ISBN: 978-3-95450-210-3 doi:10.18429/JACoW-FEL2019-TUP015

DESIGN OF HIGH-REPETITION TERAHERTZ SUPER-RADIATION BASED ON CAEP THz FEL SUPERCONDUCTING BEAMLINE*

D. Wu, K. Zhou, L. G. Yan, P. Li†, J. X. Wang, L. B. Li, Q. Pan, D. X. Xiao,
X. Luo, H. B. Wang, X. M. Shen, P. Zhang, L. J. Shan, T. H. He, M. Li
Institute of Applied Electronics, China Academy of Engineering Physics, Mianyang, 621900, China

Abstract

China Academy of Engineering Physics terahertz free electron laser (CAEP THz FEL, CTFEL) is the first THz FEL oscillator in China. CTFEL spectrum covers from 0.7 THz to 4.2 THz. However, there are still many applications requiring lower frequency. The super-radiation of the ultra-short electron beam bunches could generate ultra-fast, carrier-envelope-phase-stable, and high-field terahertz. The coherent diffraction/transition radiation (CDR/CTR) and coherent undulator radiation (CUR) can be also synchronized naturally. In this paper, the dynamic and the design of the super-radiation are introduced. The main parameters of the CDR/CTR and CUR are also discussed. A multi-color pump-probe system based on super-radiation is also proposed.

INTRODUCTION

CAEP THz FEL (CTFEL) facility is the first high average THz source based on FEL in China [1, 2], which is driven by a DC gun with a GaAs photocathode [3, 4] and two 4-cell 1.3 GHz super-conducting radio frequency (SRF) accelerator [5, 6]. The repetition rate of CTFEL is 54.167 MHz, one over twenty-four of 1.3 GHz. The effective accelerating field gradient is about 10 MV/m.

CTFEL has achieved the stimulated saturation in August, 2017[7, 8]. The terahertz frequency is continuously adjustable from 0.7 THz to 4.2 THz.

The upgrade of CTFEL is to broaden its spectrum and improve its power. There are many applications on condensed matter physics in the spectrum from 0.1 THz to 1.5 THz, such as control of antiferromagnetic spin waves[9], resonant and nonresonant over matters[10], magnetic order [11], the 2D materials[12], and so on. So, it is important to cover the lower frequency domain, and afford a high-repetition, carrier-envelope-phase-stable THz source.

When the electron beam bunch is compressed to less than 1 ps, et, less than the wavelength of THz wave, the terahertz coherent radiation will be generated as transition radiation, diffraction radiation, synchrotron radiation, or undulator radiation, which are often called as super-radiation. In this paper, a beamline is design based on CTFEL to generate a multi-color THz beams with Coherent Diffraction/Transition Radiation (CDR/CTR) and Coherent Undulator Radiation (CUR). The repetition can reach up to 54 MHz, and the pulse energy is more than 0.1 μJ.

BEAMLINE DESIGN

Figure 1 shows the layout of the CTFEL facility. High average power high-brightness electron beam is emitted from the high-voltage DC gun equipped with a GaAs photocathode. The beam is then energized by a 2×4-cell RF superconducting accelerator and gain kinetic energy from 6 MeV to 8 MeV. Passing through an achromatic section, the beam then goes into the undulator magnet field and generates spontaneous radiation. The radiation resonates in the THz optical cavity and reaches saturations.

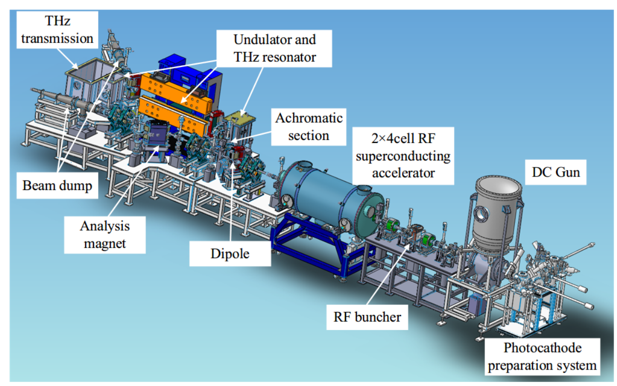

Figure 1: The layout of CTFEL facility.

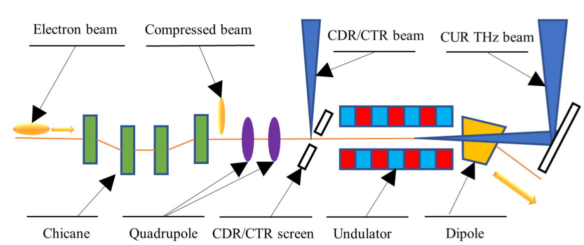

Figure 2: Schematic diagram of the super-radiation beam line.

When the electron pass straight downstream the SRF cavity, it can be used to generate the super-radiation. The schematic is shown on Fig. 2. The chirped bunch firstly passed through a chicane to be compressed, and then a screen with a hole to generate CDR beam (or CTR beam without a hole), then a short undulator to generate CUR beam.

