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STABLE GENERATION OF HIGH POWER SELF-SEEDED XFEL AT SACLA

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Abstract

A self-seeded XFEL system using a transmitted beam under Bragg diffraction has been developed at the compact XFEL facility SACLA, in order to generate a brilliant single-mode XFEL with high temporal coherence. The self-seeding setup composed of a small magnetic chicane that can generate up to 50 fs temporal delay and a diamond single crystal with the thickness of 180 μm were installed by 2013. In the beam commissioning, a monochromatic X-ray enhancement at 10 keV due to the self-seeding was observed using the single-shot spectrometer. The integrated peak intensity over 100 shorts was 5 times higher than that without seeding. The spectral bandwidth of the seeded FEL was about 3 eV in FWHM, about 1/10 of that of SASE. The hit rate was more than 80%, which was promising for future practical use. Further optimization and a long-term stabilization will be planned in the next commissioning.

INTRODUCCTION

Seeding in the X-ray free electron laser (XFEL) is an important method to improve the temporal coherence of the self-amplified spontaneous emission (SASE) and to obtain high peak brilliance with narrow spectral band width. Since there is no available laser for external seeding at very short wavelengths, the self-seeding scheme [1] has been considered to be feasible and promising in XFELs, in which the SASE X-ray pulses emitted from the first half of the undulators provides the seeding light in the latter undulators. The scheme proposed at DESY [2] makes the self-seeding more feasible, which uses a single diamond crystal in a forward Bragg diffraction (FBD) geometry, to produce a monochromatic tail components of transmitted X-ray pulses at a small time delay of several 10 fs. A compact magnetic chicane gives the delay to overlap the electron bunches and the monochromatic tail for seeding in the following undulators. The first experimental result based on this scheme is obtained at LCLS [3]. According to their experience, the seeded FEL power was sensitive to the electron beam energy fluctuation of the order of 10^{-3}, because the corresponding photon energy jitter of 0.1% r.m.s. is comparable to the spectral bandwidth of SASE.

The SPring-8 Angstrom Compact free electron LAser (SACLA) [4] is the compact XFEL facility, operated since 2011. SACLA adopted a thermionic cathode-type electron gun, which provides a highly-stable and low-emittance electron beam. The normal conducting C-band accelerator in SACLA has a superior rf stability of 0.01% in acceleration field gradient. The stability of the electron beam energy at the undulator section is as well as 0.02%. This energy stability gives us an advantage for introducing the self-seeding method.

The self-seeding system has been implemented in SACLA since 2012. The 9th undulator segment was moved to downstream and a small magnetic chicane was constructed there. In the middle of the chicane, a vacuum chamber with a diamond single crystal was installed. In 2013, the installation of all the components was completed in August and the commissioning was started in October. After a number of tuning processes, significant spectral narrowing due to the self-seeding was confirmed at 10 keV. In the following sections, the configuration, the tuning process and the experimental results are described.

SETUP

Figure 1 shows the configuration of SACLA and the self-seeding system. The electron beam from the thermionic cathode-type electron gun is sequentially accelerated and compressed at the accelerator section, to obtain high-dense electron beam with the peak current of over several kA and the bunch length of several 10 fs. Then, the electron beam is lead to the long undulator section composed of twenty-one segments of the in-vacuum undulators with the small periodic length of λ_u=18 mm and the maximum K-value (the magnetic deflection parameter) of 2.2.

Between the 8th undulator and the 10th undulator, the small magnetic chicane composed of 4 dipole magnets was installed, in order to detour the electron beam from the diamond crystal and to provide a time delay of 50 fs in maximum. In the middle of the chicane, the diamond crystal chamber was installed, in order to provide the FBD of the SASE radiation from the upstream undulators. Figure 2 shows the schematic of the chamber. A diamond single crystal with the thickness of 180 μm is mounted on the holder in the vacuum chamber. The holder is attached on a multi-axial mechanical stage. The crystal is positioned away from the beam axis during the usual SASE operation and it is inserted for the self-seeding. The crystal can be rotated, in order to adjust the Bragg angle θ. The diffracted photon is measured by a photo-diode and a CCD camera, attached on the 2θ-rotational arm.

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Since the photon energy for our commissioning was 10 keV, the Bragg angle θ was set at about 44 degree in (400) reflection of the diamond crystal. According to the theoretical calculation of FBD [2, 5], the monochromatic tail component in the transmitted radiation increases at the time delay of around 10 fs and 24 fs from the initial radiation. The electron beam delaying at the chicane was overlapped to the radiation in the downstream undulators.

