Machine Operation

Since starting the public user operation at SACLA in March 2012, we have delivered XFEL light in the self-amplified spontaneous emission (SASE) scheme with improved laser performance, especially in terms of intensity and stability.

Table 1. Achieved laser stability

Laser property	Normalized variation $\sigma_{\delta x/x}$ (%)
Intensity	≤10
Pointing	3 – 7
Wavelength	≤0.1

1. Intensity enhancement

The laser pulse energy, which was only 30 μJ before the summer shutdown in 2011 and reached 120 μJ at the end of the year, was increased to 330 μJ in autumn 2012 by elaborate tuning efforts. Since then, pulse energy higher than 300 μJ has been routinely and constantly supplied to user experiments, as shown in Fig. 1. The following three improvements have contributed to this intensity enhancement. (a) The diameter of the circular collimator, which scrapes the beam halo off an electron beam core at 500 keV, was changed from 5 to 4 mm to improve the beam slice emittance. (b) The maximum undulator K-value and electron beam energy have been increased from 1.8 to 2.1 and from 8.0 to 8.4 GeV, respectively, to enhance the SASE amplification gain over a wide photon energy range from 4.5 to 15 keV. (c) The alignment of electron beam orbit over the accelerating structures has been improved to reduce the projected emittance.

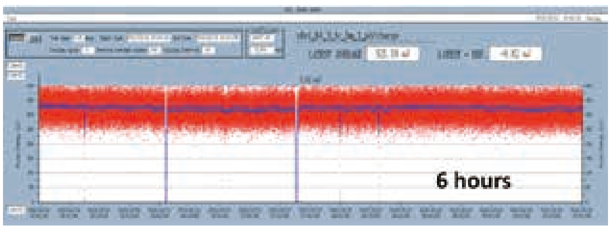

Fig. 1. XFEL intensity variation during the user experiment at a photon energy of 5.5 keV. Laser intensity was measured with the inline monitor at the optical hutch connected to the experimental hutch.

2. Stability improvement

The laser instability was reduced step by step, and the stability has reached a high level, as shown in Table 1 since the summer shutdown in 2012. Figure 2 shows the laser pointing fluctuations before and after the improvement, measured in the optical hutch where the beam size is about 200 μm FWHM. The present center of mass fluctuations are smaller than the beam sizes. The following four improvements at the injector section have contributed to lasing stabilization. On suppressing the drifts caused by RF phase shifts, (a) the precision of the temperature control for Low Level RF (LLRF) system was improved from 0.1 K to 0.01 K PP (peak-to-peak value) by reducing the temperature variation of cooling water and (b) the cavity-type band-pass filters (BPFs) in the LLRF system with high sensitivity against temperature variations were replaced by BPFs with lower temperature sensitivity. On suppressing the fast variations at approximately 0.5 Hz, (c) AC heaters used for the temperature control of RF cavities were replaced by DC ones to remove the magnetic noise causing the fluctuation of the low energy electron beam. (d) Thermometer modules were also replaced by those with fine temperature resolutions of 0.001 K to suppress the cavity temperature variation to less than 0.01 K.

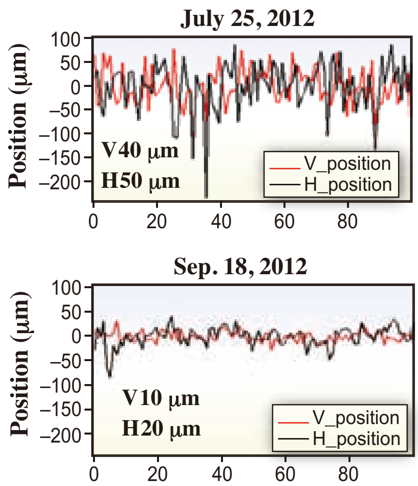

Fig. 2. Laser pointing stability at the optical hutch before and after machine improvement.

