maximum, fwhm) and a peak current of ~120 A was accomplished there. The bunch structure after the final compression will be discussed in the next section.

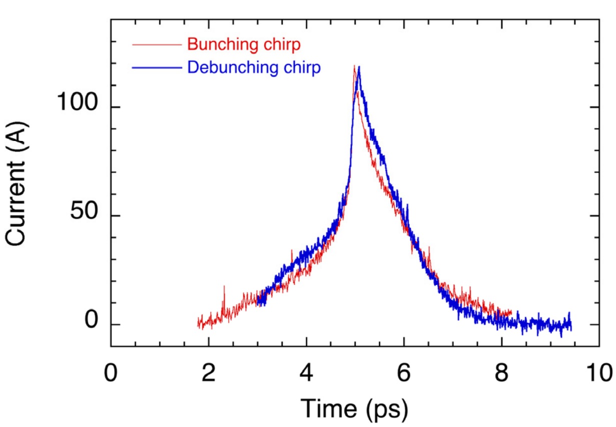

Figure 2: Longitudinal current profiles at the exit of the first bunch compressor measured by means of the rf zero-phasing method.

SOFT XFEL PERFORMANCES

The typical spatial profile of the soft XFEL pulse with a 100-eV photon energy is shown in Figure 3. The axisymmetric Gaussian distribution indicates that the self-amplified spontaneous-emission (SASE) lasing was accomplished properly in the undulator line.

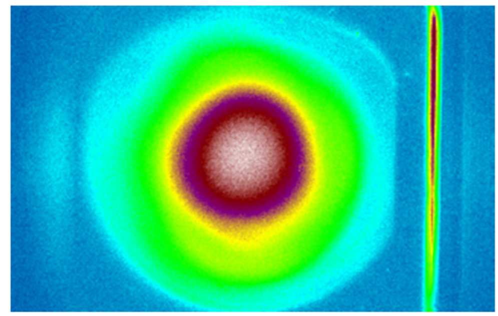

Figure 3: Spatial profile of the 100-eV soft XFEL beam. The horizontal full screen size is 17 mm.

A typical trend graph of output laser pulse energy at 93-eV is shown in Figure 4. Since the key components to make the accelerator highly-stable, e.g., the low-level rf system, the modulator power supply, and the temperature control system were also upgraded to stable and precise ones that were developed for SACLA [21, 17, 22], the 80-μJ averaged energy could be kept constant with very small fluctuation.

The property of the soft XFEL has been evaluated by measuring the FEL gain curve. Since the undulator line does not have sufficient number of units to obtain a general gain curve, the change of the FEL pulse energy when the magnet gap was opened (i.e., the K-value was changed) has been measured instead. The electron beam parameters were the energy of 780 MeV and the bunch charge of 0.23 nC. The K-value scanning range was from 0.5 to 2.1. The result is shown in Figure 5. The shot-by-shot energy fluctuation at λ=4.4 nm was same as that of the electron bunch charge since it derived from spontaneous radiation. As increasing the K-value, the pulse energy grew exponentially and the fluctuation reached to the maximum at λ=7.1 nm. Then the pulse energy increased to 110 μJ and the fluctuation decreased to 10% level around λ=10 nm, namely, the laser intensity saturation was accomplished.

Using the gain curve data, the properties of the electron beam can be analyzed with an aid of an FEL simulation code SIMPLEX [23]. The gain curve simulated is plotted in Figure 5 together with the experimental data. The beam conditions assumed in the simulation were the Gaussian temporal distribution with a peak current of 300A, a width of 0.7 ps (fwhm), and a normalized root-mean-squared emittance of 0.5 mm mrad. The SIMPLEX simulation reproduces the experimental data fairly well on the above assumption. This current profile was also compared with the simulation result performed using the PARMELA [24] and ELEGANT [25] codes in Figure 6. The beam properties obtained from both simulations do not contradict to each other.

