Beamline for X-ray Free Electron Laser of SACLA

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Abstract. A beamline for X-ray free electron laser (XFEL) has been developed at SACLA, SPring-8 Angstrom Compact free electron Laser. The beamline delivers and diagnoses an XFEL beam without degrading the beam quality. The transport optics are applicable in the range of 4–30 keV with a double-crystal monochromator or 4–15 keV with either of two double-mirror systems. A photon diagnostic system of the beamline monitors intensity, photon energy, center-of-mass position, and spatial profile in shot-by-shot and non-destructive manners.

1. Introduction

An XFEL beamline transports and diagnoses coherent and highly brilliant X-ray pulses, the characteristics of which are quite different from those of conventional synchrotron radiation [1,2]. The beamline optics should be designed carefully to deliver an XFEL beam without much degrading the wavefront of coherent beam and brilliance. In addition, shot-by-shot monitoring of the beam is mandatory in case of the XFEL that is based on the principle of self-amplified spontaneous emission (SASE). Because the stochastic nature of the SASE generation mechanism induces shot-by-shot fluctuations in radiation properties, experimental data should be related to the properties in a shot-by-shot manner. Therefore, the diagnostic system has to measure radiation parameters in every shot without interfering with experiments.

We have developed an XFEL beamline, BL3, at SACLA. The transport optics deliver pink or monochromatized beam to experimental stations. Optical elements for the beamline are designed to stand a high peak power in the order of 10 GW and to keep the wavefront of coherent beam unperturbed. The beamline is also equipped with nondestructive monitors for fundamental parameters of individual X-ray pulses. Design and specifications of the beamline optics and monitors are described in the following sections. Measured parameters of the photon beam are also shown.

2. Design of the beam-transport optics and photon diagnostic system

Figure 1a shows a schematic drawing of the BL3 transport optics in an optics hutch. It basically consists of two sets of double plane mirrors, double crystal monochromator, a four-jaw slit, solid attenuator, and gas attenuator. Design parameters of those components are listed in table 1 [3]. The mirror systems transmit a pink beam below 15 keV. One set with an incident angle of 4 mrad has a cutoff energy of 7.5 keV, and the other with 2 mrad shows higher cutoff at 15 keV. These mirror
systems reduce contribution of higher order harmonics with photon energies above the cut-off energies. The monochromator using two Si (111) crystals covers the whole range of the fundamentals of SACLA (4–20 keV) and higher-order harmonics up to 30 keV. A monochromatic beam from the crystals has a bandwidth in the order of 0.01%. The solid attenuator consists of thin silicon crystals with thicknesses from 0.1 to 3.0 mm. It can be combined with the gas attenuator, in which Ar gas works as an absorber. Appropriate crystal thickness and argon-gas pressure are selected to reduce XFEL intensity at experimental stations.

Table 1. Main components and design parameters of beam transport optics of BL3.

| Component | Parameter | Design value |
|-----------|-----------|--------------|
| Double plane mirrors (a) | Incident angle | 4 mrad |
| | Effective length | 400 mm |
| | Cut-off energy | 7.5 keV |
| Double plane mirrors (b) | Incident angle | 2 mrad |
| | Effective length | 400 mm |
| | Cut-off energy | 15 keV |
| Monochromator (double Si 111 crystals) | Incident angle | <30º |
| | Energy range | 4–30 keV |
| | Band width | 0.01% |

Figure 1. (a) Beam transport optics of the hard X-ray beamline, BL3, of SACLA. M1 and M2a (M1 and M2b): Double plane mirrors with an incident angle of 4 mrad (2 mrad). DCM: Double crystal monochromator. (b) Photon diagnostic system of BL3. PD: Photodiode. SCM: Screen monitor. BPM: Beam position monitor. SP: Spectrometer. MCP: Micro channel plate.

After the transport optics, five experimental hutch (EH1–EH5) are arranged in tandem. Kirkpatrick-Baez (KB) mirrors can be inserted into the beam axis at EH3 to focus the beam down to 1 μm (FWHM). An optical laser beam can be introduced at EH2 and EH3 for pump-and-probe
experiments. At EH5, users can irradiate their samples with both the XFEL beam and a synchrotron radiation beam from the storage ring of SPring-8.

