THz COHERENT UNDULATOR RADIATION GENERATED FROM COMPACT ACCELERATOR BASED ON PHOTOCATHODE RF GUN

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Abstract

This work presents the measured results of the THz coherent undulator radiation, which is generated by a planar undulator with short electron bunch from photocathode RF gun. This system has been developed at Kyoto University to generate intense quasi-monochromatic THz radiation. The details of experimental setups and the measured results of the total radiation intensity and power spectrum are presented. The effects of the electron space charge on the bunch form factor are also explained.

INTRODUCTION

The THz Coherent Undulator Radiation (THz CUR) source at Kyoto University has been developed since 2013 [1]. The system starts from the 1.6-cell S-band BNL-type photocathode RF-gun, which is driven by a 266 mm wavelength UV laser from a photocathode-drive laser system to produce the electrons [2]. Then, the electron bunch is focused by a solenoid maget. The electron bunch length is compressed by a magnetic chicane, which consists of four dipole magnets. The focusing condition of electron beam before injected to an undulator is controlled by triplet quadrupole magnets. At the downstream of the undulator, doublet quadrupole magnets and a bending magnet have also been installed to dump the electron beam. The maximum magnetic field, period length and number of period of the undulator are 0.43 Tesla, 0.07 meters and 10, respectively. In August 2016, this system has successfully started generating the quasi-monochromatic THz-CUR.

The main goal of this system is to generate intense quasi-monochromatic THz-CUR radiations, which cover the wavelength and frequency range from 350 to 1750 µm and 0.17 to 0.9 THz, respectively with the electron beam energy of 4.6 MeV [3]. Intense THz-CUR sources are a useful tool for various scientific fields, such as biological, physical, chemical, and material sciences. Currently, we are also studying the THz-CUR technique and its application.

This paper reports the experimental setups and the results of total intensity and the power spectrum measurements of the THz-CUR. The relationship between the radiated intensity and bunch charge were also measured. The effects of the electron space charge on the bunch form factor are discussed.

THz COHERENT UNDULATOR RADIATION

CUR is the radiation emitted from relativistic electrons when propagating through a periodic alternating magnetic fields generated by an undulator when the electron bunch length is equal to or shorter than the radiation wavelength. The total radiated energy can be written as

$$W_{total} = W_{1e}\left[N_e + N_e\left(N_e - 1\right) f(\omega,\sigma_z)\right]. \tag{1}$$

Where W_{1e} is the radiated energy of a single electron, N_e is number of electrons in bunch, $f(\omega,\sigma)$ is the bunch form factor, ω is the resonance frequency, and σ_z is the longitudinal bunch length.

This equation consists of incoherent and coherent undulator radiation terms. The term which is proportional to square of electron number N_e^2 corresponds to coherent undulator radiation [4]. Its characteristics depend on the properties of the electron beam and the undulator. The energy of coherent undulator radiations can be written as [5]

$$W_{coh} = \frac{\pi e^2 N_u}{3\varepsilon_0 \lambda_u} K^2 \gamma^2 N_e^{\,2} f(\omega,\sigma). \tag{2}$$

Where N_u is number of undulator period, γ is the relativistic factor. The undulator strength parameter K is $0.934 \cdot B_0[T] \cdot \lambda_u[cm]$. B_0 is the magnetic field and λ_u is the period length of undulator. The bunch form factor $f(\omega,\sigma)$ is defined as the Fourier transform of the longitudinal particle distribution within the bunch. In case of Gaussian distribution, it can be defined as follows

$$f(\omega,\sigma) = \left| \frac{1}{N} \sum_{j=1}^{N} e^{i\frac{2\pi z_j}{\lambda}} \right|^2 = e^{-(\frac{\omega^2 \sigma_z^{\,2}}{2})}. \tag{3}$$

The radiated peak power, P_{coh} can be calculated from the proportion of the total radiated energy expressed by Eq. (2) and slippage time or radiation pulse width $(N_u \lambda_r / c)$

$$P_{coh} = \frac{W_{coh}}{N_u \lambda_r / c}. \tag{4}$$

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Where λ_r is radiation wavelength $\lambda_u\left(1+K^2/2\right)/2\gamma^2$ and c is the speed of light.

