ISBN: 978-3-95450-132-8 doi:10.18429/JACoW-IPAC2014-THPME132

GENERATION AND DIAGNOSIS OF ULTRASHORT ELECTRON BUNCHES FROM A PHOTOCATHODE RF GUN LINAC

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Abstract

Ultrashort electron bunches are essential for time-resolved measurement methods such as pulse radiolysis from the viewpoint of time resolutions. On the other hand, generation of electro-magnetic wave in the THz range using short electron bunches has been investigated. Frequency spectra of coherent transition radiation (CTR) emitted by an electron bunch depend on bunch form factor (BFF), which is expressed by Fourier coefficients of longitudinal distribution in the electron bunch. In this study, the bunch length measurement was demonstrated by analyzing THz-waves generated by CTR. Femtosecond electron bunches were generated by a laser photocathode RF gun linac and magnetic bunch compressor. THz-waves generated by CTR, which was emitted on an interface of an aluminum mirror along the beam trajectory, were transported to a Michelson interferometer. The bunch length was measured by analyzing interferogram, which was an infrared detector output as a function of a moving mirror position. Finally, the bunch length was measured according to fitting curves for the interferogram near the centerburst. Minimum bunch length of 1.3 fs was obtained at a bunch charge of ~1 pC.

INTRODUCTION

Ultrashort electron bunches whose durations are picoseconds and femtoseconds have been applied to the accelerator physics applications including free electron lasers and laser Compton X-rays. Such electron bunches are also the key elements in time resolved measurements such as pulse radiolysis [1]. Pulse radiolysis is a powerful and useful tool for investigating ultrafast phenomena induced by the electron bunches. Recently, 100-fs electron bunches were generated using a laser photocathode RF gun linac and a time resolution of ~240 fs was achieved in pulse radiolysis [2]. The time resolution of pulse radiolysis strongly depends on the bunch length of the electron bunches. Therefore, the ultrashort electron bunches are demanded to improve the time resolution of pulse radiolysis and observe the initial process of the radiation chemistry.

On the other hand, it is also important to develop a measurement system to diagnose the bunch length of such ultrashort electron bunches. Femtosecond streak camera is generally used as a measurement technique of the bunch length, however, its time resolution is limited to ~100 fs in rms. Therefore, alternative methods to obtain information of the longitudinal profile of the ultrashort electron bunches have been investigated. One of the promising techniques is a method to observe CTR using an interferometer [3]. CTR is a phenomenon that an electron bunch emits intense radiation at a wavelength longer than the bunch length when crossing a boundary between different media. The CTR spectrum depends on the bunch form factor, which is a square modulus of Fourier transform (FT) of the longitudinal bunch distribution. In other words, information of the bunch length can be obtained from the observation of CTR.

In the present study, to improve the time resolution of the pulse radiolysis technique, generation and bunch length measurement of the femtosecond electron bunches were investigated by monitoring CTR using a Michelson interferometer. The ultrashort electron bunches were generated by a photocathode-based linac with a magnetic bunch compressor. Bunch length measurement is also important for characterizing electron bunches. Enabling analysis of broadband electromagnetic (EM) waves up to 50 THz, the technique using a Michelson interferometer with two detectors could be a useful and effective method for characterizing a wide range of bunch lengths.

EXPERIMENTAL ARRANGEMENT

Generation of Femtosecond Electron Bunches using a Photocathode-based Linac

In this study, ultrashort electron bunches were generated using an S-band (2.856 GHz) photocathode-based RF gun linac and an arc-type magnetic bunch compressor [4,5,6]. The linac is composed of a 1.6-cell S-band (2.856 GHz) RF electron gun with a copper cathode, a 2-m-long S-band acceleration tube, and a magnetic bunch compressor. Irradiating the cathode by the third harmonic of Ti:Sapphire femtosecond laser, femtosecond electron bunches were generated at the RF gun. The incident angle of the laser on the cathode was ~2° with respect to the electron beam axis. The beam energy was 4 MeV at the exit of the gun and 32 MeV at the exit of the accelerating tube and the charge of the electron bunches were estimated using an integrating current transformer. The bunch charges were suppressed to the pico coulomb order to reduce the bunch-length growth due to the space charge effect. The femtosecond electron bunch was compressed by rotating the phase-space distribution in the magnetic bunch compressor. The compressor was composed of a pair of 45° bending magnets, two pairs of quadrupole magnets,

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and a pair of sextupole magnets. The sextupole magnets in the compressor served to compensate for the second-order effect, which would cause bunch-length growth because of the nonlinear transformation of the energy-phase correlation. The electron bunch was compressed by the compressor, and the bunch length measurements were conducted on the compressed bunch using the Michelson interferometer.

