OPTIMIZATION OF ELECTRON BEAM PROPERTIES FOR GENERATION OF COHERENT THZ UNDULATOR RADIATION AT PBP-CMU LINAC LABORATORY

N. Chaisueb†, S. Rimjaem, J. Saisut, C. Thongbai, Plasma and Beam Physics (PBP) Research Facility, Department of Physics and Materials Science, Faculty of Science, Chiang Mai University, Chiang Mai 50200, Thailand

Abstract

Relativistic femtosecond electron bunches produced from the linear accelerator at the Plasma and Beam (PBP) Physics Research Facility are currently used to generate THz radiation via transition radiation. An upgrade to increase the intensity of the THz radiation by using a coherent undulator radiation method is conducted. Optimizations, measurements and analysis of the electron beam properties, which include current, energy and energy spread as well as electron bunch length, are performed to investigate the capability of electron beam production from the current accelerator system. This is also to estimate the possibility to produce the coherent undulator radiation of the PBP-CMU linac. Expected characteristics of the coherent undulator radiation are studied and reported in this contribution.

INTRODUCTION

The terahertz (THz) radiation is the electromagnetic radiation, which lies between the microwave and the infrared spectrum. It has a wavelength range of 100 - 1000 μm. The THz wave can pass through non-metallic materials, whereas it is reflected by metal and is absorbed by liquid. With this unique feature of it can be applied in several researches and applications involved THz imaging and the well-known THz spectroscopy technique. It can be used, for example, to study the characteristics of various intermolecular bonds, such as hydrogen bonding, Van der Waals forces, and molecule-ion attractions because the THz frequency range is significantly corresponding with rotational and vibration modes of many molecules. This technique is very useful for medicine identification, crystal polymorphism analysis, and DNA structure study [1].

The linac-based THz source at the Plasma and Beam Physics (PBP) Research Facility, Chiang Mai University, consists of an S-band thermionic RF electron gun, an alpha magnet for magnetic bunch compressor, a travelling-wave S-band accelerating structure for post acceleration, and various beam diagnostic equipments. Relativistic electron bunches produced from the PBP-CMU linac system are firstly used to generate the THz radiation via transition radiation technique [2]. The coherent transition radiation is emitted when electrons passing through a boundary between two different dielectric media. The produced transition radiation is used for THz imaging with radiated power in milliwatt scale, which results in low-resolution THz images. Therefore, a plan to increase the radiation power of the THz radiation by using an undulator radiation method is conducted. Studies on generation of the undulator radiation by using the existing accelerator system are performed. Some study results are presented and discussed in the following sections.

ELECTRON BEAM PROPERTIES

At the PBP-CMU linac system, electron beam qualities were measured after the linac by using several diagnostic instruments, which include current transformers for measuring the beam current, a Faraday cup for measuring the total charge, a Michelson interferometer to monitor the electron bunch length, and an integration of a dipole magnet, a phosphor view screen and a Faraday cup for measurement of the beam energy downstream the linac [2]. The experimental results show that the maximum kinetic energy of the electron beam departing from the linac was 8 - 12 MeV with a macropulse length of about 0.8 μs, a peak current of up to 54.2 A. Then, the total charge per bunch was calculated to be 22.4 pC. The measured results of the electron beam properties at the experimental station are listed in Table 1 [2].

Table 1: Measured Electron Beam Properties After the Linac Acceleration

Parameters	**Value**
Average beam energy	9.81 MeV
Microbunch length (σ_z)	~50 μm
Peak current (I_b)	54.2 A
Number of electrons per bunch (N_e)	1.4×10^8