SETUPS AND RESULTS OF COHERENT UNDULATOR RADIATION MEASUREMENTS

Total Radiation Intensity

The THz radiation was reflected by titanium foil inside in the vacuum chamber and travelled through a fused silica window with transmission of 75%. Then, it went to the experimental setup as shown in Fig. 1. The 1st parabolic mirror made a parallel beam and the 2nd parabolic mirror was used to focus beam to the detector. The focal lengths of the 1st and 2nd parabolic mirrors are 177.2 mm and 101.6 mm, respectively. Firstly, the spatial distribution was measured and scanned in the longitudinal axis to investigate the focusing point by using a pyroelectric detector with the sensitivity diameter of 1 mm (PYD-1/2, PHLUXi). It was found that the focusing point is far from 2nd parabolic mirror by 68 mm. This position was used to install a new detector, which was a thin-film pyroelectric detector with the sensitivity diameter of 10 mm (THz 10 and VPA amplifier module, Sensor und Lasertechnik) whose sensitivity is 7.95 MV/J.

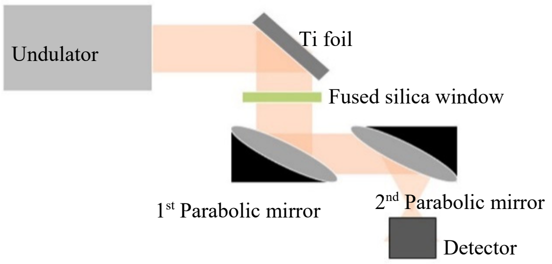

Figure 1: Total intensity experimental setup.

Figure 2 shows the undulator radiation energy and the peak radiated power depending on the gap of undulator. In the measurement, the signals of total intensity were measured as the function of undulator gap. The measured intensity can be changed to the radiation energy by calculating with the sensitivity of detector. The bunch charge was kept constant at 160 pC. The result of radiated energy looks to decreases when the gaps are opened from 30 mm to 60 mm. While the peak power for each undulator gap depends on both the total radiation energy and the radiation pulse width which can be calculated from Eq. (4). In case of 30 mm undulator gap, the radiated energy and the peak power were 620 nJ and 10.6 kW, respectively. Although, the undulator radiation energy was highest at the undulator gap of 30 mm but its peak power was lower than that of the 40 mm undulator gap because the value of slippage time is higher.

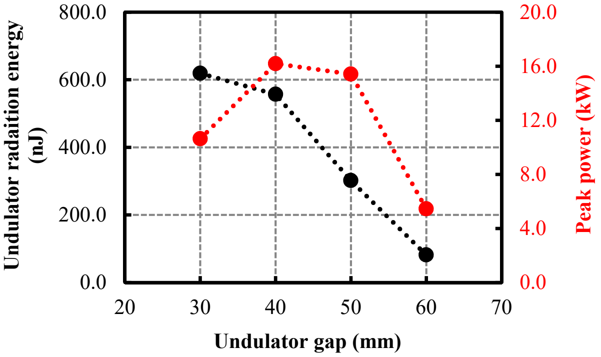

Figure 2: The undulator radiation energy and the peak radiated power at various gaps of undulator.

Power Spectrum

The experimental setup called “Michelson interferometer” has been used to measure the power spectrum as shown in Fig. 3. The THz beam transmitted from a fused silica window traveled to 1st and 2nd parabolic mirror for focusing the beam and straightly moved to the 3rd parabolic mirror, which was installed at the focusing point. Then the transported beam was separated into two beams by a beam splitter (Inconel coated pellicle beam splitter, Edmund Optics). The reflected beam was injected to fixed mirror and reflected back. The transmitted beam was injected to a movable mirror on a linear stage and reflected back. Both beams were merged and focused by the 4th parabolic mirror before detected by a pyroelectric detector (PYD-1/2, PHLUXi). The signals of intensity as a function of the path difference (interferogram) were measured then they were converted to power spectrum by using Fast Fourier Transform (FFT).

