BUNCH LENGTH MEASUREMENT BASED ON INTERFEROMETRIC TECHNIQUE BY OBSERVING COHERENT TRANSITION RADIATION

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Abstract

Generation and diagnosis of ultra-short electron bunches are one of the main topics of accelerator physics and applications in related scientific fields. In this study, ultra-short electron bunches with bunch lengths of femtoseconds and bunch charges of picocoulombs were generated from a laser photocathode RF gun linac and an achromatic arc-type bunch compressor. Observing coherent transition radiation (CTR) emitted from the electron bunches using a Michelson interferometer, the interferograms of CTR were measured experimentally. The bunch lengths were diagnosed by performing a model-based analysis of the interferograms of CTR.

INTRODUCTION

Generation of ultra-short electron bunches with femtosecond bunch lengths has been progressed with the development of accelerator technologies such as photocathode RF (Radio Frequency) guns, bunch compression techniques and plasma acceleration techniques. The femtosecond electron bunches are essential for physical application in accelerator science such as free-electron lasers[1], laser-Compton scattering x-ray sources[2] and terahertz-light sources based on coherent radiation[3]. In addition to the application mentioned above, it takes an important role in time-resolved measurement like pulse radiolysis in radiation chemistry. The pulse radiolysis is one of the most powerful tools in radiation chemistry to investigate ionizing radiation-induced phenomena. As for this measurement, the ultra-short electron bunch is used as a pump source to ionize the chemical sample, and the kinetics of the radiation-induced phenomena is measured as transient absorption using an ultra-short laser pulse stroboscopically, so the time resolution of the system is mainly determined by the electron bunch lengths. So far, much effort has been paid to improve the time resolution, and the best time resolution of 240 fs was attained using 100-fs electron bunches generated from a laser photocathode RF gun linac and a magnetic bunch compressor at Osaka University in 2011[4].

On the other hand, longitudinal diagnosis of the ultra-short electron bunches is also one of the key topics in accelerator physics and its related fields. The main reason to activate this study is that there is no established bunch length measurement technique for <100-fs electron bunches. Hitherto, many bunch length measurement techniques have been proposed and experimentally demonstrated to diagnose the <100-fs electron bunches. For example, bunch length measurements using coherent radiation (CR)[5,6], electro-optic (EO) crystals[7] and deflecting cavities have been proceeded to diagnose the temporal bunch length of femtosecond electron bunches.

In this study, bunch length measurement based on interferometric technique was demonstrated by monitoring coherent transition radiation (CTR). Details will be described below, but the bunch lengths were estimated by analyzing an autocorrelation of CTR measured using a Michelson interferometer.

EXPERIMENTAL SETUP

Photocathode RF Gun Linac

Figure 1 shows the schematic of the linac system at Osaka University. The linac system has three beam lines, and achromatic-arc beam line was used to generate the ultra-short electron bunches. The linac system is mainly composed of three sections: a photocathode RF gun with a copper cathode, an S-band acceleration cavity and an achromatic arc-type magnetic bunch compressor. The photocathode is driven by a 266-nm femtosecond UV pulse of the third harmonic of a Ti:sapphire femtosecond laser with a regenerative amplifier (Tsunami with Spitfire, Spectra Physics). The electron bunch is accelerated at 4 MeV at the exit of the gun and the solenoid mounted at the exit of the gun is used for emittance compensation. The electron bunch is accelerated by the RF electric field inside the 2-m long S-band traveling wave cavity. The beam energy of the electron bunch at the exit of the linac is 35 MeV, and the electron bunch is energy-correlated inside the cavity for bunch compression using the achromatic arc-type magnetic bunch compressor. The bunch compressor is composed of two bending magnets, four quadrupole magnets and two sextupole magnets. The sextupole magnets in the compressor served to compensate for the second-order effect due to the fringing fields of the magnets, which will cause bunch length growth because of the nonlinear transformation of the energy-phase correlation.

