DEVELOPMENT OF BUNCH LENGTH MONITORS USING A CSR DETECTOR AND A STREAK CAMERA AND MEASUREMENT RESULTS AT THE SCSS TEST ACCELERATOR

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Abstract

To measure the femtosecond bunch length (10 – 1000 fs) of the XFEL facility at SPring-8, we developed a coherent synchrotron radiation (CSR) monitor and a streak camera system. The CSR is emitted from a dipole magnet and is detected by a pyro-electric detector. The streak camera system obtains the temporal structure of optical transition radiation (OTR) generated by a metal screen. We tested these monitors at the SCSS test accelerator. The bunch length was changed by the rf phase of the S-band accelerator upstream of the bunch compressor. A strong correlation between the CSR intensity and the S-band phase was observed. We obtained a sub-ps bunch length from the streak camera. The streak camera data showed the same tendency as the CSR data. Thus, the bunch compression characteristics were appropriately measured by these two monitors in the bunch length region of 400 fs – 2 ps (FWHM).

INTRODUCTION

A short wavelength SASE (self-amplified spontaneous emission) FEL machine, such as an X-ray FEL (XFEL), requires a high peak-current electron beam of several kilo-ampere. In the case of the X-ray FEL project at SPring-8 (XFEL/SPring-8), for example, the peak current is demanded to be 3 kA [1]. The peak current of XFEL/SPring-8 is increased by three bunch compressors consisting of magnetic chicanes. Rf accelerating cavities before each bunch compressor give a longitudinal energy slope to the beam and the bunch length is shortened by the path length dependence on the electron energy in the bunch compressor. The temporal bunch length of XFEL/SPring-8 should be compressed to 30 fs (FWHM) to achieve the demanded peak current [1]. To obtain a stable peak current, the bunch length should be monitored and the monitored data should be fed back to the rf phase of the upstream accelerator to stabilize the bunch length by feedback control.

The bunch lengths of XFEL/SPring-8 after the first, second and third bunch compressors are approximately 3 ps, 300 fs, and 30 fs (FWHM), respectively. Therefore, the time resolutions of bunch length monitors for XFEL/SPring-8 are necessary to be 10 fs – 1 ps. To cover these demanded bunch lengths for monitoring, we have developed several bunch length monitors: a coherent synchrotron radiation (CSR) monitor, a streak camera system [2], a transverse rf deflector cavity system (RFDEF) [2,3], an EO sampling method [2] and an rf zero-phasing method [2,4].

We tested the CSR monitor and the streak camera system at the SCSS test accelerator [5], which has been operated to check the feasibility of XFEL/SPring-8. In this paper, the conceptual designs, the experimental setups and the beam test results of the CSR monitor and the streak camera system are described.

CONCEPTUAL DESIGN

CSR Monitor

A CSR monitor detects CSR intensity from a dipole magnet and a bunch length is estimated from the CSR intensity. In this section, the characteristics of CSR and the conceptual design of the CSR monitor are described.

The CSR flux as a function of the wavelength, $P(\lambda)$, can be represented by [6]

$$P(\lambda) \simeq Np(\lambda) + N^2 f(\lambda) p(\lambda),$$

where N is the number of electrons, $p(\lambda)$ is the radiation flux from a single electron, and $f(\lambda)$ is the longitudinal form factor of the bunch. The form factor is defined by

$$f(\lambda) = \left| \int S(z) \exp\left(2\pi j \frac{z}{\lambda}\right) dz \right|^2,$$

where $S(z)$ is the electron distribution function in case that the transverse beam width can be neglected. The CSR spectra of the electron beams at 30 fs, 300 fs and 3 ps bunch lengths (FWHM) are shown in Fig. 1. These spectra were calculated by SPECTRA [7]. In our case, a CSR frequency region is from 0.1 THz to 100 THz. A CSR spectrum has a cutoff frequency corresponding to

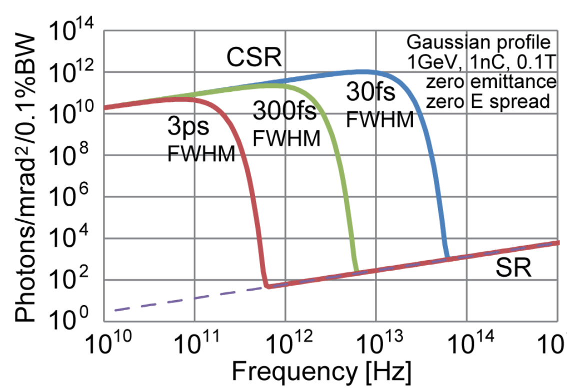

Figure 1: CSR spectra of the electron beams at 30 fs, 300 fs, and 3 ps in FWHM bunch lengths. The temporal profile of the beam is assumed to be Gaussian. The beam energy is 1 GeV, the beam charge is 1 nC, and the B field is 0.1 T. The beam emittance and the energy spread are set to zero.