UNDULATOR RADIATION

The electromagnetic undulator magnet has been designed and constructed at the PBP facility. It will be inserted at the new experimental station in the future set up of the accelerator system (as shown in Fig. 1). This undulator consists of 71 magnet poles, return yokes and conducting coils. Specifications of the undulator magnet are shown in Table 2. When the relativistic electrons travel in the magnetic field of the undulator magnet, which is periodic alternating along the length of the undulator, they are oscillating in the transverse direction and thus emitting the radiation with a wavelength related to the electron energy and the undulator parameter (K) as

$$\lambda_r = \frac{\lambda_u}{2n\gamma^2}\left(1+\frac{K^2}{2}+\theta^2\gamma^2\right). \quad (1)$$

---

† Corresponding author: natthawut_chai@cmu.ac.th

ISBN 978-3-95450-147-2

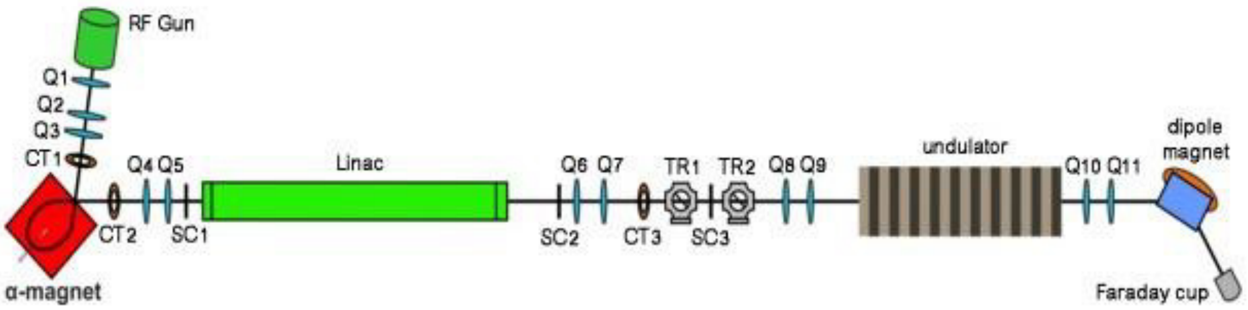

Figure 1: Future setup of the PBP CMU-linac with undulator magnet. The letters Q, CT, SC and TR represent quadrupole magnets, current transformers, screen stations, and transition radiation stations.

Table 2: Specifications of the Designed Undulator Magnet

Parameters	**Value**
Undulator parameter (K)	0.3 - 1
Period length (λ_u)	64 mm
Pole gap	10.5 mm
Number of periods (N_u)	35

Types of Coherence

A word “coherence” refers generally to the phase difference of a wave at different points, which is constant in time. The coherent wave often depends on the properties of its source. Normally, the radiation emitted from the relativistic particles subjected into periodic fields will be considered as the coherent radiation when the electron bunch length is equal or shorter than the radiation wavelength (λ_r). Types of the coherence radiation include the temporal and the spatial coherence.

The temporal coherence occurs when the phase difference between two considered points along the direction of propagation is constant. It is determined by a coherent length (l_c) involved with a relative spectral bandwidth $(\Delta\lambda_r/\lambda_r)$ of the emitted radiation, which is given by [3]

$$l_c = \frac{\lambda_r^2}{2\Delta\lambda_r}, \qquad \text{where} \qquad \frac{\Delta\lambda_r}{\lambda_r} = \frac{1}{N_u}. \tag{2}$$

As an example, the maximum power of the fundamental harmonic undulator radiation produced from the 35-period undulator magnet with the wavelength of about 103 μm is shown in Fig. 2. It is seen that the coherent length is around 8 mm.

The spatial coherence appears when the phase difference between two points in a plane normal to the propagated direction is constant with time. The undulator radiation will be considered as the spatially radiation when the transverse beam emittance $(\varepsilon_{x,y})$ is equal or less than the diffracted-limited emittance of the photon, which is given by [4]

$$\varepsilon_{x,y} \le \frac{\lambda_r}{4\pi}. \tag{3}$$

For the PBP-CMU Linac system, the preliminary results obtained from ELEGANT simulations show that the horizontal and vertical beam emittance values $(\varepsilon_x, \varepsilon_y)$ at the experimental station are 0.47 and 0.13 mm.mrad, respectively [5]. It indicates that the undulator radiation generated from the electron beam with the current properties can be the spatial coherence.

