

THz UNDULATOR RADIATION BASED ON SUPER-RADIANT TECHNIQUE AT CHIANG MAI UNIVERSITY

E. Kongmon^{*2}, N. Chaisueb^{1,3}, S. Rimjaem^{1,4}

¹PCELL, PBP, Faculty of Science, Chiang Mai University, Chiang Mai, Thailand

²Ph. D. Program in Applied Physics (Int'l program), Chiang Mai University, Chiang Mai, Thailand

³Ph. D. Program in Physics (Int'l program), Chiang Mai University, Chiang Mai, Thailand

⁴ThEP Center, MHEI, Bangkok, Thailand

Abstract

A linear accelerator system at the PBP-CMU Electron Linac Laboratory is used as an electron source for generating coherent THz radiation and MIR-FEL. To achieve high power THz radiation, the super-radiant technique using pre-bunched electrons and undulator magnet is utilized. In this study, we investigate the generation of such radiation with comparable properties as the FEL. The beamline composes of a 180° magnetic bunch compressor, a 2 m-electromagnet undulator, quadrupole magnets and diagnostic devices. This work includes the undulator design and investigation on properties of electron beam and THz radiation. Based-on the results of beam dynamic study, the optimized electron beams have an energy in a range of 10-16 MeV, a bunch charge of 100 pC, and a bunch length of 300 fs. The radiation with frequency covering from 0.5 to 3 THz yields a peak power of 5.21 MW at 1.15 THz. This information was used as an initial parameter for undulator design by using the CST-EM Studio software. It has 19.5 periods with a period length of 100 mm. The design results show that the maximum magnetic field is 0.2317 T. The results of this study are used as the guideline for construction of the undulator and the THz-FEL beamline.

INTRODUCTION

Terahertz (THz) radiation occupies the frequency gap between microwave and infrared in the electromagnetic spectrum with the frequency in the range from 0.3 to 10 THz (100 - 1000 μm) [1]. With the dominant feature of the THz radiation having low photon energy, it is non-ionizing radiation that does not cause damage on living tissues. Furthermore, it can penetrate non-conducting materials i.e. plastic and wood and can be absorbed by water [2]. It thus has been used in many areas such as the semiconductor industry, biological science, quality control of food, medical imaging, security, environmental science, etc. [3, 4].

The aim of this study is to design and develop the system to generate coherent THz undulator radiation at the PBP-CMU Electron Linac Laboratory (PCELL), of the Plasma and Beam Physics (PBP) Research Facility, Chiang Mai University (CMU) in Thailand. The energy of electron beam produced from our accelerator can be adjusted from 5 to 30 MeV. In our work, we chose the electron energy in a range of 5 to 16 MeV.

In this paper, we present the approach to design the electromagnet undulator for generating THz radiation using the super-radiant technique. This THz source will be utilized for a variety of purposes, including THz spectroscopy and pump-probe experiments.

The THz radiation can be emitted as a synchrotron radiation when electrons traveling in a sinusoidal magnetic field through an undulator magnet. The frequency of the radiation is determined by the electron energy and the strength of the undulator magnetic field (K-parameters) as Eq. (1) [5].

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

where n is the harmonic number, γ is the Lorentz's factor and θ is the radiation observation angle. In this research, we consider only the fundamental frequency, thus the harmonics number is unity ($n = 1$) and we observe only on-axis of the radiation ($\theta = 0$).

The undulator parameter K is defined as a function of undulator magnetic field intensity (B_0) and undulator period length (λ_u) as using $K = 0.934 B_0 [T] \lambda_u [cm]$. According to Eq. (1), the radiation in the THz domain was calculated by taking into account the electron energy and the undulator period length. The relationship between these variables is plotted in Fig. 1 for the undulator period length of 100 mm, which was already optimized by compomizing between available space in the accelerator hall and the aimed radiation wavelength.

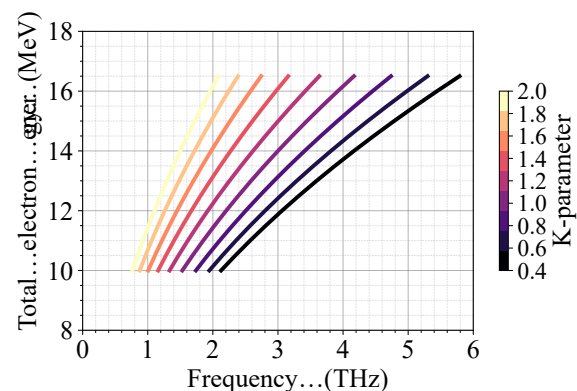


Figure 1: The relation between electron energy and radiation frequency as a function of radiation frequency for different undulator parameters (K), where the undulator period length is equal to 100 mm.

