COMMISSIONING AND PERFORMANCE OF THE BEAM MONITOR SYSTEM FOR XFEL/SPRING-8 "SACLA"

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Abstract

The construction of a beam-monitor system for XFEL/SPring 8 "SACLA" was completed. The system was developed to realize a spatial resolution of less than 3 μm to align the beam orbit for an undulator section of about 100 m long and a temporal resolution to measure bunch lengths from 1 ns to 30 fs to maintain a constant peak beam current conducting stable SASE lasing. The system principally comprises cavity-type beam-position monitors, current monitors, screen monitors and bunch-length measurement instruments, such as an rf deflector and CSR detectors. Commissioning of SACLA started from March 2011, and the monitors performed sufficient roles to tune the beams for lasing. The achieved over-all performances of the system including DAQ are: the beam position monitor has a spatial resolution of 600 nm; the bunch-length monitors observe bunch lengths from 1ns in an injector with velocity bunching to less than 30 fs after three-stage bunch compressors. The less than a 3 μm spatial resolution of the screen monitor was also confirmed in practical beam operation. By these fulfilled performances, stable lasing of SACLA is achieved.

INTRODUCTION

The construction of an X-ray free electron laser (XFEL), "SACLA", which comprises an 8-GeV linear accelerator with 400 m long and 18 in-vacuum undulators of 5 m long, has been finished. We succeeded in XFEL lasing at a wavelength of 0.12 nm in June, 2011 [1]. In order to maintain stable SASE-FEL generation at SACLA, the electron beam should be precisely overlapped with x-rays through an undulator section within 4 μm [2] and a 30 fs (FWHM) bunch length, which directly determines the peak beam current of 3 kA, formed by the bunching process should be also tightly kept [3]. Therefore, beam monitors for SACLA should have a spatial resolution of less than 1 μm, and a temporal resolution of less than 10 fs. We have developed and constructed beam monitors, as illustrated in Fig. 1, to satisfy demands; they are already and effectively used for beam commissioning in SACLA. For spatial observations of electron beams, such as the position and the profile, 57 cavity-type beam-position monitors (RF-BPM) [4] operated at 4760 MHz and 49 high-resolution screen monitors (SCM) [5] using optical transition radiation (OTR) and scintillation of Ce:YAG, were installed in SACLA. These demanded resolutions are less than 1 μm for the BPM and 5 μm for the SCM, respectively.

The electron bunch is compressed from 1 ns to 30 fs along a SACLA accelerator by using the velocity bunching process in multi-sub-harmonic bunchers (SHB) of the injector [6] and the magnetic bunching process in 3 bunch compressors (BC) using a 4 bending magnets chicane. To observe the electron bunch lengths along the bunching process, 2 fast differential current transformers (DCT) [7] with a pulse response of 150 ps for the beginning part of the injector, 3 coherent synchrotron radiation monitors (CSRM) [8] for the BCs, an OTR bunch-length monitor using a streak camera (FESCA-200, Hamamatsu Photonics Co.Ltd) and a HEM-11 mode C-band rf beam deflector (RFDEF) [9] operated at 5712 MHz to observe the final longitudinal bunch structure after the BC3 were also installed. The 33 DCTs in total used to measure the charge amount of the beam were also installed in another accelerator part without the beginning of the injector. The performances of the beam monitors, such as the spatial and temporal resolutions, in the beam commissioning are mainly described in this paper.

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SPATIAL BEAM MONITORS

BPM

The BPM, as depicted in Fig. 2, comprises a position detection cavity with a TM110-mode and a reference cavity with a TM010-mode, both operated at a resonant frequency of 4760MHz. The position detection cavity has four coupling slots with antennas, two for the x-direction and the other two for the y-direction. The detection sensitivity of the BPM is 16 mV/nC/μm, which was measured at the SCSS test accelerator. After mass production of the BPMs, they were installed into the SACLA accelerator and an undulator beamline. Their performances were evaluated when the beam commissioning of SACLA was proceeded. The position resolutions of the 20 BPMs along the undulator beamline were precisely checked, because of the resolutions directly connected to the performance of the beamline tuning for SASE amplification. The position resolution of a BPM is evaluated from the difference value between a measured position and an estimated one from other neighbouring BPMs. We analysed the resolutions of the 20 BPMs along the undulator beamline.

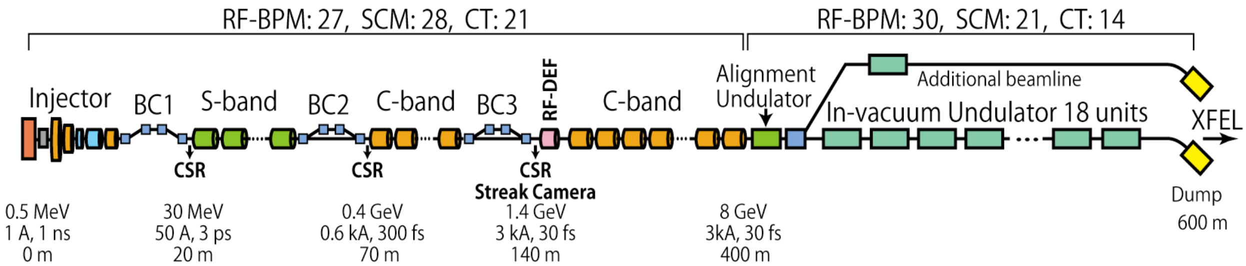

Figure 1: SACLA accelerator layout and the number of beam monitors.

