13th Int. Particle Acc. Conf. IPAC2022, Bangkok, Thailand JACoW Publishing
ISBN: 978-3-95450-227-1 ISSN: 2673-5490 doi:10.18429/JACoW-IPAC2022-TUPOPT027

NUMERICAL SIMULATION OF A SUPERRADIANT THz SOURCE AT THE PITZ FACILITY

N. Chaisueb*[1,2], P. Boonpornprasert[3], M. Krasilnikov[3], X-K. Li[3],
A. Lueangaramwong[3], S. Rimjaem[1,4]
[1]PCELL, PBP, Faculty of Science, Chiang Mai University, Chiang Mai, Thailand
[2]also at Ph. D. Program in Physics, Chiang Mai University, Chiang Mai, Thailand
[3]DESY, Platanenallee 6, Zeuthen, Germany
[4]also at ThEP Center, MHESI, Bangkok, Thailand

Abstract

An accelerator-based THz source is under development at the Photo Injector Test Facility at DESY in Zeuthen (PITZ). The facility can produce high brightness electron beams with high charge and small emittance. Currently, a study on development of a tunable high-power THz SASE FEL for supporting THz-pump, X-ray-probe experiments at the European XFEL is underway. An LCLS-I undulator, a magnetic chicane bunch compressor, and THz pulse diagnostics have been installed downstream the previously existing setup of the PITZ beamline. Additional to the SASE FEL, a possibility to generate superradiant THz undulator radiation from short electron bunches is under investigation, which is the focus in this study. Numerical simulations of the superradiant THz radiation by using sub-picosecond electron bunches with energy of 6 - 22 MeV and bunch charge up to 2 nC produced from the PITZ accelerator are performed. The results show that the radiation with a spectral range of 0.5 to 9 THz and a pulse energy in the order of sub-μJ can be obtained. The results from this study can be used as a benchmark for the future development.

INTRODUCTION

The PITZ facility can produce high brightness electron beam with small emittance by using a photocathode RF gun [1]. The photocathode laser system can generate various temporal pulse shapes including flattop, Gaussian, and 3D (ellipsoidal) profiles [2]. The electron bunches have a beam energy up to 22 MeV and a bunch charges up to 4 nC. The transverse emittance is around 1 - 10 mm.mrad and the energy spread is about 0.5%. The peak current of the present beamline can be adjusted up to 200 A.

The PITZ facility develops the RF electron guns for FLASH and the European XFEL [3, 4]. Thus, characteristics of the electron beam produced from the RF electron guns at PITZ and the European XFEL are identical. The European XFEL has planned to perform pump-probe experiments by using x-ray and THz pulses. The PITZ accelerator is suitable to be used to develop a prototype for a high power tunable THz source for this experiment because the THz radiation generated at PITZ will have the same pulse train structure and is synchronized with the x-ray pulses at the European XFEL [5]. The THz pump and X-ray probe experiment requires THz pulses with μJ - mJ pulse energies. Frequency of the emitted radiation covers the range of 0.1 - 30 THz, which is equivalent to a wavelength range of 3 mm - 10 μm [6]. There are four options to produce THz pulses at PITZ, including SASE FEL, seeded FEL, coherent transition radiation and superradiant FEL. This paper focuses on the superradiant or coherent undulator radiation technique. It requires ultra-short and high-charged electron bunches. When the electron bunch length is equal to or shorter than the radiation wavelength, the radiation emitted from different undulator poles overlaps and interferes constructively. This leads to coherent radiation pulse with intensity proportional to number of electron squared. Therefore, the possibility to generate the superradiant THz FEL from high brightness electron bunches produced at PITZ was investigated.

The basic setup of the accelerator and beamline at the PITZ facility consists of a photocathode RF gun, a booster cavity, and several electron beam diagnostics. To develop the beamline to be an intense THz source, a chicane bunch compressor, an LCLS-I undulator magnet, and THz pulse diagnostics have been inserted at the end of the previously existing setup. The LCLS-I undulator magnet, which is a planar permanent undulator magnet with a period length of 30 mm and an undulator parameter of 3.58, will be used as a radiation source. Specifications of the LCLS-I undulator magnet are shown in Table 1. The vacuum chamber of the undulator magnet is rather small. This significantly affects to electron beam dynamics and generation of the THz radiation.