Bunch Length Measurement System

Figure 2 shows the schematic diagram of the bunch length measurement system based on a Michelson interferometer. In this scheme, the CTR was emitted from the electron bunches at a boundary between a vacuum and an aluminium mirror (M1). The mirror (M1), scintillators (ZnS) and an infrared light source (IRS, IRS-001C, IR System) for calibration of the measurement system were mounted on the rotational stage, so the transverse beam shape could be checked during the measurement. The CTR was collimated to parallel light by an off-axis parabolic mirror (OAP1) since it could be considered to be a point source of electromagnetic (EM) waves in infrared region. After that,

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ISBN 978-3-95450-177-9

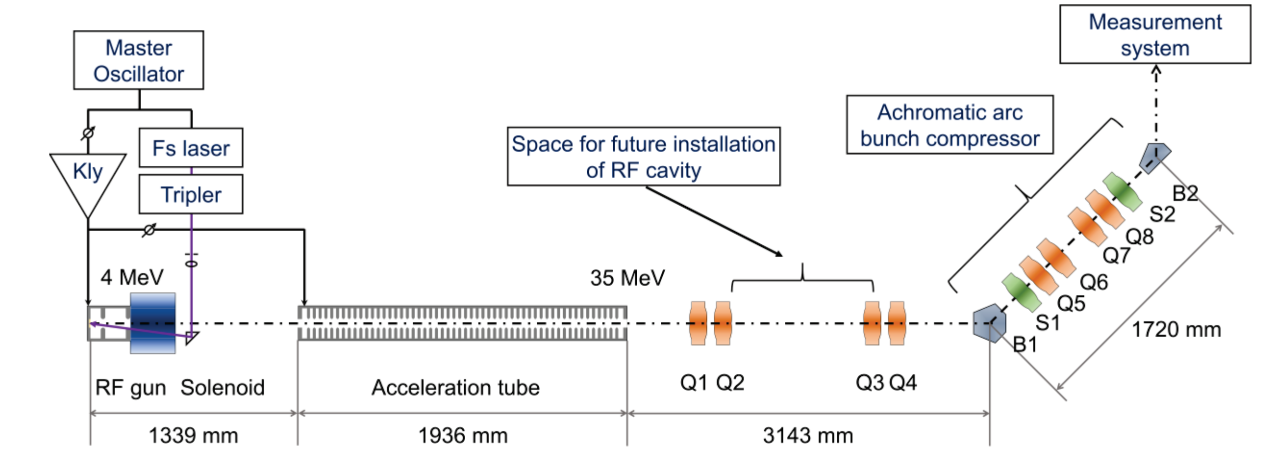

Figure 1: Schematic diagram of a laser photocathode RF electron gun linac and a magnetic bunch compressor. Q: quadrupole magnet; B: bending magnet; S: sextupole magnet.

the EM waves were guided to the Michelson interferometer. The CTR was collimated and then split in two by a beam splitter (BS1) made of a 375-um 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 detectors. The autocorrelated signal as a function of the position of M5 is called as an interferogram. Two infrared light detectors were used simultaneously for the detection of the interferograms. One is a liquid-helium-cooled silicon bolometer (general purpose 4.2-K system, Infrared Laboratories) and the other is a liquid-nitrogen-cooled MCT photoconductive detector (P2748, Hamamatsu photonics). 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 bunch can be obtained by analyzing the interferogram. All optical elements except for infrared detectors were placed in a vacuum. The bunch length measurement system was optimized and calibrated by using the IRS. 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 blackbody radiation according to Planck's law.

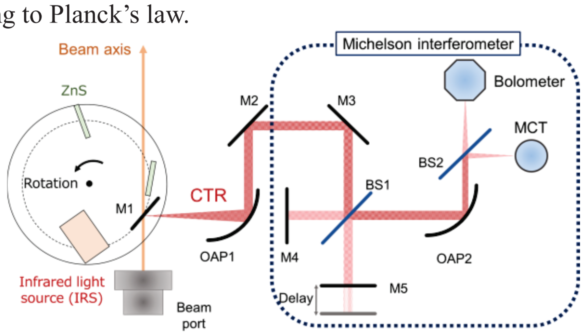

Figure 2: Schematic diagram of the Michelson interferometer. M: aluminium mirror, OAP: off-axis parabolic mirror, BS: beam splitter, MCT: Mercury cadmium telluride detector.

RESULT AND DISCUSSION

Observation of Coherent Transition Radiation

In general, the intensity of CR is known to be proportional to the bunch charge of the electron bunch. Thus, dependence of CTR on the bunch charge was checked experimentally in order to confirm whether the measured radiation was CTR or not. Figure 3 shows the result of the dependence of CTR on the bunch charge. The horizontal and vertical axes denote the bunch charge and the integral of the signal detected using the bolometer. The bunch charge was measured by a current transformer at the exit of the bunch compressor. The solid line denotes the quadratic function fitted to the experimental data by means of the least-squares method. As a result, the experimental data were agreed well with analytical model, and it means that the radiation measured in this experiment was CR.