As shown in figure 1b, photon monitors are arranged along the beam paths in the optics hutch; seven Si PIN photodiodes, seven screen monitors, two beam position monitors (BPMs) [4], one spectrometer, and one gas intensity monitor. The PIN photodiode is suitable to measure intensity of a weak beam in the range of $10^3$–$10^8$ photons/pulse with the aid of a precise amplifier system developed at SACLA [5]. The screen monitor consists of two fluorescent screens, Ce:YAG and B-doped diamond screens, which are mounted on a linear translator along with the PIN photodiode. The diamond screen works as a nondestructive profile monitor because of its high X-ray transmittance. The BPMs, spectrometer, and gas intensity monitor detect scattered and diffracted X-rays from thin foils or gas with a large X-ray transmittance. Highly sensitive Si PIN photodiodes and a multiport charge coupled device (MPCCD) allow us to monitor the multiple parameters simultaneously with only small portions (typically 0.01%) of an incident beam. The BPM was calibrated with an X-ray radiometer which provides absolute intensity of the XFEL beam [6,7].

Additionally the transport optics is equipped with a phosphor screen with an image intensifier (micro-channel plates). This device is utilized for fine tuning of an electron-beam trajectory in undulators [2]. The electron trajectory at each undulator segment is probed by taking images of a monochromatized beam of spontaneous radiation.

3. Radiation parameters of the XFEL beam at BL3

3.1. Pulse energy and spectrum measured at the optics hutch

Representative radiation parameters at 9.98 keV are listed in table 2. Each parameter is obtained by averaging shot-by-shot data. For example, the pulse energy (236±38 μJ/pulse) is an average of 100-shot data. The intensity fluctuation (one standard deviation; $\sigma$) amounts to 16% of the average. Figure 2a shows a spectrum, which has a full-width-at-half-maximum (FWHM) of 62 eV. The center values of photon energy show a small fluctuation of only 0.08% ($\sigma$), indicating stable operation of the accelerator.

Table 2. Photon-beam parameters at 9.98 keV.

| Parameter                          | Value               |
|-----------------------------------|---------------------|
| Pulse energy $^{a,b}$             | 236±38 $\mu$J       |
| Center photon energy $^a$         | 9.98±0.008 keV      |
| Band width (FWHM)                 | 0.6%                |
| Fluctuation in beam position      | 40 μm (horizontal)  |
| (σ of centre-of-mass positions)   | 19 μm (vertical)    |
| Beam size $^a$                    | 310±50 μm (FWHM)    |

$a$ Averaged values over 100 pulses.
$^b$ Measured with BPM1 (see figure 1b).

Table 3 shows typical pulse energies measured with BPM1 in the range of 5.5–15 keV. Since photon beams at respective photon energies are produced at different electron-beam energies and undulator gaps, the pulse energies do not change monotonically with photon energy. In general, the pulse energy decreases as the photon energy increases at a fixed electron-beam energy [2]. Contribution of the third harmonic is estimated at approximately 1% of the total radiant power at 4.4 keV (0.3% at 7.9 keV) [2,7]. The third harmonic of 4.4 keV was measured by filtering out the lower harmonics with Si filters [6]. Higher-order harmonics contribution at different photon energies can be measured by using the double crystal monochromator.

Table 3. Typical pulse energies.$^{a,b}$

| Photon energy /keV | Pulse energy /μJ |
|--------------------|------------------|
| 5.5                | 226±40           |
| 7.3                | 186±21           |
| 9                  | 200±26           |
| 12                 | 178±26           |
| 15                 | 82±15            |

$a$ Averaged values over 100 pulses.
$^b$ Measured with BPM1 (see figure 1b).
3.2. Spatial profile and pointing at experimental hutches

Figure 2b shows a spatial profile of a single 10-keV pulse which is transported to EH2 with the double mirrors, M1 and M2b. A hundred beam profiles indicate that the beam has an FWHM of 310±50 μm. We evaluated pointing stability of the beam with BPM2, which is placed about 2 m upstream from the upstream end of EH1. The center-of-mass position has σ values of 40 μm and 19 μm in horizontal and vertical directions, respectively. These values correspond to 0.4-μrad (horizontal) and 0.2-μrad (vertical) deviations of the beam axis.

The beam trajectory is aligned to a fixed axis within an error of 2.5 μrad by using SCMs in the optics hutch and experimental hutches. Owing to this tuning procedure, stable operation of the beamline has been achieved. For example, we are able to fix focal position and waist size of a focused beam at EH3 without frequent tuning of the KB-mirror system.

Figure 2. Typical spectrum (a) and spatial profile (b) of the XFEL beam at 10 keV. The spectrum was measured by scanning the Bragg angle of the double-crystal Si (111) monochromator which has a bandwidth of 0.01%. Intensity signals were accumulated over 10 shots for each data point. Energy intervals between adjacent data points are 5 eV.

4. Outlook

New optical components, monitors, and experimental instruments will be installed in BL3; for example, split-and-delay optics, tight focusing systems, monitors for arrival timing between XFEL and optical laser pulses, and high-resolution single-shot spectrometers. In parallel with the upgrade of BL3, beam-transport optics and experimental stations for a soft X-ray beamline (BL1) are being constructed.

References

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