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the temporal bunch length and the total CSR flux also depends on the bunch length. Therefore, CSR intensity is sensitive to the bunch length.

For the XFEL/SPring-8 machine, the CSR intensity is detected by a pyro-electric detector, which is sensitive to a wavelength region of 0.1 – 100 THz. Therefore, the CSR monitor covers the whole bunch length region of XFEL/SPring-8. However, an absolute bunch length cannot be measured by the CSR monitor itself. Therefore, the absolute bunch length must be calibrated with the streak camera or the RFDEF system. Since the CSR monitor is non-destructive, the CSR intensity can be fed back to the rf phase of the accelerator in order to regulate the bunch length by a feedback control.

Streak Camera System

The streak camera system obtains the time structure of optical transition radiation (OTR) emitted from a metal screen which is hit by an electron beam. Since the OTR is prompt radiation, the temporal structure of the OTR is the same as that of the electron beam. Therefore, the streak camera directly detects the temporal structure of the electron beam.

We employed a FESCA-200 streak camera (Hamamatsu Photonics) [8], which is the world fastest streak camera having 200 fs resolution. Therefore, the resolution of the streak camera system is expected to be several 100 fs. Since an OTR radiator is a destructive device, the electron beam is lost at the radiator during the streak camera measurement.

EXPERIMENTAL SETUP

A schematic layout of the SCSS test accelerator is illustrated in Fig. 2. The CSR monitor is installed at the third magnet of the magnetic chicane downstream of the C-band accelerator. The OTR radiator for the streak camera is located just before the undulator. In this section, the SCSS test accelerator is briefly introduced and the setups of the CSR monitor and the streak camera are described.

SCSS Test Accelerator

An electron beam from a CeB_6 thermionic electron gun is accelerated to 1.2 MeV by 238 MHz and 476 MHz accelerating cavities and the bunch length is shortened by a velocity bunching process using these cavities. The beam energy is boosted to 45 MeV by an S-band alternating periodic structure (APS) cavity and an S-band traveling wave accelerator (TWA). The S-band TWA also gives an energy chirp to the beam for bunch compression and the bunch length is compressed to 300 fs (FWHM) by a bunch compressor. This bunch compressor has an R_{56} value* of –20 mm. The beam is then accelerated to 250 MeV by C-band accelerators and fed into a chicane, which does not compress the bunch length. Finally, the beam is injected into the in-vacuum undulator and an extreme ultra-violet (EUV) FEL with the wavelength region of 50 – 60 nm is generated.

CSR Monitor

A schematic view of the CSR monitor is shown in Fig. 3. CSR from the third dipole magnet of the chicane is extracted from a fused silica viewing port. The CSR is reflected by gold mirrors and transported to a pyro-electric detector. A terahertz lens, Tsurupica [9], is used to focus the CSR light on the detector. The focal length is 100 mm. The pyro-electric detector is SPH-62 [10] of Spectrum Detector Inc. The pyro-electric detector is mounted on a XY stage to adjust the detector position at the focal point of the terahertz lens.

Streak Camera

A schematic view of the streak camera system is shown in Fig. 4. The OTR light is generated by a gold mirror

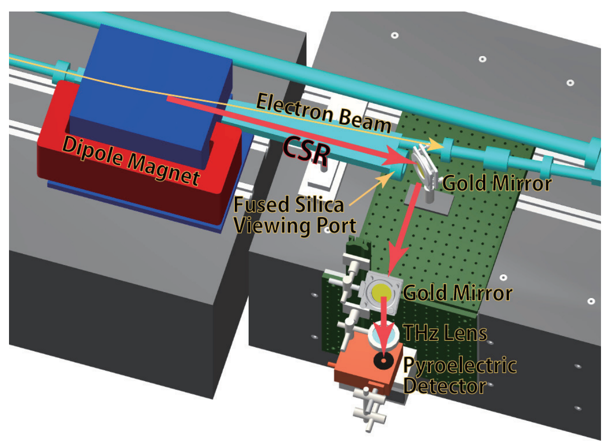

Figure 3: Schematic view of the CSR monitor.