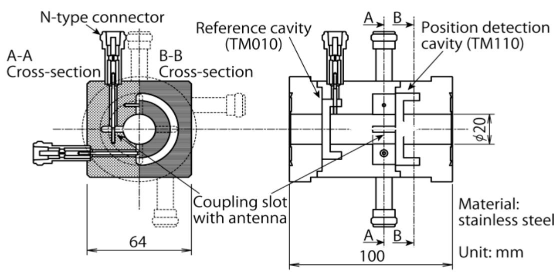

Figure 2: Drawing of the RF-BPM cavity.

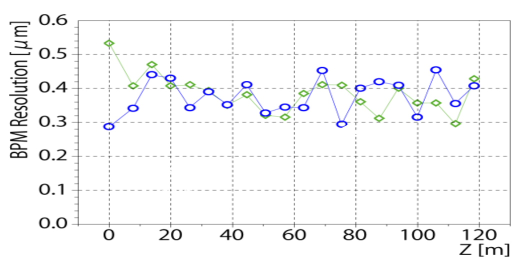

Figure 3: Position resolutions of the BPMs along the undulator beamline. The resolutions are less than 0.6 μm (STD).

In order to estimate the beam position at a given RF-BPM, the data of the other 19 RF-BPMs were used. The beam positions of the given RF-BPM to individual beam shots were estimated by the least-squares method. In this analysis, constraints coming from transfer matrices were imposed on a beam orbit and the positions and slopes of the beams at the given RF-BPM were determined so as to reproduce the other BPM data. By using an electron beam with a bunch charge of 0.1 nC and a beam energy of 7 GeV, we analyzed the position resolutions of the RF-BPMs on the undulator beamline. Figure 3 shows the evaluated position resolutions of the 20 BPMs.

SCM

The SCM comprises a vacuum chamber, an in-vacuum screen of stainless-steel foil (100 μm thick) or Ce:YAG to radiate OTR or scintillation, focusing lenses with 3 groups and 4 pieces, and a CCD camera system. The lenses are placed near the screen with the distance between the front lens and the screen surface being 100 mm; the lenses have a large aperture of 2 inches. This optical-geometrical structure is effective to obtain a wide numerical aperture. The calculated resolution of an image on the screen is 2.5 μm. The observed images of the SCM, which are a beam profile and its pitched profiles to measure an electron bunch length by the RFDEF, are shown in Fig. 4.

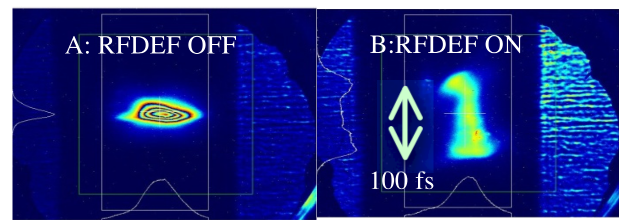

Figure 4: A, the beam profile taken with the Ce:YAG screen and B, the beam image pitched by the RFDEF.

TEMPRAL BEAM MONITORS

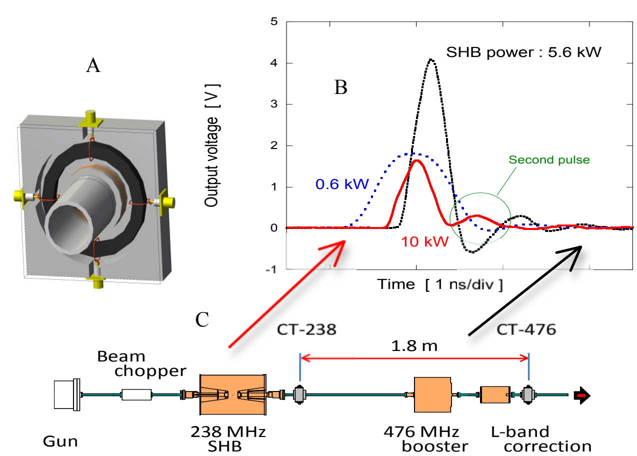

Figure 5: A, DCT. B, Bunching of an electron beam observed with the DCT, when changing the SHB rf power. C, Injector layout.