Table 1: Specification of the LCLS-I Undulator Used at the PITZ Facility

Specifications	Value
Type	Planar
Period length (mm)	30
Number of periods	113
Total length (m)	3.42
Peak magnetic field (T)	1.28
Undulator parameter (K)	3.58
Vacuum chamber size (mm)	11×5

---

* natthawut_chai@cmu.ac.th

PARAMETER SPACE OF ELECTRON BEAM PROPERTIES

This section presents the influence of electron beam properties of the PITZ accelerator on characteristics of the superradiant THz pulse. The SPECTRA program [7] was used for superradiant radiation calculation in this study. One of the results from the SPECTRA program is the angular flux density, which refers to the number of photons emitted per second per solid angle into a relative photon energy bandwidth of 0.1%. To get a common optical property, the angular flux density is simplified to the spectral energy for a single electron. Then, the radiated energy of a single electron can be obtained by integrating over all frequencies [8]. Thus, the total pulse energy of an electron bunch is calculated from the radiated energy of a single electron, the number of electrons per bunch, and the bunch form factor. For parameter space study, the longitudinal distribution of the electron bunch was assumed to be the Gaussian distribution and thus the Gaussian form factor was used to calculate the total pulse energy expressed in this section.

Limitation of Coherent Part of Undulator Radiation

The coherent part of the total pulse energy relates to the bunch length of electron beam. Figure 1 shows the total pulse energy at the first harmonic for different electron bunch lengths based on the LCLS-I undulator specifications and the electron beam properties at PITZ. The bunch charge was fixed to 500 pC and the beam energy was varied from 6 to 22 MeV for tuning the radiation wavelength.

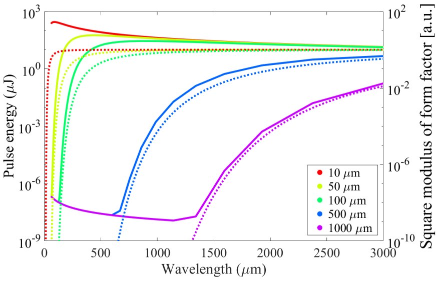

Figure 1: Pulse energy and square modulus of form factor at fundamental harmonic for electron beam with rms bunch lengths of 10, 50, 100, 500, and 1000 µm. Solid lines refer to the pulse energy and dot lines are square modulus of form factor.

The figure show that the pulse energy and the form factor drop significantly at wavelengths shorter than about the doubled bunch length. These present clearly the difference between incoherent and coherent radiations. The pulse energy of the coherent part is up to 10 - 100 µJ for a bunch length shorter than 100 µm. It is 10^9 times higher than that of the incoherent part. This conforms extremely to the theoretical suggestion that the coherent radiation is proportional to the number of electrons squared, while the incoherent radiation scales with the number of electrons. An electron beam with a shorter bunch length generates the undulator radiation with higher pulse energy.

Manipulation of Electron Bunch Length, Bunch Charge and Pulse Energy

Dependency of electron bunch length and bunch charge on total pulse energy of the superradiant undulator radiation was studied for the electron beam energies of 7, 8, 10, 17, and 22 MeV, which provide radiation with first harmonic frequencies of 0.5, 0.7, 1, 3, and 5 THz, respectively. From a technical note of terahertz science at European XFEL published in [6], many applications require intense THz radiation with pulse energy of at least 10 µJ for all frequencies. Thus, the limitation of dependency between bunch length and bunch charge to obtain the pulse energy of 10 µJ for different radiation frequencies was investigated as plotted in Fig. 2.

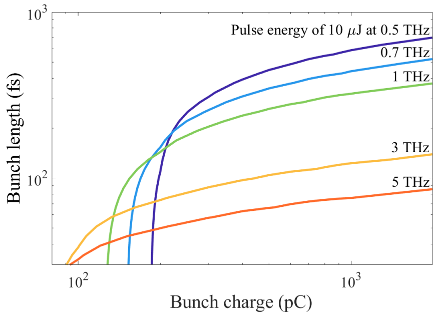

Figure 2: Dependence of bunch length and bunch charge of electron beam to get a THz pulse energy of 10 µJ for different frequencies at first harmonic.