Bunch Length Measurement System

Figure 1 shows the schematic diagram of the measurement system using a Michelson interferometer. All optics except for detectors were placed in a low vacuum. The switchable optics for detection of an infrared light source (IRS, IRS-001C, IR System) and CTR from electron bunches were shown in Fig. 1(a) and 1(b), respectively. The interferometer was calibrated and optimized by IRS. The light from the IRS was modulated to 1 kHz by an optical chopper and the intensity and position of a tunable mirror were simultaneously acquired using a digital lock-in detection technique for precisely optimizing the interferometer. The filament temperature of the IRS was set to ~1173 K. The surface of the filament was coated with a black-body spray (JSC-3, Japan Sensor) to generate black-body radiation according to Planck's law. The EM waves from the IRS were collimated and were then split in two by a beam splitter (BS) made of a 380-µm-thick high-resistivity silicon (HRSi) wafer. 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, Hamamatsu photonics). The signal was acquired by sweeping the tunable mirror (M5). Therefore, the interferogram was obtained as a function of the tunable mirror's position, which can be converted to time delay. The frequency spectrum was obtained using the FT of the interferogram. After optimizing the optics with the IRS, the IRS part was switched to the optics for electron bunch measurement. CTR was emitted from the electron bunches at a surface of an aluminium mirror (M1). The electron bunch was introduced to the mirror at 45° after passing through titanium foil. By sweeping the tunable mirror (M5), interferograms were obtained using the infrared detectors.

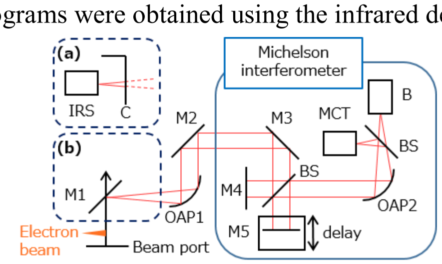

Figure 1: Schematic diagram of the measurement system using a Michelson interferometer for (a) IRS and (b) CTR from electron bunches.

Theoretical Description for Analysis of the Interferograms

Information of the bunch length of the electron bunches can be obtained from the analysis of the interferograms of CTR. On the assumption that the longitudinal distribution is a Gaussian distribution, the bunch form factor $F_b(\omega)$ is expressed as a function of angular frequency ω and rms bunch length σ as follows:

$$\mathrm{F_b}(\omega) = \mathrm{e}^{-\sigma^2\omega^2} . \qquad (1)$$

In an ideal situation where the detection system including detectors has sensitivity at any frequency, frequency spectra of CTR follow the bunch form factor. However, the system has limited sensitivity from the viewpoint of experiment. In this study, the system's frequency sensitivity $S(\omega)$ was defined as follows:

$$\mathrm{S}(\omega) = \frac{\mathrm{I_{IRS}}(\omega)}{\mathrm{B}(\omega)} \qquad (2)$$

where $I_{\mathrm{IRS}}(\omega)$ and $B(\omega)$ denote an experimentally obtained frequency spectrum acquired by measuring an IRS and the theoretical black body radiation according to Planck's law, respectively. Therefore, $S(\omega)$ is obtained as numerical values, which are characteristic of the applied measurement system. Assuming the frequency spectrum of CTR can be expressed as a product of the bunch form factor and the frequency sensitivity, frequency spectrum $K(\omega)$ and interferogram $k(\tau)$ are expressed as follows:

$$\mathrm{K}(\omega) = \mathrm{F_b}(\omega)\mathrm{S}(\omega) = \mathrm{e}^{-\sigma^2\omega^2}\mathrm{S}(\omega) \qquad (3)$$

$$\mathrm{k}(\tau) \propto \int \mathrm{K}(\omega)\mathrm{e}^{\mathrm{i}\omega\tau}\mathrm{d}\omega = \int \mathrm{e}^{-\sigma^2\omega^2}\mathrm{S}(\omega)\mathrm{e}^{\mathrm{i}\omega\tau}\mathrm{d}\omega \qquad (4)$$

In Eq. (4), the interferogram will be obtained from the inverse FT, according to Eq. (3). Both the frequency spectrum and the interferogram will be obtained as numerical values. In this report, the electron bunch analysis based on Eq. (4) will be called the sensitivity model.