3. Short pulse generation

The elaborate efforts on beam tuning have brought about significant improvement of the electron beam brilliance. As a result of this improvement, the gain length denoting the laser amplification efficiency has decreased to 2.3 m as shown in Fig. 3. FEL simulations reproducing the gain curve (Fig. 3) suggest that the peak power is larger than 30 GW and the laser pulse duration is less than 10 fs. This condition is routinely reproducible and the short-pulsed laser with high peak intensity has been constantly delivered to user experiments.

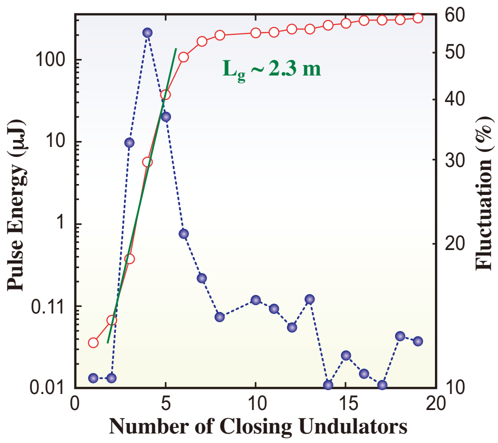

Fig. 3. SASE gain length at 10 keV. Pulse energy (left ordinate) is plotted against the number of closing undulators together with pulse energy fluctuation (right ordinate). Gain length in an exponential gain region is estimated to be 2.3 m. After power saturation, the pulse energy fluctuation is nearly 10%.

4. Two-color SASE generation

In 2012, the two-color XFEL operation was achieved for the first time in hard X-rays [1]. Figure 4 shows a schematic layout of SACLA BL3. A magnetic chicane, which creates a detour for the electron beam and causes a delay, is located in the middle of 18 undulators. For the two-color operation, the magnetic gaps of the undulators are set at different K values before and after the chicane to generate two photon pulses at different wavelengths. Figure 5 shows a spectrum of the two-color XFEL measured by a scanning monochromator. The time delay between two pulses can be finely tuned by adjusting the chicane with attosecond resolution. Since two photon pulses are emitted from the same electron bunch, there is no time jitter between them. In addition, we have a wide tuning range for the wavelengths of two colors. Thus, the two-color XFEL has significant capability for performing X-ray pump X-ray probe experiments, which enables researchers to exploit a novel experimental technique.

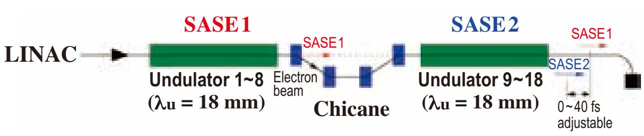

Fig. 4. Schematic layout of the undulator beamline of SACLA BL3.

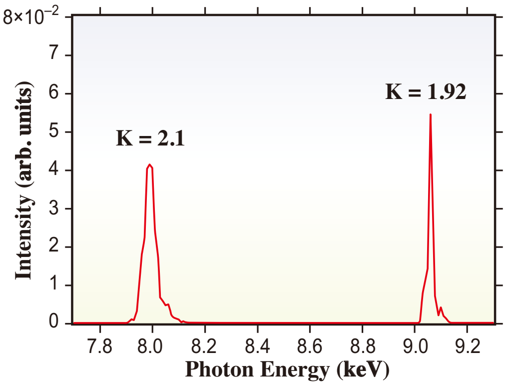

Fig. 5. Measured spectrum of two-color XFEL. K-value was set at K=1.92 for five undulators before the chicane, and at K=2.1 for ten undulators after the chicane. Electron beam energy was 7 GeV.

Beamline and Experimental Stations

As the first compact XFEL facility in the world, SACLA successfully completed its initial commissioning by the end of 2011. Following the commissioning, SACLA started user operation in March 2012. Stable XFEL light has been routinely provided for users without serious downtime. 52 experimental proposals from various fields including biological imaging, femtosecond protein crystallography, ultrafast materials science, high energy density science, nonlinear X-ray optics, and industrial applications, were approved by the JASRI Proposal Review Committee and conducted in the period of 2012A (March to July, 2012) and 2012B (September 2012 to March 2013). In parallel to the user operation, exciting and useful information on radiation properties of XFEL has been obtained by utilizing instruments and methods newly developed for SACLA. In this section, we will introduce methods for the control and characterization of the unique properties of XFEL light, which are important for achieving robust operation of light sources and reliable analysis of experimental data. We also describe the development status of new infrastructures.