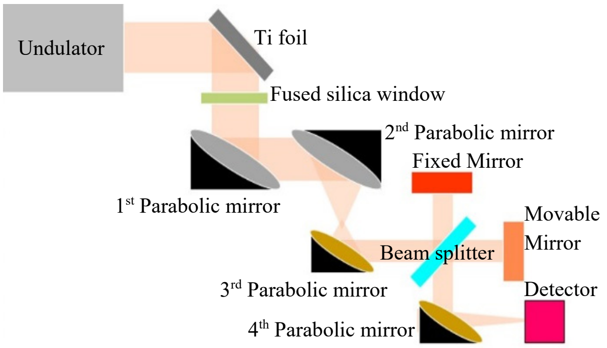

Figure 3: Michelson interferometer schematic.

In order to investigate the power spectrum at the undulator gap of 30 mm, the interferograms were measured as a function of bunch charge from 35 pC to 160 pC with the path difference of 4 cm. The measured results are shown Fig. 4. The variations of power spectrum versus the bunch charge at the 30 mm undulator gap are also plotted. The spectral peak intensity decreases when the bunch charge was reduced. The amplitudes of intensity are 0.58, 0.5, 0.35, and 0.15 for the bunch charges of 160 pC, 125 pC, 75 pC, and 35 pC, respectively. The resonance frequency of THz-CUR remains unchanged at 0.16 THz because it is independent of the bunch charge.

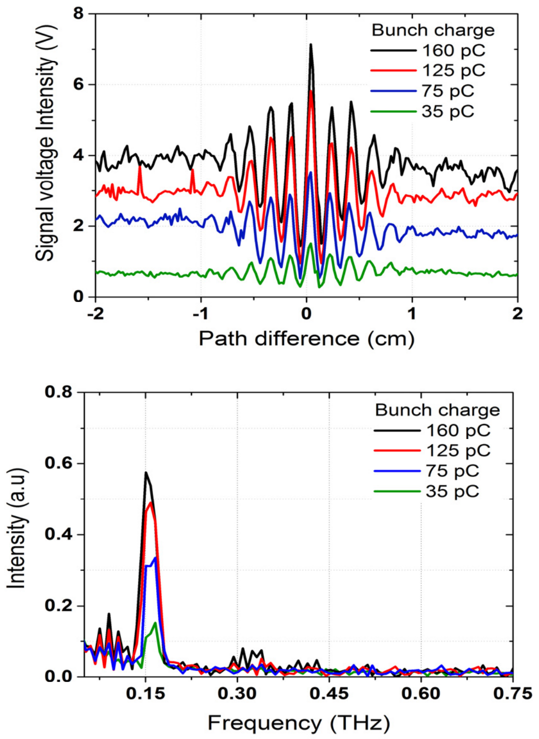

Figure 4: Interferograms (top) and Power spectrum (bottom) at the undulator gap of 30 mm as varied as the bunch charge.

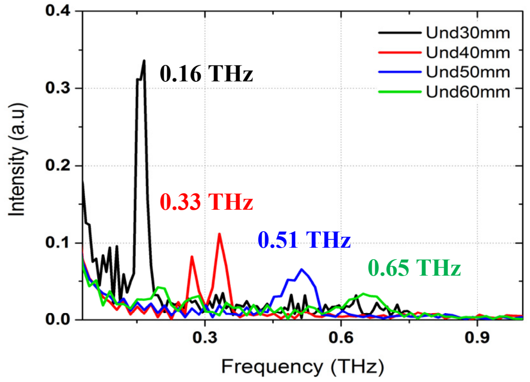

Figure 5: The power spectrum with the bunch charge of 60 pC.

Figure 5 shows the power spectrum of the THz-CUR with different undulator gap. As one can obviously see that the developed THz-CUR source can generate quasi-monochromatic THz radiation in the frequency and wavelength ranges from 0.16 to 0.65 THz and 1870 um to 450 um, respectively, which were under the condition of bunch charge of 60 pC. The resonance frequency, total radiation energy, and the expected radiated peak power of THz-CUR are concluded in Table 1.