RESULTS

Characterization of the Measurement System using the IRS

Figure 2(a) and 2(b) shows the frequency spectra of IRS detected with the bolometer and the MCT detector, and the spectral radiance of black body radiation by the Planck's law. The frequency spectra were obtained by FT of the measured interferograms. The frequency spectrum obtained from the FT of the interferograms acquired by the MCT detector had broadband sensitivity of 11 to 50 THz and no signal in the low-frequency region (up to 11 THz) because of insufficient sensitivity, as shown in Fig. 2. Conversely, the frequency spectrum obtained from the interferogram taken by the bolometer had narrow sensitivity of 3 to 15 THz because of the limited sensitivity of the bolometer. For simplicity, comparison of the detection frequency region was made at 10% of each detector's maximum intensity. The lower and upper cutoff frequencies of the MCT detector originated from the band-gap energy and transmittance, respectively, of the HRSi

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beam splitter. The two cutoff frequencies of the bolometer resulted from the diffraction-limit and the transmittance, respectively, of the polyethylene window. The dip observed around 20 THz is explained by lattice absorption in silicon. The IRS spectrum attained maximum intensity around 70 THz, as calculated by the Planck's law, but the experimentally obtainable signals could not be reproduced, even if the MCT detector was used in the experiment. Therefore, the sensitivity model will be required for properly evaluating the obtained spectra. Before the bunch length measurement, the IRS part was replaced with the mirror, as shown in Fig. 1(b).

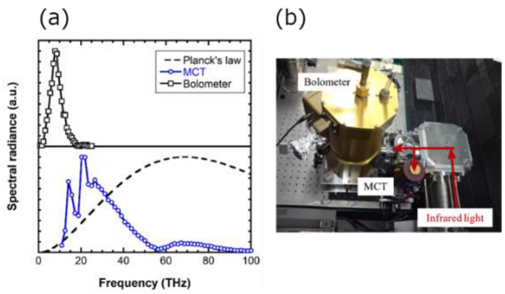

Figure 2: Frequency spectra of the IRS obtained from measurements using the bolometer and the MCT detector, and spectral radiance of Planck's law.

Bunch Length Measurement using the Infrared Detectors

The bunch length measurement was conducted using the Michelson interferometer as shown in Fig. 1. CTR from the femtosecond electron bunches compressed by the magnetic bunch compressor was detected using the bolometer and the MCT detector. The accelerating phases in the gun was 15° and the bunch charge was 2.1 pC. Initially, using the bolometer, the dependence of rms bunch length on accelerating phases in linac was examined to optimize the linac phase for the generation of ultrashort electron pulses. The rms bunch length was estimated by least-squares fittings of the interferogram by the sensitivity model. According to the shapes and bunch length estimated by fitting of the interferograms, the optimal acceleration phase in the linac was determined to be 105° for the present condition. The interferograms of CTR measured using the bolometer and the MCT detector were shown in Fig. 3. The fitting curves using the sensitivity model were depicted in the figure. The accelerating phase in the linac phase was fixed to 105°. As shown in Fig. 3(a), the rms bunch length was estimated to be 26 fs using the bolometer. On the other hand, Fig 3(b) shows that the bunch length was determined to be 8.9 fs using the MCT detector. The difference of the estimated bunch lengths was due to the difference of sensitivity between the two detectors. The MCT detector was adequate to diagnose the bunch length of the electron bunches whose bunch length was femtosecond order, because the MCT detector can detect the EM waves at higher frequency than the bolometer as shown in Fig. 2(a). On the contrary, the bolometer was suitable for the detection of CTR from the bunch of the length of several tens of femtoseconds. The difference of the shapes of the interferograms was due to the cutoff frequency at low frequency region. The oscillation of the measured interferogram lying down beside the centerburst can be explained by the effect of the band gap energy. The fitted curve by the sensitivity model could express the whole interferogram including oscillations [7]. In the case of lower charge than the present study, possibility of 1.3-fs bunch was also indicated at ~1 pC.

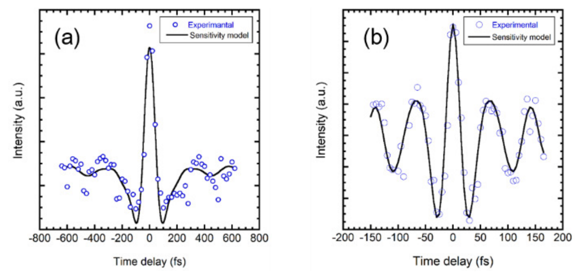

Figure 3: Comparison of interferograms measured using (a) the bolometer and (b) the MCT detector.

CONCLUSION

Femtosecond electron bunches were generated using a laser photocathode RF gun linac and the bunch length measuremen using CTR was investigated based on a Michelson interferometer with two infrared detectors. According to the interferometer's measurement of the IRS, the sensitivity of the bolometer and the MCT detector ranged from 3 to 15 THz and 11 to 50 THz, respectively. CTR emitted from an electron bunch of 2.1 pC and 32 MeV was measured using the interferometer with the bolometer and the MCT detector. To analyze the interferograms, 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 of 8.9 fs was obtained in the measurement using the MCT detector while it was 26 fs in the measurement using the bolometer. The cause of the difference was explained by the sensitivity of the detectors.

ACKNOWLEDGMENT

We thank the staff of the research laboratory for quantum beam science at the Institute of Scientific and Industrial Research, Osaka University, for the experimental setup. This work was supported by KAKENHI (21226022, 23109507, and 25870404).

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