The first noticeable point from Fig. 2 is the bunch charge should be greater than 90 - 200 pC in order to generate the superradiant THz radiation with pulse energy of 10 µJ at PITZ. The electron beam with lower average energy produces the radiation with a longer central wavelength. Thus, it can have a longer bunch length than that of the electron beam with higher average energy to achieve the same order of the radiation pulse energy. As an example at the bunch charge of 2000 pC, the possible highest bunch length is around 90 fs for a 22 MeV electron beam (relates to a frequency of 5 THz), while the possible highest bunch length of a 7 MeV electron beam (relates to a frequency of 0.5 THz) can be longer up to about 830 fs. This is consistent with electron beam production at PITZ. A higher energy electron beam can be compressed to have a shorter bunch length than a lower energy electron beam after passing through a bunch compressor.

PULSE ENERGY CALCULATION FROM SIMULATED ELECTRON BEAM

Start-to-end (S2E) beam dynamic simulations of 17 MeV electron beams with bunch charges of 10 - 2000 pC were performed by [9]. In the simulation, the electron beam was produced from a photocathode RF gun and accelerated through the booster cavity to the chicane entrance by using the ASTRA code. Then, the simulation from the chicane to the undulator entrance was carried out by using program IMPACT-T [10]. For each bunch charge, the booster phase was optimized to get a result of full compression or the shortest rms bunch length at the undulator entrance. The optimization results show that the rms bunch length covers from 200 - 1600 fs for the bunch charge of 10 - 2000 pC.

To calculate the total pulse energy of the superradiant radiation, the bunch form factor should be evaluated first by assuming the electron beam as the Gaussian distribution or using the Fourier transform of the longitudinal beam profile. The simulated electron beams with different bunch charges have not only different bunch lengths but also various longitudinal beam distributions as illustrated in Fig. 3. These indicate that the longitudinal profile of the electron beam after passing through the magnetic chicane is a non-Gaussian distribution due to the space charge effects and the coherent synchrotron radiation effect in the chicane.

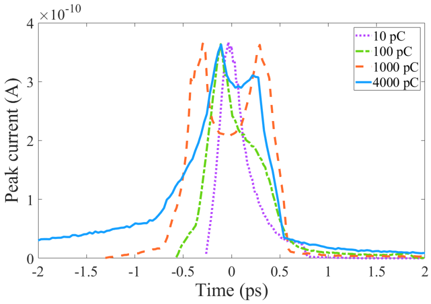

Figure 3: Longitudinal profiles of simulated electron beams for bunch charges of 10, 100, 1000, and 4000 pC.

The form factor calculated from the Fourier transform of the longitudinal beam profile was chosen for evaluating the total pulse energy in this section. The longitudinal profiles of the simulated electron beam with bunch charges of 10, 100, 1000, and 4000 pC (Fig. 3) were used to calculate square modulus of the form factor shown in Fig. 4. The electron beam profile with a short bunch length provides a broad form factor and thus the coherent part of the superradiant radiation occupies a broad frequency range.

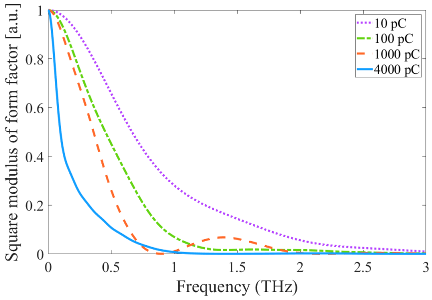

Figure 4: Square modulus of form factor for bunch charges of 10, 100, 1000, and 4000 pC.

Electron beam properties from the S2E simulation were used to calculate the total pulse energy of an electron bunch. The simulated electron beam has an energy of 17 MeV and produces the radiation with central frequencies of 3, 9, and 15 THz for the first, third, and fifth harmonics, respectively. The result in Fig. 5 shows that the total pulse energy at the first harmonic is in the order of sub-nJ to 100 nJ. The maximum pulse energy can be reached at the electron bunch charge of around 600 - 700 pC because the rms bunch length drops significantly and resulting in appropriate manipulation between bunch length and bunch charge. The pulse energy at the third and fifth harmonics is lower than 0.01 nJ. To get higher pulse energy, the bunch length should be shorter at all bunch charges. Dashed lines refer to FWHM bandwidth of the spectrum for the first three harmonics. The spectral bandwidths of all harmonics get broader when the electron bunch charge is higher as a result of larger energy spread.