Table 1: The radiation energy and the radiated peak power with the bunch charge of 160 pC and the frequency with the bunch charge of 60 pC.

Undulator Gap (mm)	Frequency (THz)	Radiation energy (nJ)	Peak power (kW)
30	0.16	620	10.6
40	0.33	560	16.1
50	0.51	300	15.4
60	0.65	81	5.45

BUNCH FORM FACTOR AND THE SPECTRAL PEAK POWER OF RADIATION

Normally, the bunch form factor in Eq. (3) depends on the bunch length and it also relates to the radiation intensity versus bunch charge square. Currently, the bunch length has not been measured, but we can estimate the bunch length by using General Particle Tracer (GPT) code [6]. The results of bunch form factor as calculated from bunch length of 1.0 ps (302 um) and 1.5 ps (450 um) are presented in Fig. 6. The bunch length (FWHM) of 1.0 ps was calculated from GPT. For the bunch length of 1.0 ps, it decreases almost zero at the frequency above 0.65 THz. Moreover, it can be seen that the value of bunch form factor with the bunch length of 1.5 ps promptly goes to zero from the frequency of 0.5 THz.

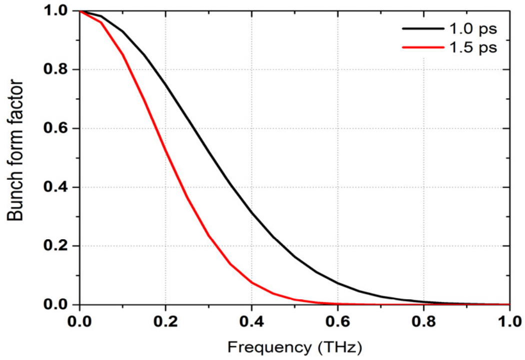

Figure 6: The curves of bunch form factor for two different the bunch lengths of 1.0 ps and 1.5 ps.

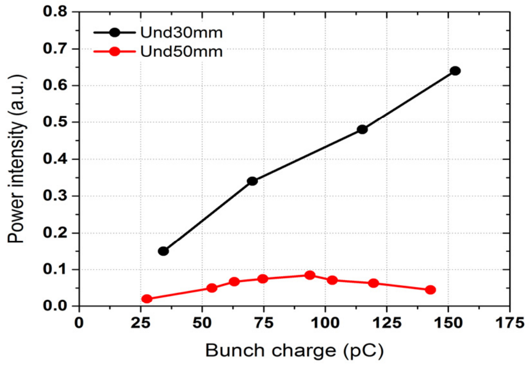

Figure 7: The plot of spectral peak intensity and bunch charge consisting of undulator gap of 30 mm and 50 mm.

The dependence of CUR spectral peak intensity at the resonance frequency (0.16 and 0.51 THz) on the bunch charge is illustrated in Fig. 7. For the undulator gap of 50 mm, the spectral peak intensity gradually reduced if the bunch charge was higher than 90 pC. But it seems to continuously increase for 30 mm undulator gap even though the bunch charge was higher than 160 pC. These measured results are in good agreement with the reduction of bunch form factor corresponding to the bunch lengthening (see Fig. 6). This is affected by the effect of electron space charge.

CONCLUSION

A THz-CUR source based on photocathode RF gun has been developed at the Institute of Advanced Energy, Kyoto University. Several experiments to characterize the radiation properties of THz-CUR were conducted. As the results of experiments, it was confirmed that the developed THz-CUR source can generate the THz radiation with the total radiated energy and the peak power of 620 nJ and 10.6 kW, respectively at the resonance frequency of 0.16 THz. In addition, the THz-CUR can cover the frequency range and the wavelength from 0.16 – 0.65 THz and 1870 – 460 um, respectively with the bunch charge of 60 pC by changing the undulator gap from 30 mm to 60 mm. However, at the high frequency and high bunch charge, the bunch form factor is reduced due to the space charge effect. Therefore, the results of radiation energy and peak power are not so high. Mitigation or good management of the space charge effect is essential to generate much higher radiation intensity.

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