CSR BUNCH LENGTH MONITOR FOR XFEL/SPRING-8 "SACLA"

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Abstract

SPring-8 Angstrom Compact free electron Laser (SACLA) is now under commissioning operation, aimed at the generation of a sub-angstrom free electron laser (FEL). In order to ensure the stable FEL generation, non-destructive bunch length monitors utilizing coherent synchrotron radiation (CSR), which were proposed to indirectly observe bunch lengths from 10 ps to 30 fs, were installed at each of three bunch compressors (BC1, BC2, BC3). The CSR is detected by a pyroelectric detector with a simple organic lens optical system. We examined the CSR monitor at BC2, and measured the bunch lengths using it combined with that of an rf deflector cavity. The results indicated that the monitor enables us to measure the sub-picosecond bunch length with a precision of less than 10%.

INTRODUCTION

SPring-8 Angstrom Compact free electron Laser (SACLA) in Japan is now in a commissioning stage for the X-ray SASE FEL generation. In the linear accelerator of SACLA, an electron bunch is compressed from 1 ns, 1 A to 30 fs, 3kA by velocity bunching and three bunch compressor chicanes (BC1,2,3) [1]. Rf accelerator cavities before each bunch compressor give an energy chirp along the bunch. Therefore, a bunch length at each end of the BCs can be controlled by shifting the rf phase of the cavities. In order to obtain a stable intensity FEL, the stabilization of the peak current of the beam is essential. To stabilize the peak current, the bunch length should be monitored and the monitored results should be fed back to the rf phase of the upstream accelerators of the BC. The requirement to the bunch length stabilization is less than 10% [2].

We have developed a bunch length monitor utilizing coherent synchrotron radiation (CSR) generated at the final bending magnet of a 4 bending magnets bunch compressor chicane (BC). A prototype CSR monitor was experimented at SCSS in 2010, and obtained a good performance [3]. Based on the result, we developed an improved CSR monitor for SACLA. The monitors installed at the downstream of the last bending magnet of the three bunch compressors, respectively, and were commissioned. In this report, we explain a design, a setup, and a commissioning result of the monitor.

Table 1: Parameters at the BC sections [5].

Section	Beam Energy	Magnetic Field	Bunch Length
BC1	30 MeV	0.044 T	~3 ps
BC2	403 MeV	0.184 T	~ 0.3 ps
BC3	1.40 GeV	0.291 T	~0.03 ps

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OVERVIEW OF CSR MONITOR

Coherent Synchrotron Radiation

When an electron beam passes a bending magnet, it emits synchrotron radiation. For the wavelengths of the radiation longer than the bunch length, the radiation from multiple electrons is in a coherent phase, and the radiation power increases with square of the number of electrons N_e [4]. The photon flux is expressed by

$$P_{\mathrm{csr}}(\lambda) \sim P_{\mathrm{e}}(\lambda)\left[N_e + {N_e}^2 F(\lambda)\right], \tag{1}$$

where λ is the wavelength, $P_{\mathrm{e}}(\lambda)$ is the synchrotron radiation flux from one electron. $F(\lambda)$ is called the form factor of an electron bunch shape, expressed as

$$F(\lambda) \equiv \left|\int_{-\infty}^{\infty} f(z) e^{-i\frac{2\pi z}{\lambda}}\, dz\right|^2, \tag{2}$$

where $f(z)$ is the normalized longitudinal distribution of an electron beam.

In Table 1, we tabulate typical parameters at the individual BC sections where the CSR monitors are installed. By using these parameters and the simulated longitudinal distributions [5], we calculated CSR spectrum by SPECTRA [6]. The result is shown in Fig. 1. The results show that the cut off frequencies of photon fluxes are 50 GHz at the BC1, 300 GHz at the BC2, and 2 THz at the BC3. The cut off frequency depends on the bunch length, and the total CSR photon flux also depends on the bunch length. Therefore, CSR intensity is sensitive to the bunch length, and we can observe the variation of the bunch length by measuring the CSR intensity.