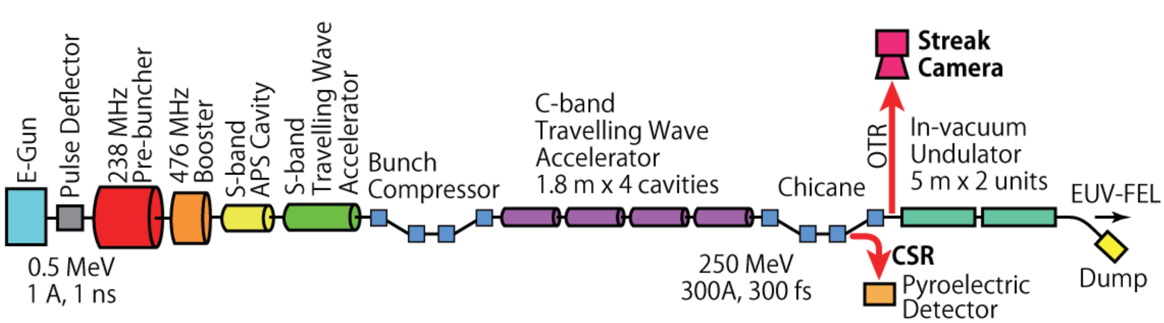

Figure 2: Schematic layout of the SCSS test accelerator.

*R_{56} is an element of the beam transfer matrix to represent the path length dependence on the beam energy.

inserted into the beam pipe. The OTR light is collimated by an achromatic lens and transported to the streak camera located at the klystron gallery by using some mirrors. A low-pass filter with a cutoff wavelength of 650 nm is inserted near the streak camera. Since the streak camera is sensitive to the wavelength shorter than 800 nm, the detected wavelength region is from 650 to 800 nm. There are two reasons to use the low-pass filter. One is to reduce the deterioration of the temporal resolution due to the chromatic aberration. The other is because the streak camera has better resolution for a longer wavelength [8].

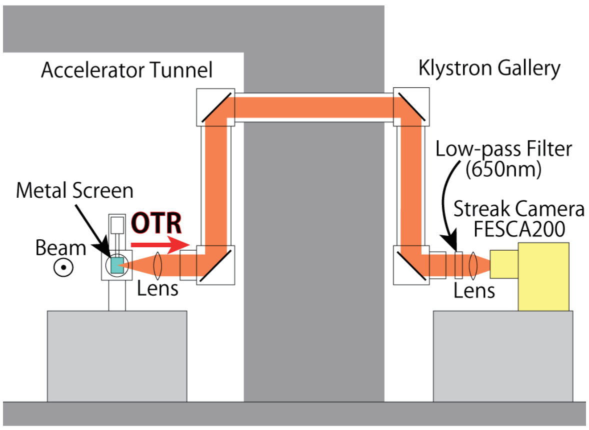

Figure 4: Schematic view of the streak camera system.

RESULTS

The signal from the CSR monitor was obtained by an oscilloscope. A waveform of the CSR monitor with the lasing condition is shown in Fig. 5. A clear pulse signal was observed and the rise time was 1 ms. The peak voltage was approximately 60 mV and the noise was 1 mV (RMS). The peak voltage of this signal is used for the following analysis.

A streak camera image of the OTR from a single beam shot is shown in Fig. 6. The temporal bunch structure is the projection of this image to the vertical axis. Since the OTR intensity of each shot was very low, 50 shots of the images were accumulated to obtain a clear temporal bunch profile and the accumulated data is used in the following analysis. Before the accumulation, the peak of the temporal structure of each shot is adjusted to a specified timing in order to correct the trigger jitter of the streak camera.

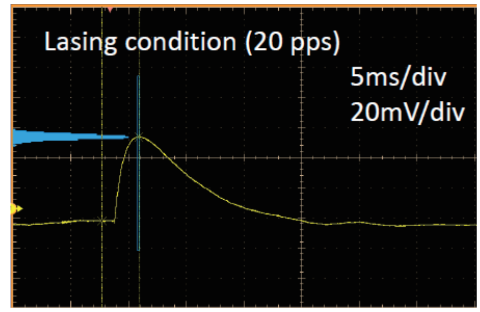

Figure 5: Waveform of the pyro-electric detector taken by an oscilloscope. The accelerator is tuned to generate a stable FEL light.

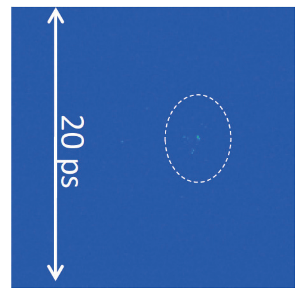

Figure 6: Streak camera image of the OTR from single beam shot. The temporal structure is vertically stretched and the full width of the time range is 20 ps. The OTR signal can be seen in the circle.