* Ekkachai_kong@cmu.ac.th

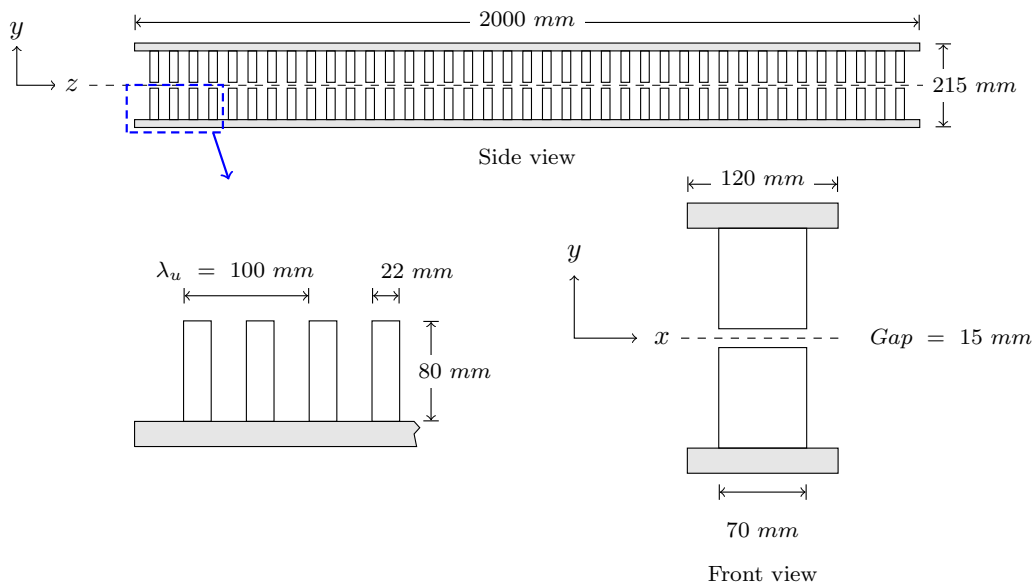


Figure 2: The 2D drawings of electromagnetic undulator and its dimensions without conducting coil.

ELECTROMAGNETIC UNDULATOR

Undulator Design

The electromagnetic undulator was designed by using the CST-EM Studio software [6] to provide a three-dimensional (3D) magnetic field (B_x, B_y, B_z). To bend electrons in horizontal direction, magnetic field in vertical direction (B_y) is used. Thus, in this study, we focus on the magnetic field B_y along the travelling axis (z-axis) of electron beam.

Based on the relation in Eq. (1), the period length (λ_u) of undulator magnet was calculated and its optimized value is equal to 100 mm. Therefore, based on the required THz radiation wavelength and the energy of electron beam produced from our accelerator, the maximum K-parameter of 2 was designed. The design parameters are listed in Table 1.

Table 1: PCELL Accelerator and Undulator Specifications

Parameter	Value
Electron kinetic energy	5-16 MeV
Bunch charge	100 pC
Energy spread	<3 %
Bunch length	100 fs
Undulator period length	100 mm
Undulator gap	15 mm
Number of periods	18.5 periods
Number of poles (including end poles)	39 poles
Undulator length	2 m

Figure 2 shows the dimensions of the designed electromagnetic undulator without a conducting coil. This undulator has 18.5 periods for the main poles and one period for the corrective poles resulting in the total of 39 periods.

Magnetic Simulation

To achieve 3D magnetic field distribution (B_x, B_y, B_z), CST-EM Studio software was used for simulation. With the optimum number of coil turns per pole of 236 turns, the average peak magnetic field is equal to 0.2267 T, which corresponds to the maximum applied current for main poles and correcting poles of 6 A and 3 A, respectively.

The simulation results of the vertical magnetic field (B_y) intensity along z-direction and x-direction are shown in Fig. 3 and Fig. 4, respectively. This magnet design has a magnetic field uniformity with the field difference of less than $0.9 \mu\text{T}$. For x-direction, the uniform magnetic field length is around 10.5 mm.

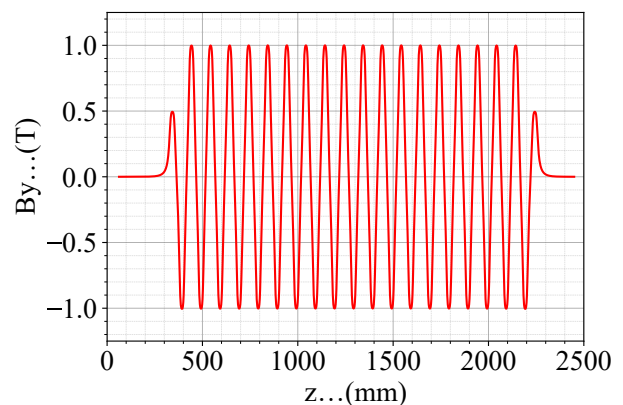


Figure 3: A normalized vertical magnetic field intensity B_y along z-direction obtained from CST-EM studio simulation.