Charecteristics of Undulator Radiation

Generally, the undulator radiation is collimated in forward direction and has narrow spectral range at a well-specified wavelength [6]. The total radiation field produced from an electron bunch is derived by superposition of the fields from the individual electron in the bunch [7]. While, the total radiated energy is proportional to absolute value of the total electric field squared [4]. In this study, the total power is consider in the central cone, which refers to the on-axis radiation $(\theta = 0)$. This condition leads to the horizontal polarization and odd harmonics of the emitted radiation [8].

The total radiated power from the bunch of N_e electrons can be expressed as

$$P_{tot}(\lambda_r) = P_{le}(\lambda_r) N_e [1 + (N_e - 1) f(\sigma_z, \lambda_r)]. \tag{4}$$

The first term in the brackets describes the incoherent radiation, while the second term determines the coherent one. The spectral power from single electron in the central cone as a function of the wavelength $P_{le}(\lambda_r)$ can be calculated by

$$P_{le}(\lambda_r) = \frac{\pi e N_u I_b}{2\varepsilon_0 N_e \gamma^2 \lambda_r^2} \left(\frac{\Delta\omega}{\omega}\right) \left(2n\gamma^2\lambda_r - \lambda_u\right) F_n(\lambda_r), \tag{5}$$

where $$F_n(\lambda_r) = \left(J_{(n+1)/2}(Y) - J_{(n-1)/2}(Y)\right)^2, \tag{6}$$

and $$Y(\lambda_r) = \frac{1}{4\gamma^2\lambda_r}\left(2n\gamma^2\lambda_r - \lambda_u\right). \tag{7}$$

Here, $F_n(\lambda_r)$ is the multiplicative factor related with the power transfer from the fundamental harmonic $(n = 1)$ to the higher harmonics $(n > 1)$ and is defined by the difference of the Bessel function [3]. The spectral bandwidth $(\Delta\omega/\omega)$ of 0.1%BW is used to calculate the radiated power in this paper. The bunch form factor

$f(\sigma_z, \lambda_r)$ associated with the coherence enhancement of the radiation is estimated to be the Gaussian distribution with a standard deviation (σ_z) expressed by Eq. 8 [9]. The longitudinal Gaussian form factor is independent from the transverse distribution [4], which is

$$f(\sigma_z, \lambda_r) = e^{-(2\pi\sigma_z/\lambda_r)^2}. \tag{8}$$

Since the undulator radiation characteristics depend greatly on the specific properties of the electron beam and the undulator magnet, all results presented here based on the parameters shown in Tables 1 and 2. The 0.1%BW total radiation power for different bunch lengths are displayed in Fig. 2. The minimum wavelength, which can be produced from the beam and the undulator magnet with properties listed in both tables, is equal to 87 µm. As shown in Fig. 2, the total radiation power for the beam with 50 µm bunch length consists of only the coherent radiation. While the total power for the beams with the bunch lengths of 80, 110, and 140 µm consisted both incoherence and coherence radiation.

The incoherent part occurs when the wavelengths is equal or shorter than the bunch length with the factor 2π expressed in Eq. 8, where the phase of the emitted radiation is random and thus the total power becomes proportional to the number of electrons. In contrast, the total power of the coherent part scales with the number of electron squared as shown in Eq. 4. Furthermore, the shorter bunch length, the broader the coherent radiation with higher total power can be generated.