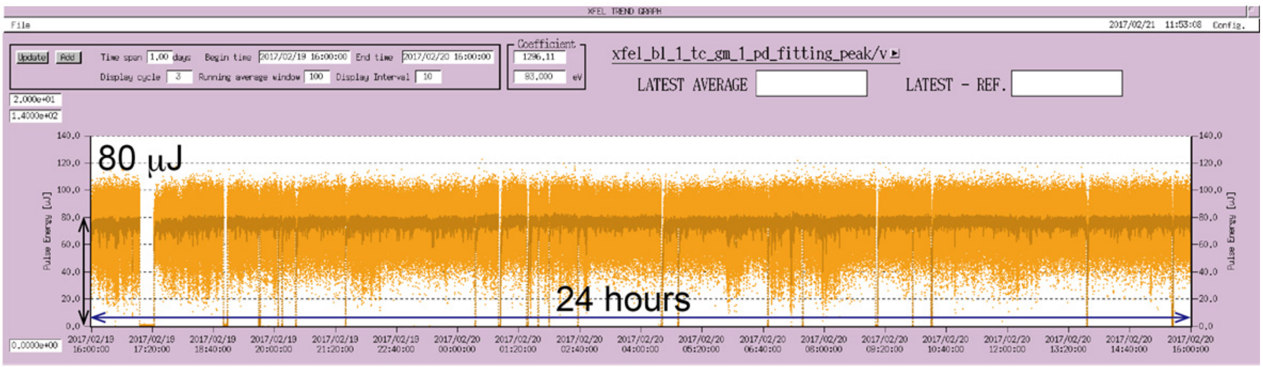

Figure 4: Trend graph of laser pulse energy at a 93-eV photon energy in 24 hours. The orange and brown dots indicate single shots and 100-shot-averaged, respectively. Stable laser pulses are delivered to experimental users for a long time.

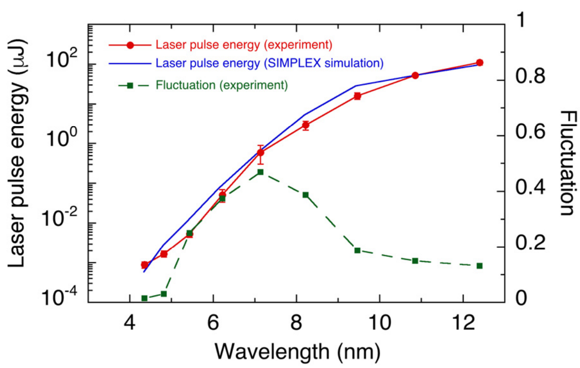

Figure 5: FEL gain curve of the SACLA-BL1. The radiation wavelength was scanned by means of changing the undulator's K-value.

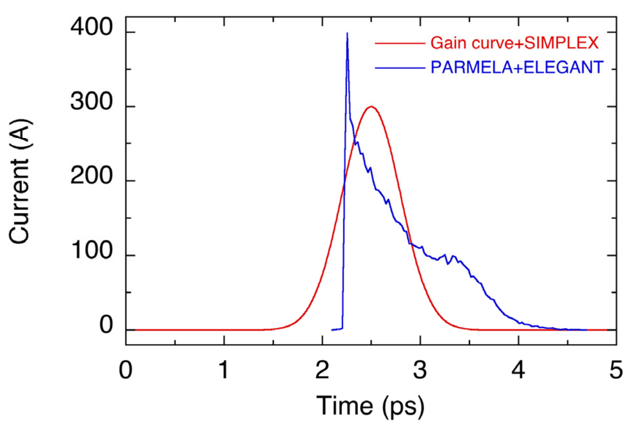

Figure 6: Electron current profiles at the undulator line obtained by the SIMPLEX and the PARMELA-ELEGANT simulations.

NEXT AND FUTURE UPGRADE

Since the injector of the SACLA-BL1 does not have a correction rf cavity operating with the higher-harmonic frequency, the beam is over-bunched after the longitudinal compression at the magnetic chicanes. In order to avoid the over-bunching and increase the effective electrons contributing to laser amplification, we are considering the introduction of higher-order multipole magnets at the BC1, instead of the correction cavity. The temporal second-order nonlinearity derived from the rf cavities and the chicanes can be corrected by adding nonlinear kicks to the bunch at the dispersive section of the BC1. Combination of plural sextupole-magnets may work as the nonlinear corrector. We will perform a theoretical study and a numerical simulation to find the optimum magnet parameters.

Since the BL-1 has enough free space between the linac end and the undulator entrance, additional seven C-band units can be installed and the maximum energy can be increased from 800 MeV to 1.8 GeV. In this case, the fundamental radiation wavelength reaches to the water-window region (2-4 nm). In the future, the other soft XFEL beamline will fill the blank wavelength between 1 and 4 keV.

CONCLUSION

In conclusion, the SACLA-BL1 has been upgraded to deriver intense soft XFEL beams to experimental users. Currently, several to one hundred μJ pulses with a photon energy range from 20 to 150 eV can be provided to the experimental station. We will try to increase the laser pulse energies by introducing the nonlinear corrector for the electron beam.

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