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DEVELOPMENT OF COMPACT THz COHERENT UNDULATOR RADIATION SOURCE AT KYOTO UNIVERSITY*

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Abstract

A new THz Coherent Undulator Radiation (THz-CUR) source has been developed to generate intense quasi-monochromatic THz radiation at the Institute of Advanced Energy, Kyoto University. The system consists of a photocathode RF gun, bunch compression chicane, quadrupole magnets, and short planar undulator. The total length of this system is around 5 meters. At present, this compact accelerator has successfully started giving the THz-CUR in the frequency range of 0.16 - 0.65 THz. To investigate the performance of the source, the relationship between the total radiation energy, peak power and power spectrum as a function of bunch charge at the different undulator gaps were measured. The results are reported in the paper.

INTRODUCTION

At present, there are several THz sources such as quantum cascade lasers, solid state oscillators, optically pumped solid state or gas devices, electron tubes and accelerator based sources. They have been developed as the useful tools in many scientific fields [1]. At the Institute of Advanced Energy, Kyoto University, a THz Coherent Undulator Radiation (THz-CUR) source (Fig. 1), which consists of a photocathode RF gun, bunch compression chicane, quadrupole magnets, and short planar undulator, has been developed [2]. It is expected to generate a quasi-monochromatic THz beam with high peak power. This project has been started since 2008 and the construction was started in end of 2013. The 1.6-cell S-band BNL-type photocathode RF-gun designed and manufactured by KEK has been installed in 2014. The electron beam was firstly generated in 2015 with the electron beam energy of 4.6 MeV with the energy spread of 1.3% [3]. And the RMS normalized transverse emittance with the bunch charge of 50 pC was reported to be 6 and 8 mm-mrad for horizontal and vertical axis, respectively [4]. The first THz-CUR in this source was observed in August 2016.

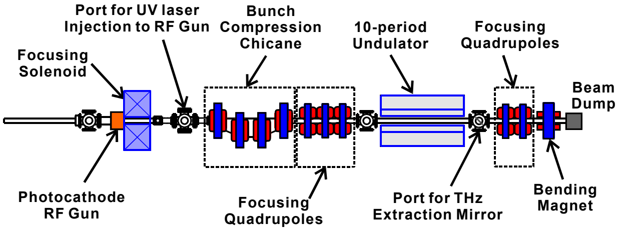

Figure 1: Layout of THz-CUR source at Kyoto Univesity.

To investigate the performance of the THz-CUR source, the measurements of total radiation energy, the radiated peak power, and power spectrum were conducted as functions of bunch charge and the undulator gap .The results are presented and discussed.

THz-CUR PROPERTIES

The coherent undulator radiation (CUR) can be emitted when the electrons are propagating in undulator. The energy of CUR can be expressed in the formula [5]

$$W_{\mathrm{coh}} = W_{\mathrm{1e}} N_{\mathrm{e}}^{2} f(\omega,\sigma_z),$$

where W_{1e} is the total energy radiated by the single electron ($W_{1e} = \pi e^2 N_u K^2 \gamma^2 / 3\varepsilon_0 \lambda_u$), N_u is the number of undulator period, γ is the Lorentz factor. The undulator strength parameter K is $0.934 B_0$ [T]λ_u[cm]. B_0 is the magnetic field and λ_u is the period length of undulator. The bunch form factor $f(\omega)$ is defined as the square of the Fourier transform of the normalized longitudinal particle distribution. For a Gaussian bunch with the RMS width of σ_z, the form factor can be given as $f(\omega,\sigma_z) = \exp(-\omega^2\sigma_z^2)$. The pulse energy is proportional to the square of electron number in the bunch. In order to have CUR, the longitudinal bunch length must be shorter than the radiation wavelength.

Up to now, the bunch length has not been measured, but it can be estimated by using General Particle Tracer (GPT) code [6]. The longitudinal bunch length is 1.0 ps in FWHM after compressing the electron bunch by using chicane magnets. As shown in Fig. 2, the bunch form factor gradually decreases to zero if the resonance frequency is higher than 0.8 THz and 0.5 THz for the bunch length of 1.0 ps and 1.5 ps, respectively.

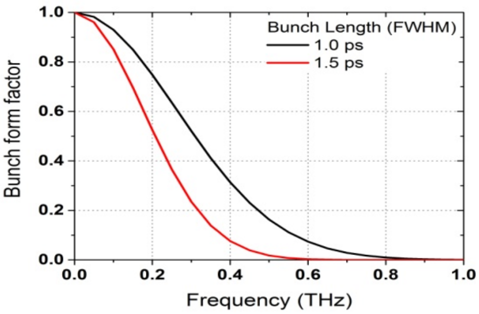

Figure 2: The bunch form factor with two bunch lengths of 1.0 and 1.5 ps in FWHM.