Properties of the FEL radiation was measured at the experimental hall. Thin-foil beam monitors in the optics hutch were used as the in-line monitors of the intensity and the center-of-mass position of the radiation [6]. The energy spectrum of the radiation was measured by the single-shot spectrometer [7]. The spectral resolution and the range are selected by changing the diffraction plane of the silicon crystal. The configuration using (220) plane has a wide measuring range of 100 eV, which was used for the measurement of the whole radiation spectrum. The configuration using (660) plane has a measuring range of 6 eV, but it has a high energy resolution of about 70 meV, which was used for the precise measurement around the Bragg diffraction.

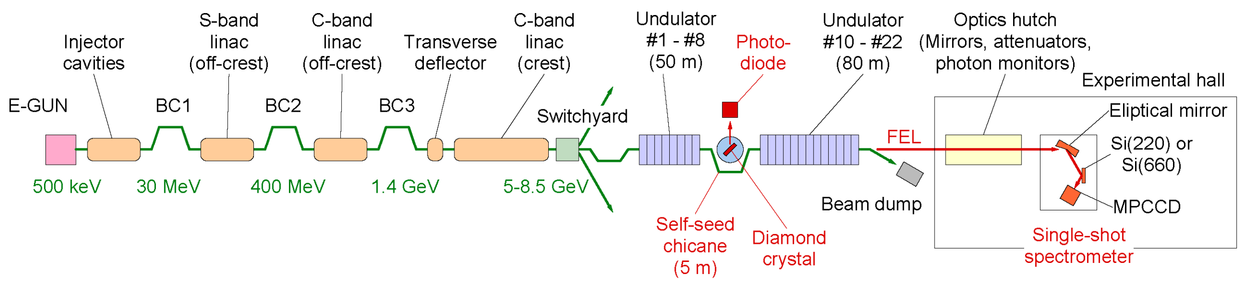

Figure 1: Configuration of the SACLA machine and the self-seeding system. BC1, BC2, and BC3 means the three bunch compression chicanes.

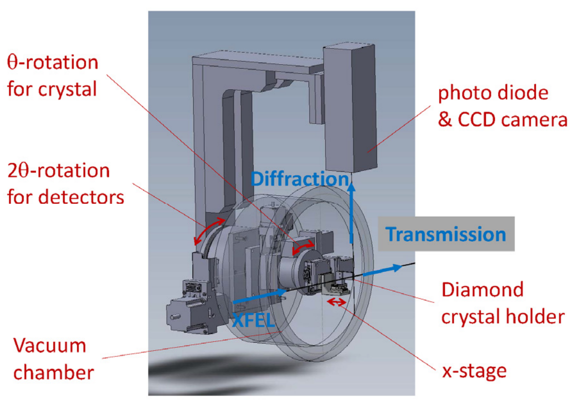

Figure 2: Diamond crystal chamber.

TEST RESULTS

Commissioning of the self-seeding was performed several times during the machine study period of SACLA operation. In November 2013, the first evidence of the seeded radiation was observed in the energy spectrum. After the electron beam stability was improved in May 2014, significant spectrum narrowing due to the self-seeding process was observed. In this section, we report the latest results of commissioning.

The electron beam energy and the photon energy for the commissioning were 7.8 GeV and 10 keV, respectively. The K-value of the undulators were set at about 2.1. The electron bunch charge was about 200 pC. The bunch length was less than 20 fs, which was measured using the transverse deflector cavity located after the final bunch compression chicane (BC3).

Adjustment of the Bragg Diffraction

Six undulator segments (#3-8) in the upstream of the diamond crystal were used to generate initial SASE radiation of about 40 μJ/shot in average. After the dipole magnets at the chicane were excited to give a delay of 15 fs to the electron beam, the diamond crystal was inserted to the beam axis. The delay time, which is slightly different from the predicted values mentioned before, was chosen to overlap the electron beam to the monochromatic tail component of the transmitted X-rays, according to the result of the previous experiment in November 2013. The Bragg angle was set at 44 degree in diamond (400) diffraction for 10 keV radiation. We optimized the undulator K values, to maximize the diffracted X-ray intensity measured by the photo-diode attached on the 2θ-rotational arm of the diamond crystal chamber. It means the Bragg diffraction wavelength was matched to the central wavelength of the SASE radiation from the upstream undulators.

Energy Spectrum of Transmitted SASE Radiation

Energy spectrum of the transmitted SASE radiation was measured using the single-shot spectrometer. At first, the diffraction plane of the silicon crystal was set to (660) for high-resolution measurement. Figure 3 shows the typical spectrum. We found a clear dip around 9.978 keV, due to the Bragg diffraction of the diamond crystal, suggesting that the diamond crystal has a good quality.

Next, we changed the diffraction plane of the single-shot spectrometer to (220), in order to measure the entire spectrum shape. We confirmed that the photon energy of the Bragg diffraction observed above was close to the peak position of the transmitted SASE spectrum.