DCT

The fast DCT, as shown in Fig. 5, which has a function to reduce any common-mode noise by differential outputs, was developed to measure the beam current. It comprises 4 outputs with a one-turn coil each and a finemet core (Hitachi Metal, Ltd.). On the other hand, the rough timing of the beam-arrival time can also be measured with the DCT, because of its fast pulse response. The pulse wave forms outputted from the DCT, as also shown in Fig. 5, were taken in the injector. The rise time of the pulse was about 200 ps (10-90%). This value, measured with a 13 GHz oscilloscope with less than 1 ps resolution, is sufficient to observe a bunch length at the place just after the SHB and to determine the beam arrival timing from an electron gun to the booster. The figure also shows the bunching evolution observed with the DCT in the injector.

CSRM

The 3 non-destructive CSRMs, as shown in Fig. 6-A, are installed at the 3 BCs, respectively. Each CSRM comprises a pyro-electric detector, an organic lens, a perforated gold-plated aluminum mirror and a gold-plated mirror. They can observe coherent synchrotron radiation (CSR) emitted from the final bending magnet of the BC comprising 4 bending magnets. The CSR flux intensity, $P_{csr}(\lambda)$, expressed by the equation $P_{csr}(\lambda) \sim P_e(\lambda)\{N_e + N_e^2 F(\lambda)\}$, is inversely proportional to the bunch-length, where N_e is the electron population and $F(\lambda)$ is the bunch form factor. Figure 6-B shows the bunch length sensitivity of the CSRM at BC2, when the energy chirp of the bunch was changed by the rf phase of the S-band cavity before BC2. The graph in the figure shows the good proportionality between the S-band cavity phase and the CSRM output signal.

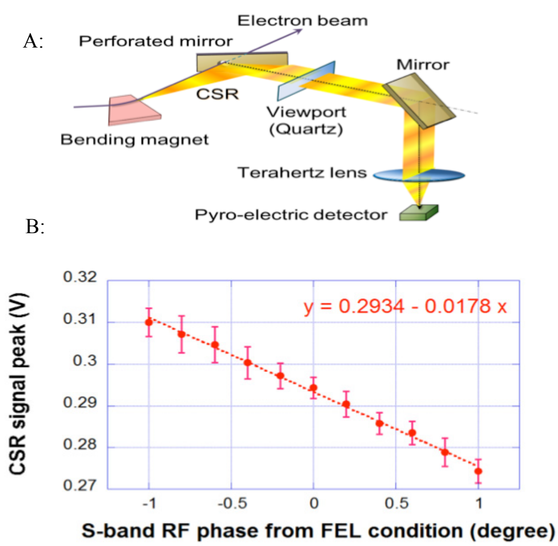

Figure 6: A. Configuration of the CSRM. B. Bunch length sensitivity of the CSRM output signal at the BC2, when the energy chirp of the bunch is changed by the rf phase in the S-band cavity.

RFDEF

The RFDEF pitches the beam bunch around its center to project the image of the longitudinally compressed bunch structure on the screen of the SCM, as shown in Fig. 7. The relation between the deflection voltage, V_y, and the projected bunch length on the screen, l_y, is given by

$$V_y = \frac{l_y}{L_d}\frac{cp_z}{ek_a\sigma_z}, \qquad (1)$$

where L_d is the drift length between the RDFEF center and the SCM, k_a is the wave number of the RFDEF, σ_z is the bunch length, and p_z is the longitudinal momentum of a bunch. V_y must be 40 MV in the planned case of L_d = 5 m [9] to obtain a bunch-length measurement sensitivity of 200 fs/mm on the screen of the developed SCM with a spatial resolution of less than 2.5 μm [5]. The RFDEF of a backward accelerator guide, which has a racetrack-shape rf coupling iris to prevent rotation of the deflection plane of the HEM11 mode, was developed. The rf conditioning of the RFDEF was successfully finished with the generation of a 60 MV/m beam pitch voltage. We finally installed the RFDEF in SACLA and tested the beam deflection performance. Figure 3-B shows a beam deflection image on the SCM. The resolution of the bunch-length measurement is about 20 fs.

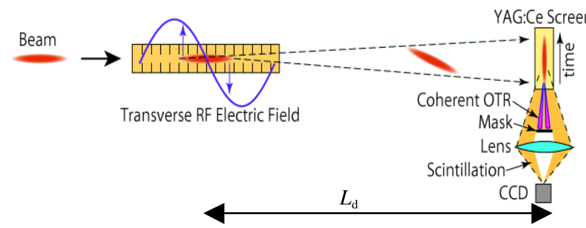

Figure 7: Bunch length measurement system using the RFDEF for a pulse width of less than 500 fs.

SUMMARY

The developed beam monitors for SACLA worked well. A BPM showed a position resolution of 0.6 μm (rms). A SCM has less 3 μm (rms) spatial resolution. A DCT, a CSRM and an rf deflector show the demanded temporal resolutions, such as the bunch-length measurement resolution of 20 fs. Since we realized sufficient resolutions, SACLA was successfully lased at 0.12 nm. This successful result was strongly supported by our developed beam-monitor system for SACLA.

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