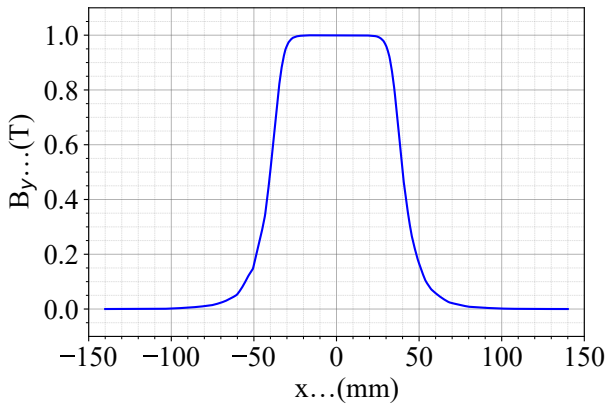


Figure 4: Simulated vertical magnetic field intensity B_y along x-direction.

Conducting Coil Design

The magnetic field of this undulator magnet can be adjusted by changing the applied electric current to the conducting coil. The optimized results from the simulation suggest that the optimum number of turns per pole is equal to 239 turns and the maximum applied current of 6 A is required to produce the maximum magnetic field is 0.2317 T. With this applied current, the conducting coil can work without cooling system. It was found from the optimization that the diameter of the wire for the conducting coil is 1.829 mm, which the copper wire No. 15 in the Standard Wire Gauge (SWG) can be used.

THZ RADIATION CALCULATION

Total pulse energy (W_{tot}) of radiation emitted from relativistic electron travelling through the undulator magnetic field is divided into two terms; incoherent and coherent radiations which can be defined as written Eq. (2) [5].

$$W_{tot} = W_{1e}N_e[1 - f(\omega)] + W_{1e}N_e^2f(\omega), \quad (2)$$

where W_{1e} is the radiated energy of single electron, and $f(\omega)$ is the longitudinal bunch form factor, which can be expressed as [5].

$$f(\omega, \sigma_t) = \exp(-\omega^2\sigma_t^2). \quad (3)$$

The bunch form factor [5] is used to describe the longitudinal distribution of the electrons in the bunch, which assumed to be the Gaussian-distribution in this study. This equation (Eq.(3)) is written as a function of radiation frequency (ω) and longitudinal Gaussian-length in term of the time domain bunch length (σ_t).

Therefore, the emitted energy of the electron is directly depends on the relationship between electron bunch length in space domain (σ_z) and radiation wavelength (λ_r). To reach the high radiation energy, the electron bunch length should be shorter than the required radiation wavelength ($\sigma_z \leq \lambda_r$). The energy of the coherent radiation term (W_{coh})

is proportional to the number of electron squared (N_e^2) and it can be calculated by [5].

$$W_{coh} = \frac{\pi e^2 N_u}{3\epsilon_0 \lambda_u} K^2 \gamma^2 N_e^2 f(\omega, \sigma_t), \quad (4)$$

where N_u is the number of undulator periods, γ is the Lorentz's factor of electron, and K is the undulator strength parameter.

With the optimized parameters as mentioned in the previous section, the radiation energy of the electron pulse can be calculated by using Eq. (2). The calculated radiation pulse energy is equal to 2.63 μ J at 1.15 THz, which corresponds to the peak power of about 5.21 MW.

CONCLUSION

The electromagnetic undulator for generating coherent THz radiation by using super-radiant technique has been developed at PCELL. The CST-EM Studio software was used to model and simulate the 3D magnetic field distribution of the undulator. The optimum undulator period length and gap are 100 mm and 15 mm, respectively. With the optimized design, the maximum magnetic field of 0.2317 T can be achieved by applying exiting current of 6 A to the conducting coil of 239 turns per coil. By utilizing optimized electron beam parameters together with this undulator design, the frequency of radiation can be adjusted in the range from 1 THz to 3 THz. The maximum pulse energy of radiation is equal to 2.63 μ J at 1.15 THz with the peak power of 5.21 MW. The results of this study are used as guideline for construction of the electromagnetic undulator and the super-radiant THz beamline at PCELL.

ACKNOWLEDGEMENTS

This research has received support from Chiang Mai University and NSRF via the Program Management Unit for Human Resource & Institutional Development, Research and Innovation [grant number B16F630068]. E. Kongmon would like to acknowledge the scholarship support from the Science Achievement Scholarship of Thailand (SAST).

REFERENCES

- [1] K. Fukunaga, *THz technology applied to cultural heritage in practice*, Springer, Japan, 2016.
- [2] E. Nichols and J. Tear, "Joining the infra-red and electric wave spectra", *The Astrophysical Journal*, vol. 61, pp. 17, 1925.
- [3] M. Tonouchi, "Cutting-edge terahertz technology", *Nature photonics*, vol. 1, no. 2, pp. 99-105, 2007. doi:10.1038/nphoton.2007.3
- [4] K. Sakai et al., *Terahertz optoelectronics*. Springer, Berlin Heidelberg, vol. 6, 2005.
- [5] J. A. Clarke, *The science and technology of undulators and wigglers*. vol. 4, Oxford University Press Inc., New York, 2004.
- [6] *CST Studio Suite 3D EM simulation and analysis software*, <http://www.cst.com/>, Accessed: 2021-12-21.