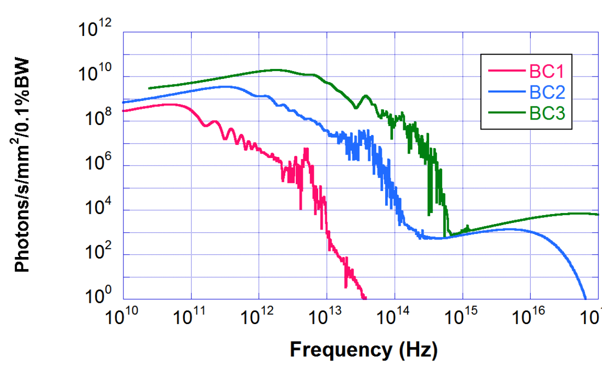
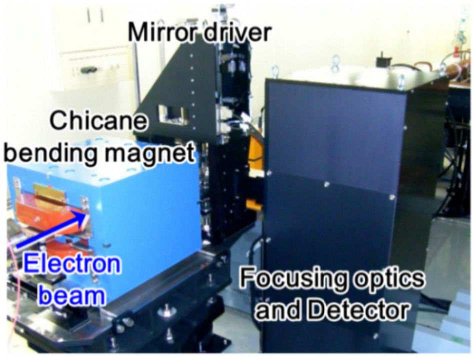


Figure 1: Calculated CSR spectrum at the BC sections by using SPECTRA [6].



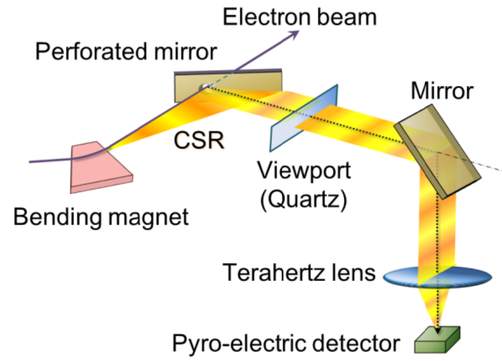


Figure 2: (Left) Set-up of the CSR monitor instruments at the BC2, and (Right) their schematic layout. The focusing optical system and detector are installed in the black case to reduce an unnecessary light from the exterior.

Setup of Monitor

In Fig. 2, we represented the view and schematics layout of the monitor. A perforated mirror is installed at downstream of the last chicane magnet, and reflects the CSR to the outside of a vacuum chamber. By an outer refracting optical system, the radiation is focused to pyroelectric detector. In the following section, we explain the detail of components of the monitor.

The mirror inserted on a beam axis has a hole with an inner diameter of 10 mm to non-destructively pass the beam. The surface of the mirror is coated by gold in order to ensure high reflectivity. By this mirror, the CSR generated at the bending magnet is perpendicularly reflected.

The reflected radiation passes through a quartz viewport and is focused on the detector by using a terahertz lens (TSURUPICA [7]). Because the refractive index of the lens in terahertz frequency is equal to that of the visible light case, we can easily align the optical system by using a visible laser.

The focused radiation is detected by a pyro-electric detector which is SPH-60 of Spectrum Inc. [8]. The pyro-electric detector generates a voltage proportional to infrared light power, and operates at room temperature. The sensitive area of the detector to the light is 2 mm$\times$2 mm, and its detectable frequency is from 0.1 to 30 THz.

The terahertz lens and the detector are displaced from the height of a beam line in order to reduce radiation damage, and are enclosed with a black case to reduce an environmental light.

To adjust the detector position at the focal point along the optical axis, the lens is mounted on a Z-stage and the detector is mounted on an XY-stage. The acquired CSR intensity data is periodically collected to the database of SACLA by the data acquisition system (DAQ) system for this monitor.

EXPERIMENT AND RESULT

In this section, we explain the commissioning and the experimental results of the CSR monitor at the BC2, as one example.

Detector Response and Focus

In Fig. 3, we show the typical output waveform of the detector with FEL lasing conditions. When injecting the CSR light into the detector, the output voltage rises within 2 ms. This pyroelectric detector characteristic could be a differential function. Therefore, we defined the peak-to-peak value of the waveform as the CSR intensity.

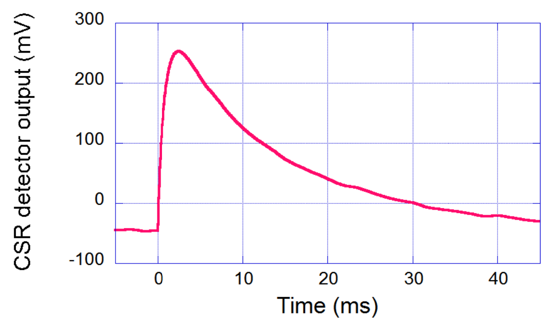


Figure 3. Waveform of the detector output voltage.

We searched the focal point of the CSR light by moving the height of a lens height and the horizontal position of the detector. As the result, the spot size of the light at the focal position was circular and its diameter was about 2.5 mm (FWHM). This result indicated that the radiation can be almost concentrated on the pyro-electric detector by the optical system without dispersion effect dependent on light frequencies.

