BUNCH-LENGTH MEASUREMENTS AT SCSS TEST ACCELERATOR TOWARD XFEL/SPRING-8

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Abstract

The SCSS test accelerator, which was constructed to check the feasibility of XFEL/SPring-8, is being operated for user experiments using stable EUV (Extreme Ultra-violet) SASE. This accelerator provides a high-quality electron beam with parameters, such as a bunch length of 300 fs and a peak current of 700 A, for power saturation of the EUV SASE. Evaluating the parameters is very important to ensure the stable generation of SASE. Bunch-length measurement systems to evaluate the parameters have been developed. The systems use the rf zero-phase crossing method, the EO sampling method with temporal decoding and an 800 nm laser, and a method for observing OTR (near the infrared region) by a streak camera (fesca-200), which is mature technology. All of the measured bunch lengths were about 300 fs (FWHM), which is consistent with the individual methods. The most important result is that the streak camera with optimum tuning directly measured the temporal structure with femto-second resolution, and the reliabilities of these systems were mutually checked.

INTRODUCTION

Constantly keeping the peak currents of the electron bunches of a free electron laser at SPring-8 (XFEL/SPring-8) [1] and the SCSS test accelerator to check the feasibility of the XFEL/Spring-8 [2.3], which are used to generate coherent and extremely intense x-rays and extreme ultra-violet (EUV) light, respectively, is one of the most important points to ensure stable generation of their lasers. In the present technology, the charge amount of a bunch can only be reliably measured by a current transformer with a reasonable accuracy of 1~5%. Therefore, measurements of the bunch shape, which determines the peak current, are very important. Furthermore, we introduced the SCSS concept [2] for the XFEL and the SCSS test accelerator. The SCSS concept employs a velocity bunching process using multi sub-harmonic bunchers (SHB) for an injector and a magnetic bunching process using a chicane bunch compressor (BC) comprising four bending magnets after the injector. For the SCSS test accelerator, a single BC is used, and for the XFEL three-stage BCs are employed after the injector. For this reason, the individual bunch compression processes have different bunch lengths; the bunch width of the velocity bunching is from 1 ns to 10 ps (1~20 A in peak current), the bunch length after the 1st BC is 2~3 ps (~70 A), the bunch length after the 2nd BC is around 150 fs (~600 A), and the bunch width after the 3rd BC is about 30 fs (~3 kA). Since the stability of the laser is extremely dependent on their bunch lengths, evaluating and properly adjusting the bunch lengths at each process are very important to ensure a stable laser. To establish the measurement reliability and adapt measurements with the different bunch lengths, different kinds of bunch-length measurement methods are employed for the XFEL and the SCSS test accelerator, even through the methods almost cover the same temporal resolution and range. Because the temporal accuracy of the individual bunch length methods in the case of a measurement with a resolution under 1ps, such as a streak camera for observing optical transition radiation (OTR) and an rf zero-crossing [4], still has some ambiguity caused by measurement errors. For example, the errors are sensitivity dependent on the wavelength, where the streak camera is used [5], and the aberration of an electron beam optical system, where rf zero-crossing is employed. Therefore, we think that the reliability on the temporal resolution of the bunch-length measurements in a femto-second region is not yet established at the present time.

Six kinds of bunch-length measurement systems, as mentioned below, to guarantee the reliability of the beam-monitor system of the XFEL have been developed, or are under development. In this paper, we report on the already developed bunch-length measurement systems using a streak-camera method, an rf zero-phase crossing method, and an EO sampling method [6] selected from the bunch-length monitors for the XFEL, which are described blow. These methods cover a temporal measurement range of several hundred femto-seconds. This time range can adapt observing the electron bunch of the 1st BC and the 2nd BC.

To check the reliability of the developed methods, and to evade any ambiguity of the measurement accuracy, the electron bunch length of the SCSS test accelerator was measured by the developed systems, and the data taken by the systems were compared. The test accelerator uses multi- SHBs of 238 MHz and 476 MHz for velocity bunching and a BC for magnetic bunching. A schematic layout of the test accelerator is illustrated in Fig. 1. The electron bunch length of the accelerator is compressed from 1 ns to a spiky lasing part of 300 fs with the 750 A peak current by the bunching process, while the final whole compressed bunch length is about 1ps, including the spiky lasing part. These bunch compression processes were numerically simulated, and their performances were experimentally confirmed by measurements.[3]

