ISBN: 978-3-95450-184-7 doi:10.18429/JACoW-IPAC2018-THPMF074

STUDY OF THE SATURATION OF RADIATION ENERGY CAUSED BY THE SPACE CHARGE EFFECT IN A COMPACT THz COHERENT RADIATION SOURCE*

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Abstract

To generate an intense quasi-monochromatic Terahertz Coherent Undulator Radiation (THz-CUR), a compact linac system, which employs a magnetic electron bunch compressor with a beam energy of 4.6 MeV, has been constructed at Kyoto University. The THz-CUR has successfully been generated in a frequency range from 0.16 to 0.65 THz with a bunch charge of 60 pC. The maximum micro-pulse energy of THz radiation was observed higher than 1 μJ at 0.16 THz with 160 pC. However, when a bunch charge was higher than 80 pC, the micro-pulse energy of THz radiation gradually went to the saturation because of bunch lengthening and degradation of electron beam quality due to the space charge effect. The dependence of a bunch length on a bunch charge has been studied by GPT simulation and compared with CTR and CUR experiments. The trends of the measured results from CUR and CTR are in good agreement with the GPT simulation.

INTRODUCTION

THz radiation is electromagnetic radiation spectrum covering a frequency range from 0.1 THz to 10 THz in the region between Microwave and infrared. Many THz sources, such as quantum cascade lasers or gas devices [1], solid-state oscillators [2], laser driven THz emitters [3], and FEL electron-based sources [4], have been developing as the useful tools to serve in many scientific fields such as biological, physical, chemical, and material sciences [5]. Especially, THz source based on an accelerator can produce high power coherent radiation, continuously tunable wavelengths, and narrow bandwidth [6, 7].

To consider a small-scale accelerator for generating intense Terahertz Coherent Undulator Radiation (THz-CUR), a compact linac system (Fig. 1) at Kyoto University has been developed and constructed, which employs a magnetic bunch compressor [8]. The system starts from a photocathode RF gun used as an electron source to produce a short electron bunch by irradiating a UV laser with a 5.8 ps width in FWHM and a wavelength of 266 nm on a copper cathode [9]. An electron bunch length can be compressed shorter than the radiation wavelength by the bunch compressor chicane. At present, our THz-CUR source can generate an intense quasi-monochromatic THz-CUR from 0.16 to 0.65 THz with a bunch charge of 60 pC by injecting a short electron beam length to an undulator [10]. The frequency of the THz-CUR can be controlled by changing the magnetic field of the undulator from 0.43 Tesla to 0.11 Tesla.

In order to study the saturation of radiation energy affected by the space charge in the short bunch, a bunch length as a function of a bunch charge needs to be measured. A direct way to measure the bunch length, a streak camera has been used in many electron beam accelerator facilities [11, 12]. However, the price of streak camera is high and the experimental setup is complicated. Therefore, to get the preliminary results of the bunch length measurements, we used CTR and CUR power spectra for estimating the bunch length. The bunch length was measured as a function of a bunch charge and compared with the result simulated by the GPT code.

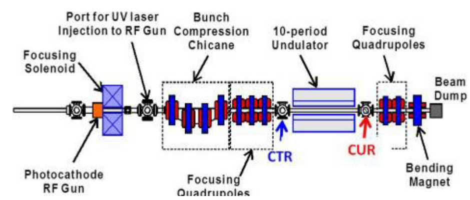

Figure 1: Schematic of THz-CUR at Kyoto University.

SATURATION OF RADIATION ENERGY

The coherent undulator radiation (CUR) is generated when an electron beam whose bunch length is shorter than a radiation wavelength passes through the undulator. The CUR energy is proportional to the square of an electron number N_e^2 [13]. Following investigation of the performance of our source, the maximum THz-CUR energy in micro-pulses was observed higher than 1 μJ with 160 pC at 0.16 THz. It can be seen that the THz-CUR energy in the micro-pulse at 0.16 THz had the quadratic dependence on the bunch charge prior to saturation, as shown in Fig. 2. The THz-CUR energy gradually went to the saturation region when a bunch charge was higher than 80 pC and completely saturated at a bunch charge of higher than 110 pC. Due to bunch lengthening, a frequency of 0.65 THz could not be generated at a 160 pC bunch charge [14].