We observed the CSR intensity and the bunch length from the streak camera as a function of the rf phase of the S-band TWA. Since the S-band TWA gives an energy chirp to the beam before the bunch compressor, the bunch compression ratio was changed by the rf phase of the S-band TWA. The obtained data is plotted in Fig. 7. The CSR intensity was small around the crest and debunching phases. When the S-band phase was shifted to the bunching direction, the CSR intensity increased around the lasing condition (–23 degrees from the crest phase), and it finally decreased for the S-band phase of less than –35 degrees. The bunch length from the streak camera also showed the same tendency. The bunch length was

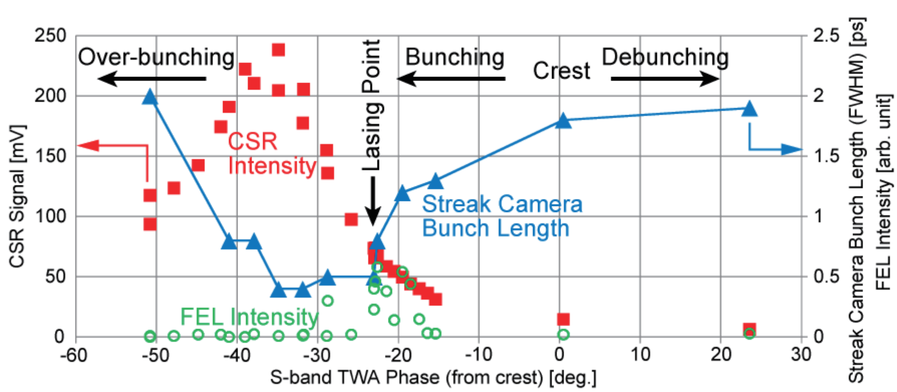

Figure 7: The CSR intensity detected by the pyro-electric detector (red square) and the bunch length measured by the streak camera (blue triangle). The horizontal axis is the rf phase of the S-band TWA. The origin of the horizontal axis is the crest acceleration phase. The FEL intensity is also plotted (green circle).

longer than 1 ps in the debunching region and was approximately 500 fs (FWHM) around the lasing condition. In the over-bunching region, the bunch length became longer. Some temporal bunch structures taken with the streak camera are shown in Fig. 8. The bunch length dependence on the S-band phase is clearly seen in these plots.

SUMMARY

We developed a CSR monitor and a streak camera system for XFEL/SPring-8 in order to measure the temporal bunch length with femto-second resolution. The CSR monitor and the streak camera were installed in the SCSS test accelerator and their performances were evaluated. The bunch length was changed by the accelerating rf phase of the S-band TWA before the bunch compressor. A strong correlation between the CSR intensity and the S-band phase was observed. The bunch length data from the streak camera also had the same tendency. Consequently, the bunch compression characteristics were appropriately obtained and the performance was confirmed to be sufficient for XFEL/SPring-8.

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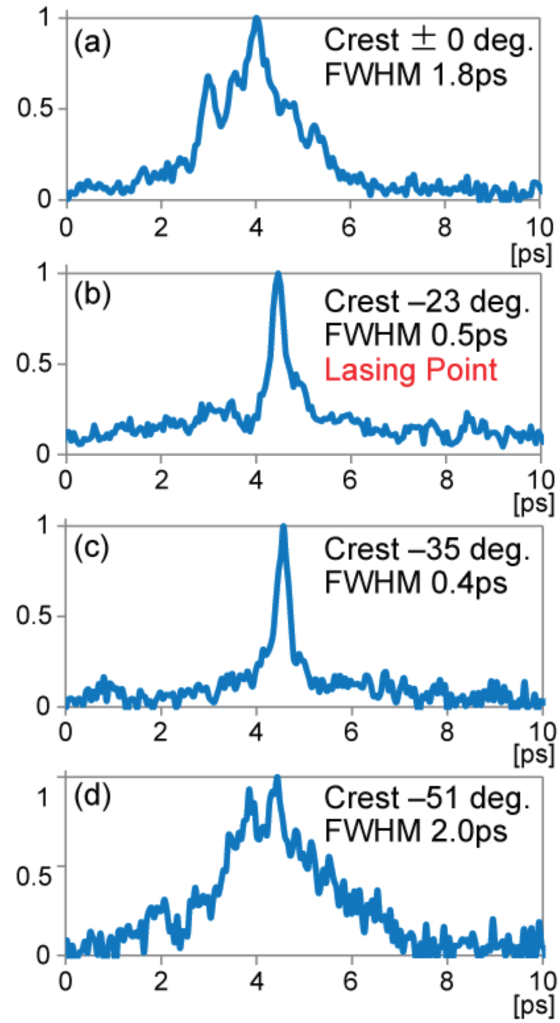

Figure 8: Temporal bunch structures observed by the streak camera for the S-band TWA phase of (a) crest, (b) –23 degrees (lasing point), (c) –35 degrees and (d) –51 degrees. The peak value of each plot is normalized to unity.