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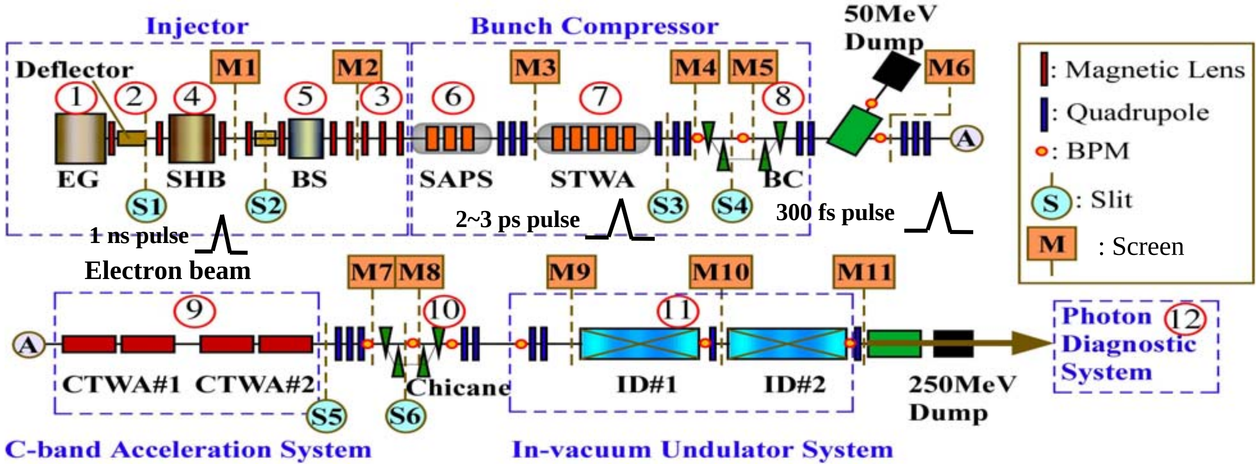

Figure 1. Schematic layout of the SCSS test accelerator. 1 EG, electron gun; 4 SHB, sub-harmonic buncher; 5 BS, booster cavity; 6 SAPS, S-band APS cavity; 7 STWA, S-band travelling wave accelerator; 9 CTWA, C-band travelling-wave accelerator; 11 ID, insertion device (undulator).

Table 1. Number of beam monitors for the XFEL and the SCSS test accelerator.

Kinds of Monitor	Number of Monitors (XFEL/SPring-8)	Number of Monitors (SCSS test accelerator)
RF cavity BPM	56	10
Screen Monitor	43	11
Current Transformer	30	12
Transverse rf Deflector	1	0
Streak Camera using OTR	3	1
EO Sampling	1	1
Waveguide Spectrometer	4 ~ 5	2 ~ 3
CSR Pyro-detector	3	1

In this paper, we firstly show a brief overview of the beam-diagnostic system of the XFEL/SPring-8, and then the experimental set-ups of the developed bunch-length measurement systems used to monitor the bunch characteristic of the test accelerator, as previously mentioned, are described and their experimental results are also reported.

OVERVIEW OF THE BEAM DIAGNOSTIC-SYSTEM FOR XFEL/SPRING-8

The beam-diagnostic system for the XFEL [7] mainly comprises rf cavity-type beam position monitors (RF-BPM), precise screen monitors (SCM), and high-speed differential current transformers (CT). Furthermore, for bunch-length measurements used to evaluate the individual bunch compression process placed along the stream of the accelerator, as mentioned above, the following instruments are used: a CT to measure a bunch length from 1ns to 500 ps at the electron gun and the 238 MHz SHB, a waveguide spectrometer [8] to detect coherent transition radiation (CTR) emitted from the SCM and to measure an electron bunch length of up to 10 ps for velocity bunching, a streak-camera (Hamamatsu Photonics, Fesca-200) system to observe optical transition radiation (OTR) emitted from the SCM and to monitor an electron bunch with a width from 10 ps to 300 fs, a pyro-detector [9] to monitor coherent synchrotron radiation (CSR) emitted from an electron bunch with a 30~1000 fs pulse passing through the bending magnet of the BC, an EO sampling system to monitor the relativistic electric field of an electron bunch and to measure up to a 100 fs bunch length, and a transverse rf deflector system [7] to measure a bunch width of less than 30 fs after all the bunch compression. The quantities of these monitors are tabulated in Table 1. The test accelerator also has some of the same beam monitors as shown in Table 1.

