6th International Particle Accelerator Conference IPAC2015, Richmond, VA, USA JACoW Publishing
ISBN: 978-3-95450-168-7 doi:10.18429/JACoW-IPAC2015-MOPTY002

BUNCH LENGTH MEASUREMENT OF FEMTOSECOND ELECTRON BEAM BY MONITORING COHERENT TRANSITION RADIATION

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Abstract

Ultrashort electron bunches with durations of femtoseconds and attoseconds are essential for time-resolved measurements, including pulse radiolysis and ultrafast electron microscopy. However, generation of the ultrashort electron bunches is commonly difficult because of bunch length growth due to space charge effect, nonlinear momentum dispersion and so on. Several bunch length measurement methods for the ultrashort electron beams have also been considered so far, which have not been established yet. In this study, the femtosecond electron beams were generated using a laser photocathode radio-frequency gun linac and a magnetic bunch compressor. The bunch length measurement was carried out using a Michelson interferometer based on monitoring coherent transition radiation (CTR), which is characterized by square modulus of the Fourier transform of the longitudinal bunch distribution. Analyzing the experimentally obtained interferograms of CTR, the electron beams with the average duration of 5 fs were generated and measured successfully at the condition of bunch charge of 1 pC. Consideration of the longitudinal bunch shapes was also carried out using the Kramers-Kronig relation.

INTRODUCTION

Ultrashort electron bunches with pulse durations of femtoseconds and attoseconds are a key for applications of accelerator physics, for example, free electron lasers[1] and intense terahertz (THz) light sources[2]. Additionally, ultrashort electron bunches play an important role in time-resolved measurements such as pulse radiolysis[3] and ultrafast electron diffraction[4] because the time resolution of the measurements strongly depends on the bunch lengths of electron beams. On the other hand, much effort has been devoted to developing bunch length measurements of <100 fs electron bunches because of lack of time resolution of conventional longitudinal beam diagnostic methods including femtosecond streak cameras. Now, many researches of alternative measurement methods using coherent radiation (CR), electro-optic (EO) crystals, deflecting cavities have proceeded in order to evaluate bunch length of femtosecond electron bunches[5,6]. In this study, a bunch length measurement technique of the femtosecond electron bunches were investigated by monitoring coherent transition radiation (CTR) using a Michelson interferometer. The femtosecond electron bunches were generated by a photocathode-based linac with an arc-type magnetic bunch compressor[3,7]. As for the bunch length measurement monitoring CR, it is very important to detect broadband electromagnetic (EM) waves because the frequency range characterizes the time resolution of the bunch length measurement. Therefore, frequency range of the measurement system has been expanded by optimizing a beam splitter and a detector in the Michelson interferometer.

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EXPERIMENTAL SETUP

Linac System for Generation of Ultrashort Electron Bunches

In this study, a laser photocathode radio frequency (RF) gun linac and an arc-type magnetic bunch compressor at the Institute of Scientific and Industrial Research (ISIR) in Osaka University were used for the generation of ultrashort electron bunches. Figure 1 shows the schematic diagram of the linac system[3,7].

This system is composed of a 1.6-cell S-band (2856 MHz) RF gun with a copper cathode, a 2-m-long S-band linear accelerating tube and a magnetic bunch compressor. In order to obtain electron beams with low emittances and short initial bunch lengths at the gun, a third harmonics of a Ti:Sapphire femtosecond laser (266 nm) was used for irradiating the copper cathode. Additionally, the charges of the electron bunches were suppressed to the picocoulomb-order to reduce bunch length growth due to the space charge effect. The electron bunches were accelerated to 4 MeV at the exit of the gun and 32 MeV at the exit of the accelerating tube. In the linear accelerating tube, an energy-phase correlation optimal for compression was also carried out for the magnetic compression. Finally, the electron bunches were

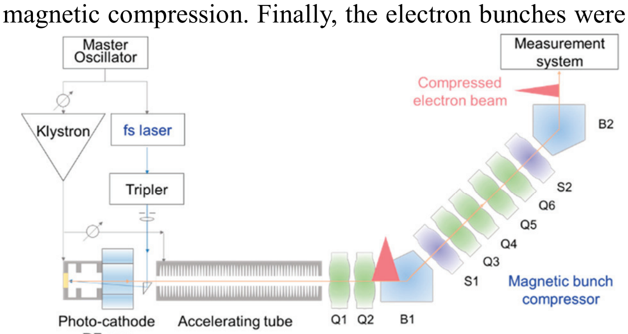

Figure 1: Schematic diagram of a laser photocathode RF electron gun linac and a magnetic bunch compressor. Q: quadrupole magnet; B: bending magnet; S: sextupole magnet.