1. Control and characterization of XFEL light

A focusing system is a key device for enhancing the high power density of XFEL light. Under close collaboration with the group of Prof. Yamauchi (Osaka University), we have decided to use a reflective focusing system, which has the advantage of a high efficiency close to 100%, as well as high tolerance to intense XFEL light. A combination of two concave mirrors in the Kirkpatrick and Baez geometry was designed for focusing XFEL light down to 1 micron in order to increase the power density to ~10^{18} W/cm^2.

This level is sufficiently high to generate nonlinear X-ray phenomena. We have optimized the focusing profile by a conventional knife-edge scanning method (Fig. 6), proving the high stability of the light source and the beamline optics at SACLA [2]. The system has been used for various types of user experiments including nonlinear X-ray optics, coherent diffraction imaging, and femtosecond protein crystallography.

We applied the system to studies of damage to optical elements under irradiation of intense XFEL light, and obtained important information for all XFEL beamlines, under an international collaboration among XFEL facilities. Damage thresholds for various elements (semiconductor substrates, metal coating, multilayers, etc.) in both normal and grazing incidence geometries have been systematically evaluated using a newly developed dedicated chamber [3].

Among the radiation properties of XFEL, intensity (pulse energy) is one of the most fundamental parameters. Conventional monitoring systems, however, cannot be utilized owing to the high intensity and pulsed nature of XFEL light. For this purpose, SACLA organized an international collaboration program with AIST in Japan, and DESY and PTB in Germany. Absolute intensity evaluated with a gas monitor detector developed by DESY-PTB was compared with that obtained with a calorimeter developed by AIST. We found that the agreement was excellent. The result has been applied to calibrate the foil-based intensity monitor developed by SACLA [4].

We have also evaluated the pulse duration of XFEL light by high-resolution spectral measurement, on the basis of the Fourier transform relationship. For this purpose, we developed a dispersive spectrometer that consists of a concave mirror to increase the beam divergence, a flat crystal analyzer to provide dispersion, and an MPCCD detector to record the spectrum in a single shot. An excellent resolution of 13 meV at 10 keV enabled us to resolve the fine spike structures originating from the SASE mechanism of XFEL generation. By combining the FEL simulation code SIMPLEX, we have evaluated the pulse duration to be from 4.5 to 31 fs [5], which is controlled by the bunch compression parameter (Fig. 7).

The ultrafast pulse duration and moderate spectral bandwidth of SASE XFEL light are promising for performing time-resolved X-ray absorption spectroscopy in a dispersive geometry. We are developing a method that uses both a high-resolution spectrometer and a grating beam splitter. The excellent capability of this method has been proved with a preliminary test.

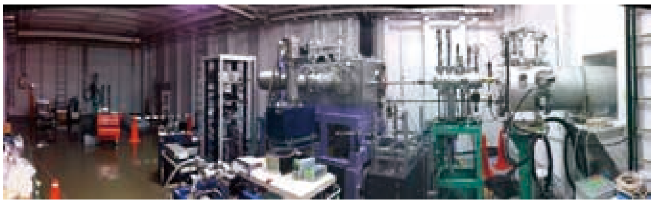

Fig. 7. Typical spectrum measured with high-resolution spectrometer. From the spike width of ~400 meV, temporal width was evaluated to be ~7 fs.

2. Experimental infrastructures

In 2011, we constructed the beamline for the SACLA-SPring-8 Experimental Facility that enables combinative experiments using SACLA and SPring-8 simultaneously. We also installed a two-stage focusing system into this facility under collaboration with the groups of Prof. Mimura (University of Tokyo) and Prof. Yamauchi (Fig. 8). In 2012, we successfully commissioned this system. We will open the facility to users in 2013A.