EXPERIMENTAL SET-UPS FOR THE DEVELOPED THREE BUNCH-LENGTH MESUREMENT SYSTEMS

To fulfill the requirements of electron bunch-length measurements for the XFEL, as mentioned above, the three measurement systems described below have been developed by using the SCSS test accelerator.

Streak camera system

Figure 2 shows a developed bunch length measurement system using a streak camera and an OTR screen (SCM). The SCM of M9 is placed just after the chicane, as shown in Fig. 1. The OTR light emitted from M9 is guided along an optical system using mirrors to feed into the streak camera. To reduce the effect due to an optical group delay along the optical pass and energy dispersion on the photoelectric surface of the streak camera dependent on a wavelength, which deteriorates the temporal resolution of this system, an optical low–pass filter is employed. The cut-off wavelength, λ_c, of the filter is 640 nm. The wavelength sensitivity of the streak camera is limited to over about 850 nm. Therefore, the wavelength sensitivity of this bunch-length measurement system is from 850 nm to 640 nm. To obtain sufficient optical intensity, which reflects an improvement of the signal-to-noise (S/N) ratio, a focusing lens placed near the streak camera is employed.

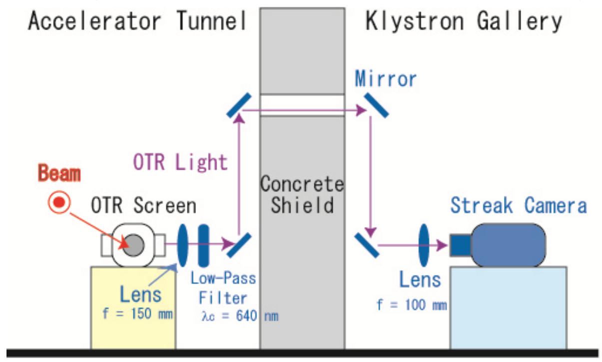

Figure 2. Experimental set-up of an electron bunch-length measurement using OTR light and a streak camera.

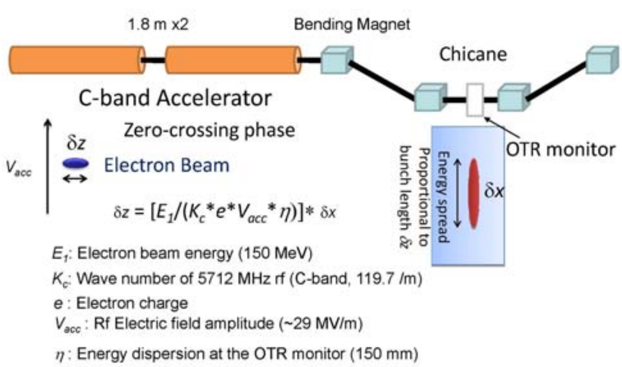

Figure 3. Measurement instrumentation configuration of the rf zero-crossing method.

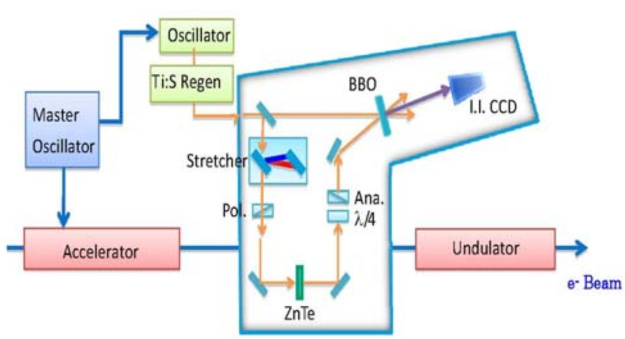

Figure 4. Experimental set-up for E/O sampling using a Zinc Telluride, ZnTe, crystal. This schematic shows the temporal decoding method.

Rf zero-phase crossing system

For measuring a bunch length by the rf zero-phase crossing method, as shown in Fig. 3, the SCM (M8 in Fig. 1) at the energy dispersive section of the chicane and the 2nd C-band traveling-wave accelerator #2 (CTWA#2) were used. When the timing of the electron bunch centroid is settled at a zero-crossing point of the acceleration rf electric field of the CTWA#2, the energy of the electron bunch is proportionally modulated along the bunch direction (Z axis) by the quasi-linear rf electric field around the zero-crossing point. Then, the beam passes through a bending magnet, and reaches M8 of the dispersive point. In this case, the beam image on the screen shows the intensity distribution of the electron bunch along a temporal direction. The bunch length, δz, is calculated from the equation of $\delta z=[E_1/(k_c*e*V_{acc}*\eta)]*\delta x$ from the length, δx, of the observed beam image, where E_1 is the acceleration energy of the electron, k_c is the wave number of a C-band rf, 5712 MHz, e is the electron charge, V_{acc} is the acceleration voltage, η is the energy dispersion at the M8.