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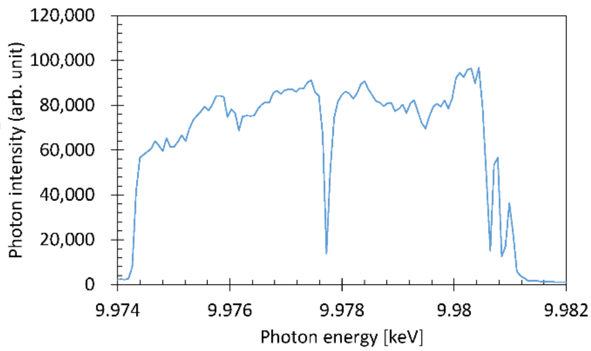

Figure 3: Energy spectrum of the transmitted SASE radiation, measured by the single-shot spectrometer with the silicon (660) configuration. There is a clear dip at 9.978 keV due to the Bragg diffraction of the diamond crystal.

Observation of Seeding

Observing the energy spectrum shape with (220) configuration, we closed the gap of the downstream 9 undulator segments (#10-18). After carefully adjusting the K value of the downstream undulators, a clear peak at 9.975 keV appeared. Figure 4 shows the energy spectrum, integrated over 100 shots. When we took away the diamond crystal from the beam axis, the peak disappeared. Therefore, we confirmed this peak was induced by the self-seeding mechanism associated with the Bragg diffraction of the diamond crystal. The peak intensity with the diamond crystal was 5 times higher than the intensity without the crystal. The bandwidth was about 3 eV in FWHM, which is about 1/10 of the SASE bandwidth. The difference between the peak position of the seeded signal in Figure 4 (9.975 keV) and the dip position in Figure 3 (9.978 keV) should not be discussed here, because of the energy scale uncertainty of two configurations.

Figure 5 shows the typical single-shot spectra with the diamond crystal. We defined the “seeded” signal as the event has a spectrum peak in 9.975±0.005 keV and the peak intensity is larger than 15,000 of the same scale as Figure 4, which is larger than most of the SASE spikes. The rate of the “seeded” event was 82% for 100 shots of the spectra. It means the SASE was seeded with high frequency, which is promising for future practical use. The pulse-to-pulse fluctuation of the peak intensity was about 50% in the standard deviation.

CONCLUSION

The monochromatic X-ray enhancement and the spectral narrowing, due to the self-seeding scheme with forward Bragg diffraction (FBD) of the diamond single crystal, was observed in SACLA. Thanks to the good pulse-to-pulse stability of the beam, a hit rate of the “seeded event” was more than 80%. However, the good seeding condition has not been kept well yet for long time. Further tuning efforts has been continued in order to release seeded X-rays as an experimental option for users.

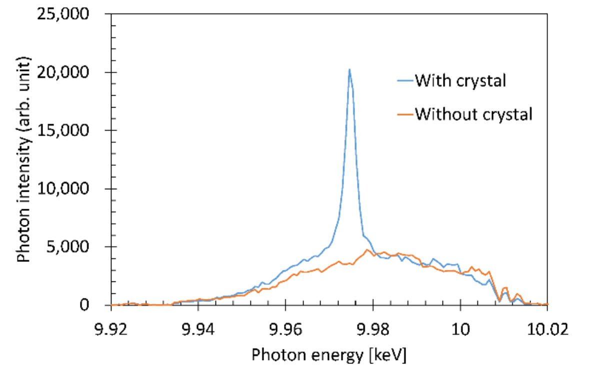

Figure 4: Energy spectra of the X-ray radiation with and without the diamond crystal, measured by the single-shot spectrometer with silicon (220) configuration. The plots are the integration of 100 shots.

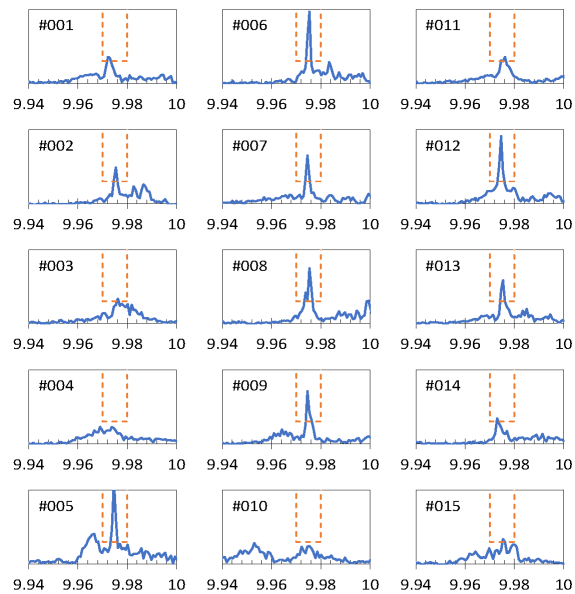

Figure 5: Typical single-shot spectra of the X-ray radiation with the diamond crystal. The red dashed box means the criteria for “seeded” events (see text).

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