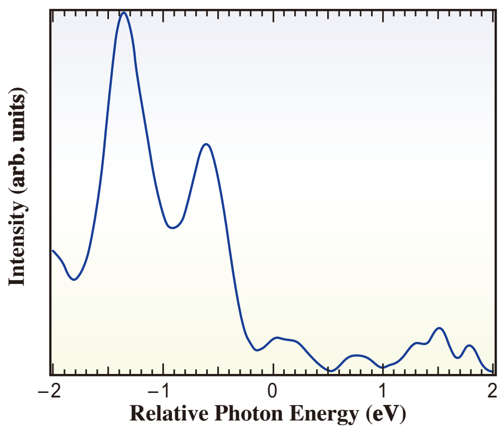

Fig. 8. Beamline components including the two-stage focusing system, installed at EH5 in the SACLA-SPring-8 Experimental Facility.

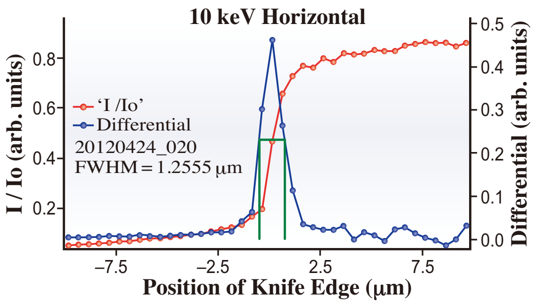

Fig. 6. Horizontal focusing profile with a width of 1.3 um (FWHM) measured by the knife-edge scan method.

The SCSS Test Accelerator

In the SASE-FEL scheme, spectra in the longitudinal phase space (i.e., the temporal and frequency domains) are composed of random and uncontrollable spikes. A seeding scheme is required for realizing a fully coherent light source with perfect longitudinal coherence. At the SCSS test accelerator (SCSS), we have chosen to develop a direct seeding system in the EUV region using the high-order harmonic generation (HHG) of Ti:S laser pulses [6,7]. By focusing intense ultrafast laser pulses into a gaseous medium, fully coherent HH radiation in the extreme ultraviolet (EUV) region can be generated.

In 2012, we continued the development of techniques for maintaining the overlap between the electron bunch and the seeding pulse in 6D phase space. One of the most crucial issues is the temporal overlap. For this purpose, we developed a feedback system with an electro-optic sampling (EOS) technique [8], in addition to an OTR monitoring system and a streak camera (Fig. 9). Using the EOS system, we measured the timing of the arrival of an electron bunch with respect to that in case of EO-probing laser pulses, which were optically split from the common laser source used also for HH generation. This system enabled us to compensate for the long-term drift of the timing of arrival. Using these devices, we finally achieved a high hit rate range of 20–30%.

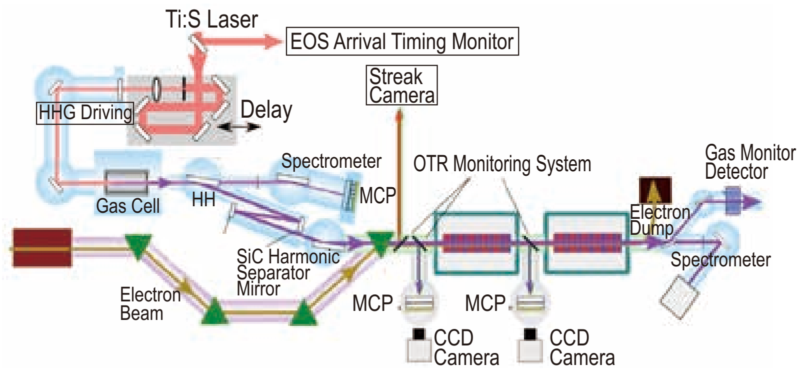

Fig. 9. Layout for HH-seeding system at SCSS.

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