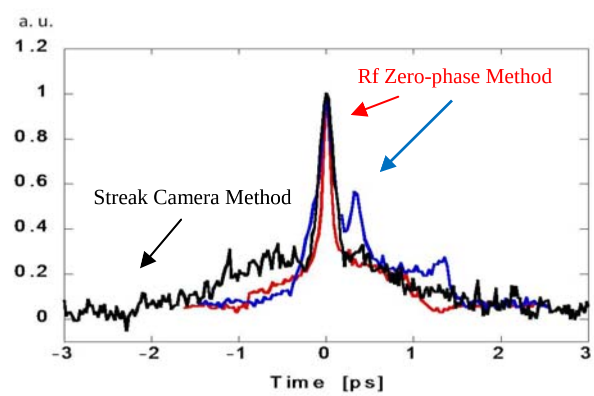

Figure. 5. Bunch-length data taken by the streak camera and the SCM, and the rf zero-phase crossing method. Red is at a bunching phase. Blue is at a debunching phase.

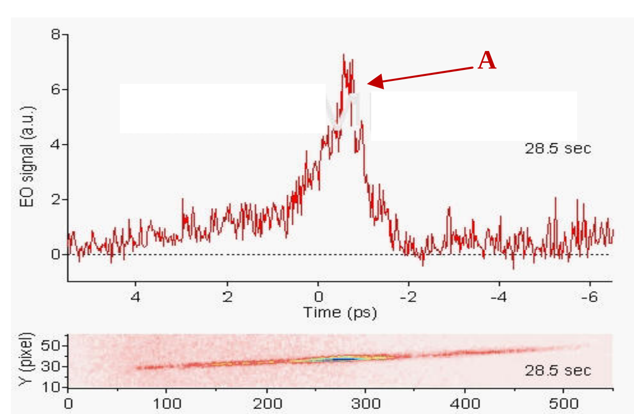

Figure. 6. Experimental result by E/O sampling with temporal decoding. The "A" could be the spiky lasing part.

EO sampling system

Figure 4 shows an electron bunch-length measurement system using the EO sampling method. EO sampling uses an optical polarizer and an electro-optical crystal, such as ZnTe, which detects the relativistic electric field of an electron beam. When the electron beam passes nearby the crystal, the electric field rotates the polarization axis of the crystal. Then, the combination of the polarization orientation between the polarizer and crystal picks up some part of an incident laser pulse of 800 nm TiSapphire to the crystal. The pulse length of this part corresponds to the electron bunch length. To detect this part, a temporal decoding method [6] using a BBO (β-BaB204) crystal as a correlator and a CCD camera with an image intensifier was used.

BUNCH-LENGTH MEASUEMENT RESULTS

Streak-camera and rf zero-phase crossing systems

Figure 5 shows the results of electron bunch-length measurements using the steak-camera method and the rf zero-phase crossing method. The bunch lengths observed by both methods were about 300 fs (FWHM), which corresponds to the spiky lasing part in the ID section, while the whole electron bunch length is about 1 ps. The bunch shape taken by the streak camera was obtained by superimposing 10 shots with which the individual bunch shapes were normalized at each peak point. The waveform measured by the rf zero-phase crossing method was single-shot data.

EO sampling system

The measured bunch length by EO sampling is shown in Fig. 6. The electron bunch length of a single-shot image in the figure is about 300 fs (FWHM), if we look at the spiky part, “A”, of the bunch shape, which could correspond to the lasing part. The whole bunch length is also 1~ 2 ps.

SUMMARY

The bunch length of the SCSS test accelerator was measured by three methods: the streak-camera method, an rf zero-phase crossing method, and an EO sampling method. The results of bunch length experiments using these methods were consistent; the measured bunch lengths were about 300 fs. This consistency mutually proved reliability of the measurement accuracy of the methods. Furthermore, the most important result is that the streak camera is mature technology with the optimum tuning, which directly measured the temporal structure of an electron beam bunch with femto-second resolution. We believe that our data taken around 300 fs (FWHM) bunch lengths by the systems are the first experimental results in the world, because of comparing these data.

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