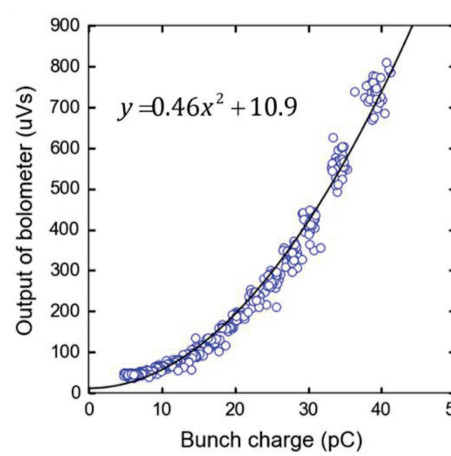

Figure 3: Dependence of intensity of CTR on bunch charge and fitting curve of quadratic function.

Bunch Length Measurement of Ultra-Short Electron Bunches

The bunch length measurement was carried out using measurement system as shown in Fig. 2. Femtosecond electron bunches were generated at the condition that the

ISBN 978-3-95450-177-9

bunch charge was 6.6 pC and the accelerating phase was set to 110°. Figure 4 shows the interferogram of CTR detected using the MCT detector. The number of the average was 5 times. The rms bunch length was estimated to be 7.4 fs by least squares fittings of the interferogram by the sensitivity model as described in reference[5]. Using this analytical model, the whole interferogram including the oscillation lying down beside the centerburst could be well expressed. This oscillation was caused by deficiency of the low frequency components.

Figure 5 shows the frequency spectrum of CTR, which was calculated by performing the Fourier transform of the interferogram of CTR. The solid line denote the fitting curve based on sensitivity model in the frequency domain[5]. The red dashed lines denote the curve calculated based on sensitivity models (1 fs) and the blue dashed line denote the sensitivity model (20 fs). Using sensitivity model, the frequency spectrum of CTR obtained experimentally was also expressed well in the frequency domain.

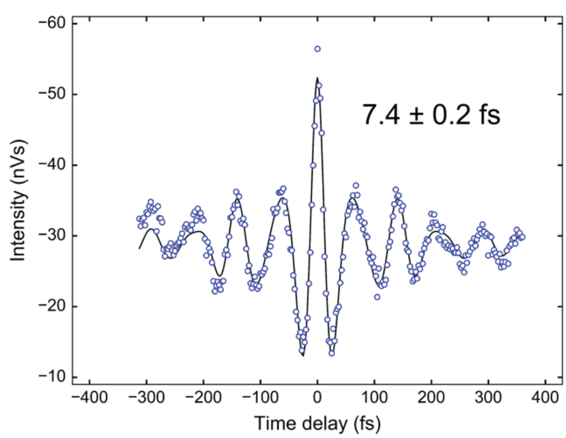

Figure 4: Interferogram of CTR and fitting curve based on sensitivity model.

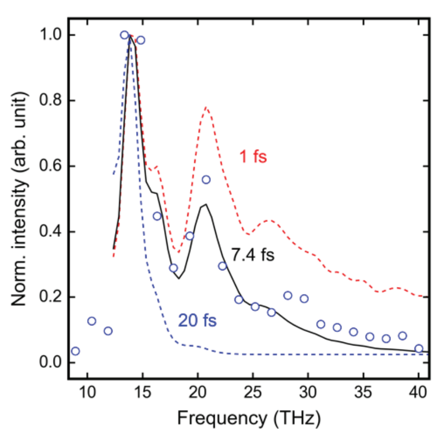

Figure 5: Frequency spectrum of CTR. The solid line denote the fitting curve based on sensitivity model. The red and blue dashed lines denote curves calculated based on sensitivity models.

CONCLUSION

The ultra-short electron bunches were generated using the linac system at Osaka University. The <10-fs electron bunch was successfully measured by monitoring coherent transition radiation with the Michelson interferometer. Experimental data of the interferogram and frequency spectrum were agreed well with the analytical model both in the time and frequency domain.

ACKNOWLEDGEMENT

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 (26249146) and JSPS Research Fellowships for Young Scientists (15J02667).

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ISBN 978-3-95450-177-9