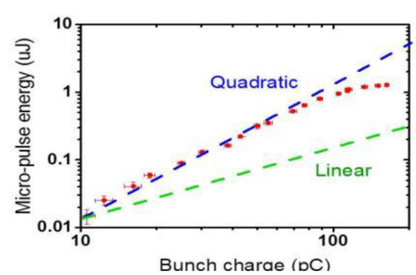

Figure 2: The total radiation energy, as a function of the bunch charge at THz-CUR frequency of 0.16 THz.

* Work supported by the MEXT/JSPS KAKENHI 26706026
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ISBN: 978-3-95450-184-7 doi:10.18429/JACoW-IPAC2018-THPMF074

Since a photocathode RF gun provides an electron beam with a high charge and a short bunch. Therefore, THz-CUR with high intensity can be generated. However, due to the high charge in the short electron bunch generated from the photocathode RF-gun, the generated electron beam is strongly affected by the large space-charge effect. This effect causes to bunch lengthening and degradation of electron beam quality.

BUNCH LENGTH ESTIMATION

GPT Simulation

To compare an experimental result with simulation, the particle tracking simulation code called General Particle Tracer (GPT) [15] has been employed for studying charged particle dynamics in electromagnetic fields. The GPT version 3.10 used in this work includes a space-charge model without wakefields and Coherent Synchrotron Radiation (CSR) effects. The number of macro-particles used in this simulation is 10,000 particles which is a sufficient number for 3D-model calculation. The longitudinal distribution can be determined from the histogram of the peak current, as shown in Fig. 3(a). Figure 3(b) shows a bunch form factor converted from the longitudinal distribution by using Fast Fourier Transform (FFT). The bunch form factor was fitted with $f(\omega,\sigma_z) = C\cdot\exp(-\omega^2\sigma_z^2)$ [16] to get the effective bunch length. The bunch lengths were simulated at the CTR and CUR stations as shown in Fig. 1.

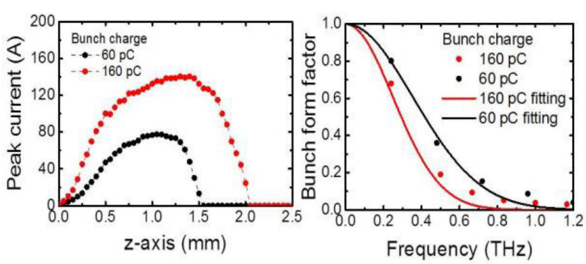

Figure 3: Typical GPT calculation results (a) Particle distribution in the longitudinal phase space and (b) bunch form factors for the bunch charge of 60 pC and 160 pC.

CTR and CUR Measurements

Experimental setup

Since the THz-CUR spectrum is proportional to the bunch form factor. The measurements of the power spectrum of Coherent Transition Radiation (CTR) and CUR have been used for estimating the bunch length. The experimental setups are explained as follows.

CTR occurs when a short-bunch-length electron beam crosses the boundary between different dielectric constants. Its spectrum has a board spectrum and depends on the longitudinal profile of an electron bunch. Therefore, the CTR is suitable for the estimation of the longitudinal bunch length. An aluminum foil of 11 µm thick was used as a CTR radiator installed at 45 degrees. The backward CTR was extracted through a z-cut natural crystal quartz window. The setup of a Michelson interferometer for measuring CTR interferograms is shown in Fig. 4(a). A Tsurupica lens was used to focus the radiated beam before injecting to the interferometer. We selected the sapphire plate with a thickness of 0.1 mm as a beam splitter (BS), because it has high efficiency. However, the efficiency of the sapphire BS drops to zero at 0.475 THz due to destructive interference. The power spectrum of the CTR was distorted by this effect. Then, the beams from a fixed mirror and a movable mirror were combined again and focused by a parabolic mirror. A pyroelectric detector (PYD-1, PHLUXi) was used to detect the intensity of the CTR after the interferometer.