Charge Dependence

In order to ensure that the detector observed the coherent radiation, we measured the charge dependence of the CSR light intensity. The CSR intensity as a function of the beam charge was observed, as shown in Fig. 4, where the intensity was proportional to the square of a beam charge. This tendency between the beam charge and the detected intensity is consistent with the $N_e^{\,2}$-dependence of Eq. (1), i.e., the monitor observed the coherent radiation.

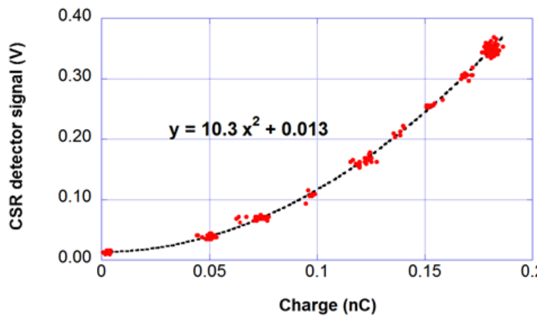


Figure 4: CSR intensity at the BC2 as the function of the beam charge.

Bunch Length Dependence

To estimate the sensitivity of the CSR monitor output to a bunch length change, we measured the correlation between a CSR intensity value and a longitudinal bunch profile which was measured by an rf deflector cavity (RF-DEF) [9]. The bunch length was varied by the rf phases of S-band accelerators which control the energy chirp along the beam bunch at the BC2. When the S-band rf phase was shifted around a FEL lasing point, typical temporal profiles were measured by RF-DEF, as shown in Fig. 5. The bunch length (FWHM) was linearly changed from 200 fs to 400 fs when the rf phase was shifted from -1° to +1° relative to the FEL lasing point.

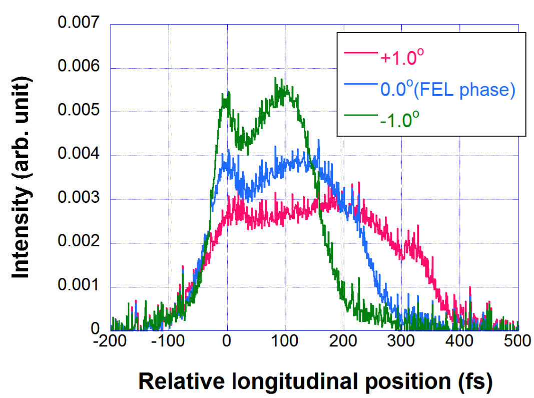


Figure 5: Longitudinal distribution of beam at the exit of BC2 measured by the rf deflector cavity. The index phases indicate the rf phase of S-band accelerators.

Based on the rf deflector measurements, we decided the phase shift dynamic range of the S-band accelerator for CSR intensity measurements by the detector system. The measured CSR intensity as a function of the S-band rf phase is shown in Fig. 6. The result indicates the CSR intensity is linearly proportional to the rf phase. We estimated the detector sensitivity to the bunch length change. The proportionality factor between the CSR intensity and the specified S-band rf phase corresponding to the specified bunch length is 0.0178 V/deg., and the fluctuation of the measured values is about 2.5 mV (STD). From these results, the precision of bunch length was estimated about 14 fs, which amounts to 5% of a 300 fs bunch length (FWHM) at the FEL lasing condition. This precision is better than the requirement to the monitor.

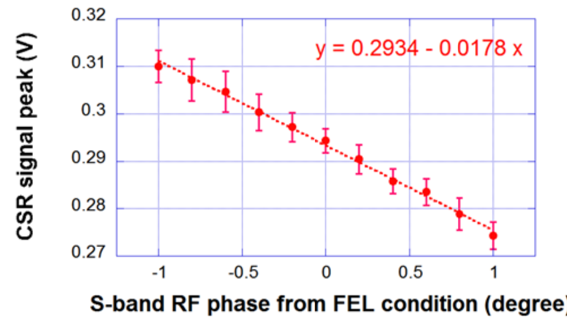


Figure 6: Rf phase dependence of CSR intensity at BC2.

SUMMARY AND OUTLOOK

We developed a non-destructive bunch length monitor for SACLA, which measures CSR intensity by using the refracting optics system and the pyroelectric detector. The detectors were installed at the downstream of three BC sections, respectively. The observed charge dependence of CSR intensity at the BC2 shows the square dependence. The measurement sensitivity of the CSR detector to a bunch length was estimated to be 5% to a sub-picosecond bunch length. This value is sufficient for the requirement to stabilize the bunch length within 10%.

In future, we will lunch up the other bunch length monitors, and will develop a feedback system to stabilize the bunch length.

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