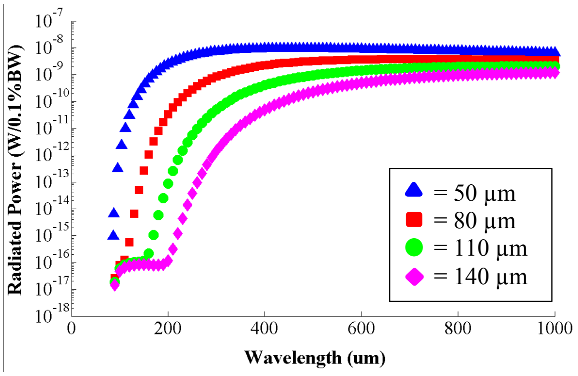

Figure 2: The total radiated power for the electron beam with bunch lengths of 50, 80, 110, and 140 µm.

The wavelength of the undulator radiation can be adjusted by changing the undulator parameter, the period length of the magnet, and the electron beam energy. In this study, the undulator period length of 64 mm and the beam energy of 9.81 MeV were considered. Thus, the wavelengths of around 90 - 130 µm can be obtained for the limited undulator parameter values of 0.3 to 1.

The study result reveals that the total power of the coherent undulator radiation is about 10^6 times higher than the coherent transition radiation for the same electron beam properties as shown in Fig. 2. However, the transition radiation can be produced with the wavelength cover from the THz to mid-infrared range, while the undulator radiation covers only the THz regime.

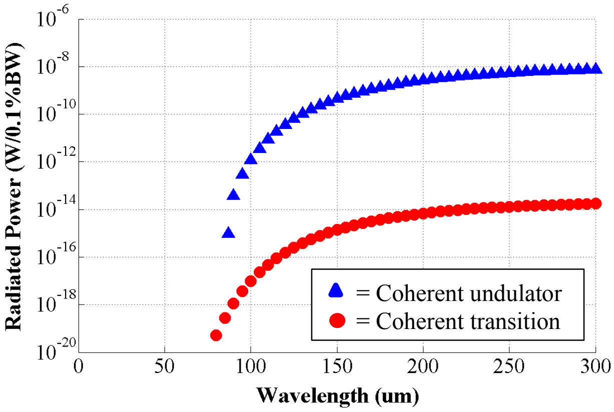

Figure 3: Comparison of the radiated power between the coherent undulator radiation and the coherent transition radiation with log scale in y axis.

CONCLUSION

The possibility of obtaining the coherent radiation by using the undulator magnet is investigated. The quality of the electron beam is significantly important for the emitted radiation characteristics. The study results show that the undulator radiation has both the temporal and spatial coherences, which can be separated by using some filtering. In this study, the undulator radiation produced from the electron beam with the bunch length as short as 165 fs, or equal to 50 µm has only the coherent contribution to the undulator radiation. The electron beams with longer bunch length produce both coherence and incoherent radiation. Therefore, it is possible to generate the coherent undulator radiation in the THz regime from the femtosecond electron bunches produced from the PBP-CMU linac.

ACKNOWLEDGEMENTS

The authors would like to express our essential gratitude to the Graduate School, Chiang Mai University. We would like to acknowledge the support by the Department of Physics and Materials Science, Faculty of Science, Chiang Mai University and the Science Achievement Scholarship of Thailand.

REFERENCES

[1] P. C. Ashworth et al., Opt. Express 17, 12444 (2009).
[2] J. Saisut, Ph.D Thesis, Chiang Mai University, (2011).
[3] D. Attwood, *Soft X-Rays and Extreme Ultraviolet Radiation*, (New York: OUP, 2007), 470.
[4] C. Settakorn, Ph.D. Thesis, Stanford University, (2001).
[5] W. Thongpakdi, Master's degree Thesis, Chiang Mai University, (2014).
[6] G. Brown et.al., Nucl. Instr. Meth. Phys. Res. B 37, 68 (1989).
[7] H. Wiedemann, *Particle Accelerator Physics*, Springer-Verlag, (New York: OUP, 2007), 948.
[8] J. A. Clarke, *The Science and Technology of Undulators and Wigglers*, (New York: OUP, 2004), 231.
[9] D. Bocek, Ph.D Thesis, Stanford University, (2006).