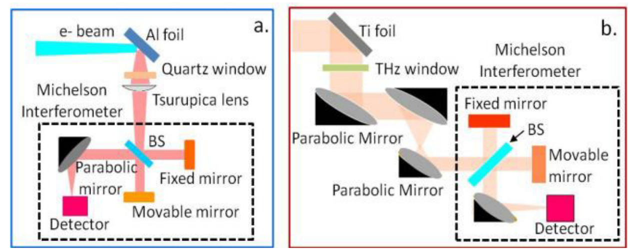

Figure 4: Experimental layout of (a) CTR and (b) CUR.

CUR generated in the undulator was reflected by a 20 µm titanium foil. The CUR was extracted through a fused silica window and sent to the Michelson interferometer, as shown in Fig. 4(b). Three parabolic mirrors were used to make a THz-CUR beam size smaller and a quasi-parallel beam to fit the Michelson interferometer. In this setup, an Inconel coated pellicle beam splitter was used as a beam splitter, because of its broadband characteristics. The reflected and transmitted beams from the beam splitter were injected to a fixed mirror and a movable mirror, respectively. Both beams were merged again and focused by a parabolic mirror before detected by a pyroelectric detector (PYD-1, PHLUXi).

Procedure of bunch length estimation

1. Interferogram: The intensity signals of the CTR and CUR were measured as a function of path difference, as shown in Fig. 5(a) and Fig. 5(b), respectively. The path difference is equal to the position of the movable mirror multiplied by factor 2. For measurements of the CUR and CTR, the positions of the movable mirror were scanned from -10 mm to 10 mm and from -2 mm to 2 mm with step sizes of 0.05 mm and 0.1 mm, respectively.

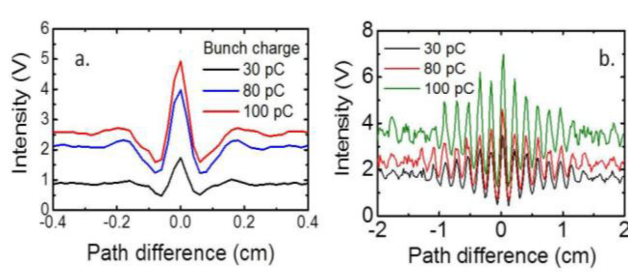

Figure 5: Interferograms of (a) the CTR and (b) the CUR with bunch charges of 30 pC, 80 pC, and 100 pC.

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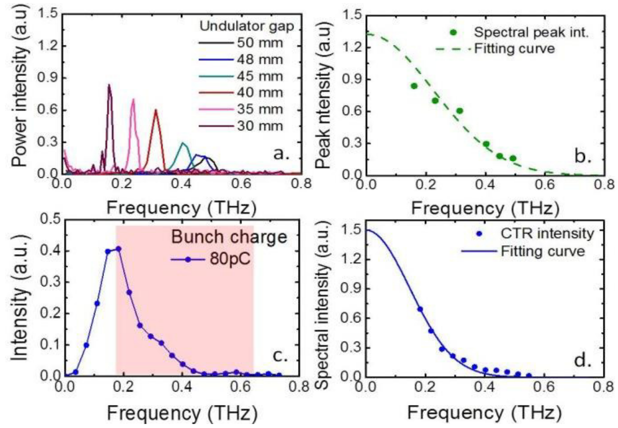

Figure 6: The measured spectral power intensity of (a) the CUR and (c) the CTR. The spectral intensity with the fitted curves for (b) the CUR and (d) the CTR with a bunch charge of 80 pC.

2. Spectral intensity: The interferograms were converted to a power spectrum by using FFT.

CTR: To avoid the distortion of the beam splitter, the power spectrum was normalized with the efficiency of the sapphire BS. In addition, the frequency range was selected from the center peak of the power spectrum located in the red box of Fig. 6(c), which is higher than the 0.16 THz, since the CTR was cut due to the limited aperture of the measurement system and the strong diffraction of low frequency (long wavelength) radiations.