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MACHINE OPERATION FOR MEASUREMENTS

As shown in Fig. 1, the system starts from the photocathode RF-gun. The photocathode is driven by a 266-nm UV laser [7]. The photocathode drive laser and electron beam parameters used in this measurement are listed in Table 1. The solenoid field was adjusted from 0.14 to 0.16 Tesla for focusing the beam. To optimize the bunch compression condition, the values of the first order momentum compaction factor (R_{56}) of chicane magnet were varied in between -44 to -48 mm. The injection phase of photocathode drive laser should be adjusted nearly 20 degrees to have suitable longitudinal phase-space for the bunch compression by the chicane. At each measurement condition, the electron beam optics and positions were optimized to have the maximum intensity of THz beam and bunch charge at the beam dump.

Table 1: Electron-Beam Parameters Used in the Measurement

Laser pulse duration:	6	ps
Laser pulse energy:	< 200	uJ
Number of laser pulse:	1- 4	pulses
Bunch charge:	< 200	pC
Beam energy:	4.6	MeV
Energy spread:	1.3	%

The undulator installed in this source is a planar Halbach type one. The gap can be manually adjusted between 30 mm to 90 mm. The period length and number of period of the undulator are 0.07 meters and 10, respectively. The peak magnetic field and undulator strength parameter as a function of undulator gap are plotted in Fig. 3.

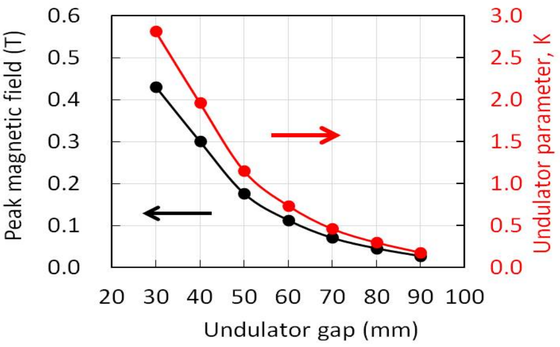

Figure 3: The peak magnetic field and undulator parameter *K*.

EXPERIMENTAL SETUP

When the short electron bunch passes through the undulator, the CUR radiation was generated. Just after the undulator, THz radiation was reflected by titanium foil with 50-µm thickness inside the vacuum chamber and traveled through a fused silica window with the transmission of 75%. Then, it went to the experimental setup [8].

Total radiation intensity: The layout is presented in Fig. 4. We used two parabolic mirrors for focusing THz beam. Two pyroelectric detectors were used for this measurement; one was a calibrated thin-film pyroelectric detector (THz10 and VPA amplifier module, Sensor und Lasertechnik) and the other is a highly sensitive pyroelectric detector (PYD-1, PHLUXi). The THz10 detector, whose detector size is 10 mm and sensitivity is 7.95 MV/J, was used for absolute intensity measurement. The PYD-1 detector, whose detector size is 1 mm, is used for spatial distribution measurement.

Power Spectrum: The Michelson interferometer shown in Fig. 4 was used to measure the power spectrum. A parabolic mirror with the focus length of 50 mm was placed 50-mm downstream of the focusing point instead of the THz10 detector used for total radiation intensity measurement. The transported beam was separated into two beams by a beam splitter. The reflected beam was injected to fixed mirror and returned. The transmitted beam was injected to a movable mirror and reflected back. Both beams were combined and focused on the PYD-1 detector by a parabolic mirror.

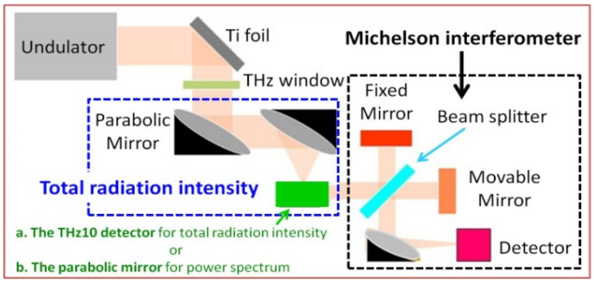

Figure 4: Experimental setup for measuring the total radiation energy and power spectrum.

RESULTS AND DISCUSSION

Total radiation energy

Firstly, the spatial distribution of THz beam with the undulator gap of 30 mm was measured by the PYD-1 detector to find the focusing point and to know the size of the radiation. The measured distribution at the focus point is shown in Fig. 5. The overlap factor between the THz10 detector and the THz beam can be determined by the ratio of integration of the measured distribution inside the 10 mm aperture and whole measured area.

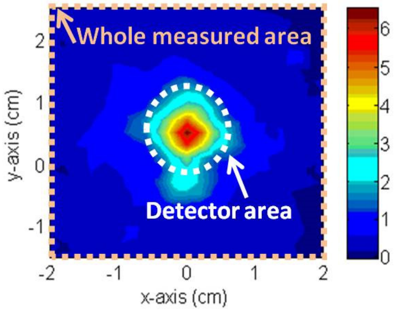

Figure 5: Spatial distribution (whole radiation area is in the orange box while the detector area is in white circle).