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compressed rotating the longitudinal phase-space distribution in the magnetic bunch compressor. The compressor was composed of a pair of 45° bending magnets (B1 and B2), two pairs of quadrupole magnets (Q3, Q4, Q5, and Q6), and a pair of sextupole magnets (S1 and S2). A pair of sextupole magnets served to compensate for the second-order effect due to the fringing field of the electromagnets. Finally, the compressed electron bunches were guided to the bunch length measurement system.

Bunch Length Measurement System

Figure 2 shows the schematic diagram of the measurement system with a Michelson interferometer. In this scheme, CTR was emitted from the electron bunches at a boundary between a vacuum and an aluminium mirror (M1). CTR was collimated to parallel light by an off-axis parabolic mirror (OAP1) since it can be considered to be a point source of electromagnetic (EM) waves. After that, the EM waves were guided to the Michelson interferometer. CTR was collimated and then split in two by a beam splitter (BS1) made of a 380-µm-thick high-resistivity silicon (HRSi) wafer or a potassium bromide (KBr) crystal. One of the EM waves was reflected by a fixed mirror (M4), while the other was reflected by a position-tunable mirror (M5) on a delay stage. Finally, the two EM waves were converged, and the autocorrelated EM wave was fed to the detector. The detector was a liquid-helium-cooled silicon bolometer (general-purpose 4.2-K system, Infrared Laboratories) or a liquid-nitrogen-cooled MCT photoconductive detector (P5274-01 or P2748, Hamamatsu photonics). This autocorrelated EM wave corresponded with an interferogram of CTR (which is a function of the position of M5). The interferogram contains information about frequency spectrum of CTR, and the spectrum has a relation with a longitudinal charge distribution of the electron bunch. Thus, information of the bunch length of the electron beam can be obtained by analyzing the interferogram (it is theoretically described a following section). All optical elements except for infrared detectors were placed in a vacuum. This interferometer was optimized and calibrated by using an infrared light source (IRS, IRS-001C, IR System). The surface of IRS was coated with a black-body spray. The filament of the IRS was set to 1173 K and was considered to emit black-body radiation according to Planck's law.

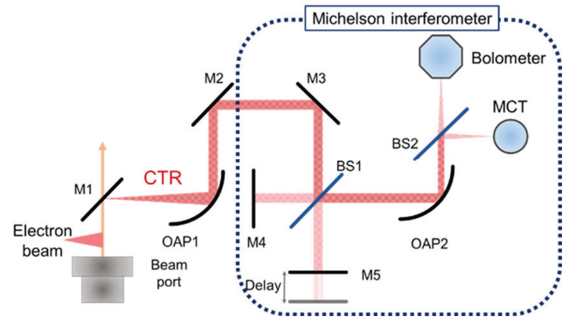

Figure 2: Schematic diagram of the Michelson interferometer. M: aluminium mirror, OAP: off-axis parabolic mirror, BS: beam splitter.

Theoretical Description for Analysis

Since the frequency spectrum of CTR contains information of the bunch length of the electron bunches[8-10], the bunch length can be estimated by analyzing the interferogram of CTR. In this analysis, the longitudinal charge distribution in the electron bunch was assumed as a Gaussian distribution with the rms bunch length σ. In general, the intensity of CR is expressed as follows:

$$I_{\mathrm{coh}}(\sigma,\omega) \propto N(N-1) f_{\mathrm{e}}(\omega) f_{\mathrm{b}}(\sigma,\omega) \quad (1)$$

where $I_{\mathrm{coh}}(\sigma, \omega)$, N, $f_{\mathrm{e}}(\omega)$ and $f_{\mathrm{b}}(\sigma, \omega)$ denote the intensity of CR, the number of electrons in a bunch, frequency spectrum of radiation emitted from an electron and bunch form factor (BFF), respectively. BFF is defined as a square modulus of Fourier transform (FT) of the longitudinal charge distribution and is described as follows:

$$f_{\mathrm{b}}(\sigma,\omega) = \exp\{-(\sigma\omega)^2\} \quad (2)$$

According to Ginzburg-Frank formula[11], transition radiation emitted from an electron is a uniform frequency spectrum. Thus, the shape of frequency spectrum calculated using Eq. 1 only depends on BFF described as follows:

$$I_{\mathrm{coh}}(\sigma,\omega) \propto \exp\{-(\sigma\omega)^2\} \quad (3)$$

On the other hand, the detection system has limited sensitivity from the viewpoint of experiments, and a practical frequency spectrum of CTR can be expressed as a product of Eq. 3 and the sensitivity of the measurement system. In our case, the system's frequency sensitivity and the effective frequency spectrum of CTR were defined as follows:

$$S(\omega) = I_{IRS}(\omega)/B(\omega) \quad (4)$$

$$I_{\mathrm{eff}}(\sigma,\omega) \propto S(\omega)\exp\{-(\sigma\omega)^2\} \quad (5)$$

where $I_{\mathrm{eff}}(\sigma, \omega)$, $I_{\mathrm{IRS}}(\omega)$ and $B(\omega)$ denote the effective frequency spectrum of CTR, an experimentally obtained frequency spectrum of IRS and the theoretical black-body radiation according to Planck's law, respectively. The analytical function of the interferogram can be obtained by inverse FT of Eq. 5 as follows:

$$i(\sigma,t) \propto \int I_{\mathrm{eff}}(\sigma,\omega)\exp(i\omega t)d\omega \quad (6)$$

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where i (σ, t) and t is the analytical function of the interferogram, a position of the sweeping mirror converted to time domain, respectively. Fitting Eq. 6 to the experimental obtained interferogram, the bunch length of the electron beam can be calculated. In this study, the electron bunch analysis based on Eq. 6 is called the sensitivity model.