CUR: The resonance frequency of the THz-CUR was varied by changing the undulator gap from 30 to 50 mm in a step of 5 mm, each (Fig. 6(a)). Only maximum peaks of power intensities at each undulator gaps are used for estimating the bunch length, as shown in Fig. 6(b). Mismatched electron beam optics due to the strong magnetic field of the undulator disturbs the power intensity of the CUR at low frequency.

3. Bunch length: the bunch length was estimated by fitting spectral intensity with the function of the bunch form factor $f(\omega,\sigma_z) = C\cdot\exp(-\omega^2\sigma_z^2)$, as plotted in Fig. 6(b) and 6(d), with the assumption of Gaussian longitudinal distribution.

RESULTS AND DISCUSSION

The results are summarized in Fig. 7. To keep the same condition with the measurement, the frequency spectrum higher than 0.16 THz was only taken into account for the bunch length estimation in the case of the GPT simulation. The bunch length estimated from the CTR measurement is longer than that of the CUR one as shown in Fig. 7(a). The measured bunch lengths with the CTR and CUR elongate more than 20% when the bunch charge increases from 30 to 100 pC. In the case of CUR measurement, the mismatched electron beam optics due to the strong magnetic field of the undulator disturbs the power intensity of the CUR at low frequency. It may result in uncertainty about the estimation of a bunch length. However, the trends of the measured results from CUR and CTR are good agreement with the GPT simulation but their values show higher than the simulation.

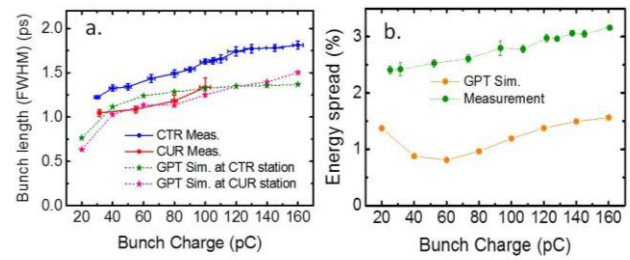

Figure 7: Comparisons of the bunch length (a.) and energy spread (b.) between the experiments and the simulation at the different bunch charges.

In this work, the energy spread of the beam as the function of the bunch charge was also measured to study the beam quality degradation since the bunch lengthening relates to the degradation of the electron beam quality such as an energy spread ($\delta\gamma/\gamma$) [17]. The results of measurement and simulation are shown in Fig. 7(b). The measurement results are higher than the simulation ones, because CSR effect was not included in the simulation. The measured energy spreads rises up to 3.2% when the bunch charge increases to 160 pC. Besides bunch lengthening, the increase of energy spread results in the lowering peak intensity and broadens the power spectrum of the THz-CUR. The detail of an experimental setup for energy spread measurements was reported in Ref. [18].

From the results of bunch length and energy spread measurements, the performance of our source is considered to be limited by the space charge effect. It could be improved by optimization of the operational condition and reducing the space charge effect by changing the shape of laser pulse to a longitudinally uniform one [19].

CONCLUSIONS

Space charge force in a short electron bunch affects to THz-CUR energy, because it results in the bunch lengthening and degradation of electron beam quality. It was found that the trend of a bunch length from CTR and CUR is in good agreement with the simulation performed by the GPT code. Bunch lengths at 80 pC from the CTR and CUR data are 1.49±0.04 ps and 1.19±0.08 ps in FWHM, respectively. Due to the space charge effect, they increase as a function of a bunch charge. Mitigation of the space charge effect is necessary for generating higher CUR energy in a THz region. Therefore, we plan to design a pulse stacking system for making uniform laser pulses before injecting to a photo cathode for reducing the space charge effect in a short electron bunch.

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ISBN: 978-3-95450-184-7 doi:10.18429/JACoW-IPAC2018-THPMF074

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