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The integration of the detector signal inside in the 10 mm aperture was 0.9548 V·cm^2 while that of the whole measured area was 1.9564 V·cm^2. Therefore, the overlap factor estimated from this result is 0.485. It means that around half of the total radiation would be measured by the calibrated detector.

Next, at the focus point and undulator gap of 30 mm condition, the dependence of the total radiation energy on the bunch charge was measured with the THz10 detector. The results are presented in Fig. 6. The curve of micro-pulse energy with the bunch charge seems to have the quadratic function prior to the saturation. The saturation was obvious when the bunch charge got higher than 80 pC. At the bunch charge condition of 160 pC, the total radiation energy was around 1300 nJ. Accordingly, the radiated peak power was evaluated to be higher than 20 kW with the assumption of 10-cycle pulse duration and 0.16-THz radiation frequency. The expected peak power obtained by theoretical calculated is approximately ~5 MW which is estimated from the proportion of the total radiated energy and radiation pulse width. It can be defined by $W_{coh}/(N_u\lambda_r/c)$, where λ_r is radiation wavelength $\lambda_u(1+K^2/2)/2\gamma^2$ and c is the speed of light. The experimentally determined peak power is much lower than the calculated value.

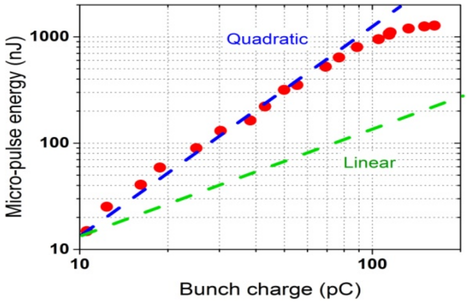

Figure 6: The total radiation energy as a function of the bunch charge at the undulator gap of 30 mm.

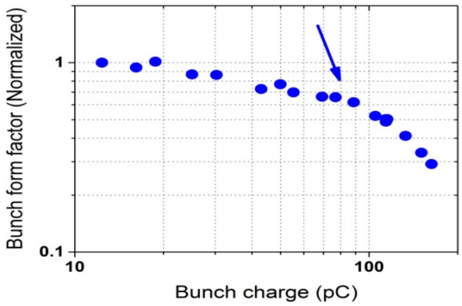

Figure 7: The normalized bunch form factor estimated from the measured total radiation energy and square of bunch charge.

From the measured result of total radiation energy, we estimated the change of the bunch form factor. Normally, the bunch form factor is proportional to the total radiation energy divided by the square of the bunch charge, $f(\omega,\sigma_z)\propto W_{coh}/Q^2$, where Q is the bunch charge. Figure 7 presents the decreasing in the normalized value of bunch form factor with the increasing of bunch charge. It is shown that the value of bunch form factor reduces promptly when the bunch charge is raised up more than 80 pC. The result can lead to bunch lengthening, due to the effect of the electron space charge.

Power Spectrum

The intensity signals as a function of the path difference of two beams in the interferometer (so called interferogram) were measured. Then the power spectra of the radiation were obtained by Fast Fourier Transform (FFT) of the interferograms. The power spectrum measurements were performed at the undulator gap conditions of 30, 40, 50 and 60 mm with two different bunch charges of 160 and 60 pC. The measured results are shown in Fig. 8. It is worth noting that the THz-CUR can be generated in the range of frequency from 0.16 – 0.65 THz with the 60-pC bunch charge by changing the gaps of undulator. While with the bunch charge of 160 pC, the frequency of 0.65 THz cannot be generated.

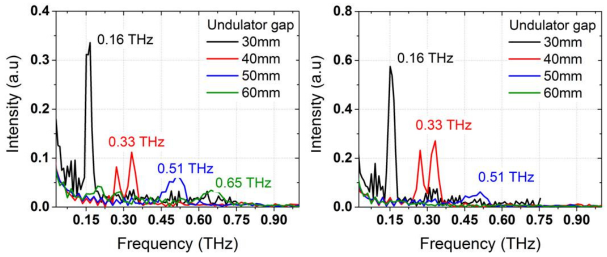

Figure 8: Power spectrum as a function of undulator gap with the bunch charges of 60 (left) and 160 pC (right).

CONCLUSION

A THz-CUR source based on photocathode RF gun has been developed at the Institute of Advanced Energy, Kyoto University. Some commissioning experiments to check the performances of the THz-CUR source have been performed. As the results show, the saturation of total radiation energy has been observed when the bunch charge was higher than 80 pC, because of the bunch lengthening. It can be confirmed that our THz-CUR source can generate the THz radiation with the total radiated energy and the radiated peak power of about 1300 nJ and higher than 20 kW, respectively at the resonance frequency of 0.16 THz and the bunch charge of 160 pC. Moreover, the source can cover the frequency range from 0.16 - 0.65 THz when the bunch charge was 60 pC. Due to the space charge effect, the frequency of 0.65 THz cannot be generated when the bunch charge was 160 pC. The performance of the source could be improved by mitigating the space charge effect.

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