RESULTS AND DISCUSSION

Optimization and Characterization of the Measurement System

The optical system as shown in Fig.2 was optimized using IRS. The criterion for the optimization was the intensity at the centerburst because the signals of the all frequency components are known to be intensified at the position. In other words, the signal intensity at the centerburst gave reliable information for achieving the correct alignment about frequency components. Thus, the signal at the centerburst was experimentally maximized in this study. Additionally, it was important to characterize the measurement system because the detectable frequency range determined the time resolution of this bunch length measurement system. Thus, the combination of the infrared detectors with the beam splitters was considered in order to expand detection range of EM waves. The frequency spectra of IRS detected by different combination of the infrared detectors with the beam splitters were shown in Fig. 3. The frequency range was the broadest in case of using the MCT detector and the KBr beam splitter. For simplicity, comparison of the detection frequency region was carried out at 10% of each detector's maximum intensity. As a result, the frequency range was from 20 to 120 THz in case of using the MCT detector and the KBr beam splitter while it ranged from 11 to 50 THz in case of using the HRSi beam splitter. The Michelson interferometer equipped with the bolometer and the HRSi beam splitter detected the EM waves at frequencies from 3 to 15 THz. Therefore the MCT detector and the KBr beam splitter were selected to use the bunch length measurement.

Bunch Length Measurement

The bunch length measurement was carried out using the Michelson interferometer equipped with MCT detector and the KBr beam splitter. Femtosecond electron bunches were generated at the condition that the accelerating phase in the gun was 15° and the bunch charge was ~1 pC. The accelerating phase was set to 105° which was the optimal phase in the present study. Figure 4 shows the interferogram of CTR detected by the MCT detector. The number of the average was 19 times. The rms bunch length was estimated to be 5 fs by least-squares fittings of the interferogram by the sensitivity model as described in Eq. 6. You can see the oscillation of the measured interferogram lying down beside the centerburst could be expressed using Eq. 6. This oscillation was caused by deficiency of the low frequency components due to the effect of the band gap energy of KBr.

CONCLUSION

Femtosecond electron bunches were generated using a laser photocathode RF gun linac and the bunch length measurement using CTR was investigated based on a Michelson interferometer. According to the measurement of the IRS, the optical system was optimized and its sensitivity of the whole optical system was evaluated. As a result, the sensitivity of the optical system equipped with the MCT detector and the KBr beam splitter was ranged from 20 to 120 THz, and it was the broadest frequency range in our case. CTR emitted from electron bunches of 1 pC and 32 MeV was measured using the interferometer. In order for analyzing the interferograms, the sensitivity model was used and the oscillation of the measured interferograms was well expressed using the model. By fitting the sensitivity model to obtained interferograms, a bunch length was estimated to be 5 fs.

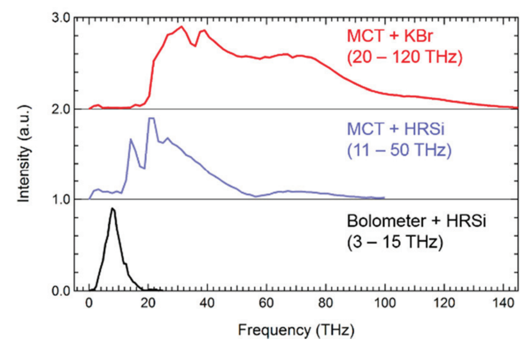

Figure 3: Frequency spectra of IRS detected in case of different combinations of infrared detectors with beam splitters.

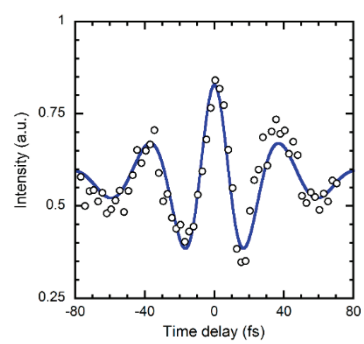

Figure 4: Interferogram of CTR and fitting curve using Eq. 6.

ACKNOWLEDGMENT

We thank the staff of the research laboratory for quantum beam science at the Institute of Scientific and Industrial Research, Osaka University. This work was supported by KAKENHI (21226022 and 26249146) and JSPS Research Fellowships for Young Scientists.

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