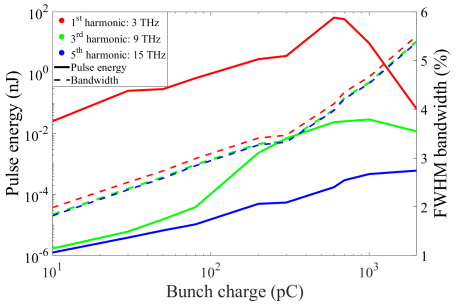

Figure 5: Radiation pulse energy of simulated electron beam with bunch charge of 10 - 2000 pC.

SUMMARY AND OUTLOOK

The superradiant THz radiation at the PITZ facility was calculated by using the SPECTRA program. From the parameter space study, a total pulse energy of 10 μJ within the frequencies of 0.5 - 5 THz and 5 - 9 THz can be accomplished at the first and third harmonics, respectively, if an electron beam has average energy of 7 - 22 MeV, bunch charge of 90 - 2000 pC, and bunch length of 90 - 830 fs. However, the results from S2E simulation show that the superradiant radiation with total pulse energy in the order of sub-μJ at the first harmonic can be produced from 17 MeV electron beam with bunch charge of 10 - 2000 pC and bunch length of 200 - 1600 fs. To get higher pulse energy, the operating parameters of the PITZ beamline, such as laser pulse length, gun phase, and quadrupoles matching upstream the chicane, should be optimized more in order to achieve a short electron bunch. In addition, a low-energy electron beam should be considered because it generates a long central wavelength and thus the acceptable bunch length can be longer to perform the coherent radiation.

ACKNOWLEDGEMENTS

This research has received supports from Chiang Mai University and the NSRF via the Program Management Unit for

Human Resources & Institutional Development, Research and Innovation [grant number B16F630068]. The authors are grateful to the generous support from the European XFEL research and development program. We would like to express essential gratitude to Dr. Takanori Tanikawa from EU-XFEL, Hamburg, Germany for valuable recommendations about the SPECTRA program.

REFERENCES

[1] M. Krasilnikov *et al.*, "Experimentally minimized beam emittance from an *L*-band photoinjector", *Phys. Rev. ST Ac-cel. Beams*, vol. 15, pp. 100701, Oct. 2012. `doi:10.1103/PhysRevSTAB.15.100701`

[2] C. Koschitzki *et al.*, "Status of Chirped Pulse Laser Shaping for the PITZ Photoinjector", in *Proc. FEL'19*, Hamburg, Germany, Aug. 2019, pp. 437–439. `doi:10.18429/JACoW-FEL2019-WEP050`

[3] Y. Renier *et al.*, "Statistics on High Average Power Operation and Results from the Electron Beam Characterization at PITZ", in *Proc. IPAC'17*, Copenhagen, Denmark, May 2017, pp. 1806–1808. `doi:10.18429/JACoW-IPAC2017-TUPIK051`

[4] F. Stephan *et al.*, "Detailed characterization of electron sources yielding first demonstration of European X-ray Free-Electron Laser beam quality", *Phys. Rev. ST Accel. Beams*, vol. 13, pp. 020704, Feb. 2010. `doi:10.1103/PhysRevSTAB.13.020704`

[5] M. Krasilnikov, F. Stephan, E. Schneidmiller, and M. V. Yurkov, "Tunable IR/THz Source for Pump Probe Experiments at the European XFEL", in *Proc. FEL'12*, Nara, Japan, Aug. 2012, paper WEPD55, pp. 503–506.

[6] P. Zalden *et al.*, *Technical note: Terahertz Science at European XFEL Version 1.0*, 2018.

[7] T. Tanaka, "Major upgrade of the synchrotron radiation calculation code *SPECTRA*", *Journal of Synchrotron Radiation*, vol. 28, pp. 1267–1272, Jul. 2021. `doi:10.1107/S1600577521004100`

[8] T. Tanikawa *et al.*, "A superradiant THz undulator source for XFELs", *Journal of Instrumentation*, vol. 14, pp. 05024, May 2019, `doi:10.1088/1748-0221/14/05/p05024`

[9] A. Lueangaramwong *et al.*, "Numerical Study of Beam Dynamics in PITZ Bunch Compressor", in *Proc. IPAC'21*, Campinas, Brazil, May 2021, pp. 3285–3288. `doi:10.18429/JACoW-IPAC2021-WEPAB274`

[10] J. Qiang, *IMPACT-T User Document Beta Version 2.0*, 2021.