* Work supported by National Natural Science Foundation of China with grant (11575264, 11605190 and 11805192), Innovation Foundation of CAEP with grant (CX2019036, CX2019037)
† burnlife@sina.com

ISBN: 978-3-95450-210-3 doi:10.18429/JACoW-FEL2019-TUP015

DYNAMIC SIMULATION

There are two ways to achieve ultra-fast electron beam, by velocity bunching or by chicane. Figure 3 (a) shows the ultra-fast beam's longitudinal phase space compressed by velocity bunching. The undulator is located 12 m downstream of the cathode. The velocity bunching keeps the longitudinal rms length of the beam less than 200 fs within 1 m (as shown in Fig. 3 (b)), which is enough to place a CTR/CDR target and and 10-period short undulator. The energy spread is wider than the requirement of free electron laser but it has less effect on super-radiation. One of the superconducting cavity is used to be as a buncher, so the energy of the electron beam is a little low, as shown in Fig. 3 (c). The kinetic energy is about 5.2 MeV, which will reduce the with of CDR/CTR spectrum.

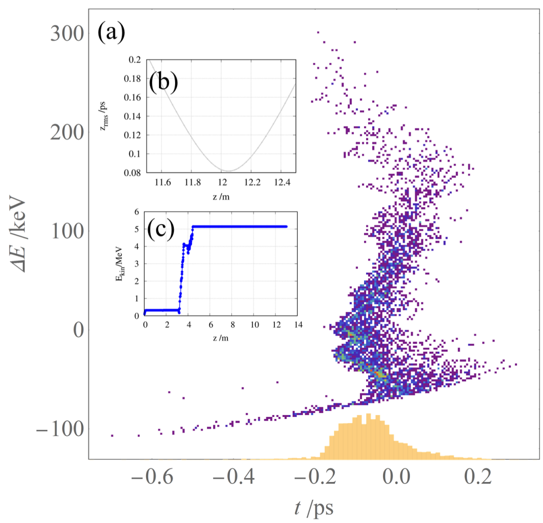

Figure 3: Longitudinal phase space of the electron beam compressed by velocity bunching.

When the chicane is on, the longitudinal distribution grows wider than the velocity bunching because of the coherent synchrotron radiation (CSR), as shown in Fig. 4 (a). However, the length increases much slower after the longitudinal focal point, as shown in Fig. 4 (b). And the energy of the electron beam could be larger than 7 MeV to generate a broader spectrum.

SUPER-RADIATION CALCULATION

When an electron beam generate a coherent radiation, its energy spectrum can be described as:

$$U(\omega) = U_e(\omega)[1 + N(N-1)F(\omega)], \tag{1}$$

where U_e is the spectrum generated by a single electron, it differs from the radiation type, such as undulator radiation (UR), diffraction radiation (DR) or transition radiation (TR), and so on; N is the electron number, and $F(\omega)$ is called the form factor. Ignoring the horizontal effects, the form factor

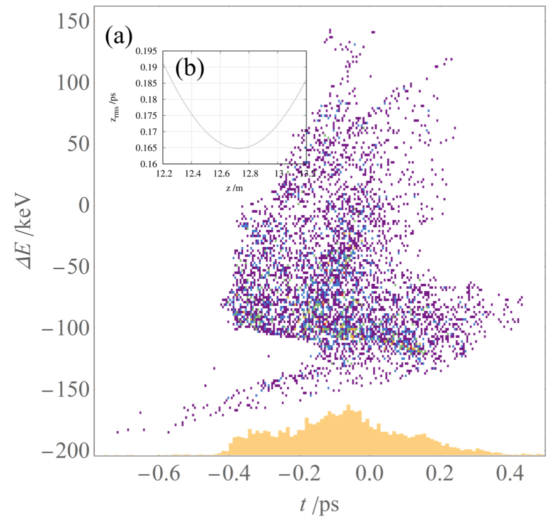

Figure 4: Longitudinal phase space of the electron beam compressed by a chicane.

can be written as:

$$F(\omega) = |\int_{-\infty}^{\infty} \rho_{long}(t)\exp(-i\omega t)\mathrm{d}t|^2, \tag{2}$$

where $\rho_{long}(t)$ is the longitudinal distribution of the beam.

When the diffraction radiation happens, the single electron spectrum $U_{e,DR}$ is[13]:

$$\frac{d^2U_{e,DR}}{d\omega d\Omega} = \frac{e^2}{4\pi^3\varepsilon_0 c}\frac{\beta^2\sin^2\theta}{(1-\beta^2\cos^2\theta)^2}T(\theta,\omega), \tag{3}$$

where

$$T(\theta,\omega) = [T_b(\theta,\omega) - T_a(\theta,\omega)]^2,$$

$d^2U_e/(d\omega d\Omega)$ is the radiation energy distribution of DR when a single electron passes into an infinite metal radiator, e is the electron charge, ε_0 is the vacuum dielectric constant, c is the speed of light in vacuum, and β is the relativistic speed of the electron. T is the form factor of the radiator, $T_b(\theta,\omega)$ is determined by the radius of the aperture b and $T_a(\theta,\omega)$by the entire radiator a, ω is the frequency, θ is the observation angle relative to direction of the beam, Ω is the solid angle of radiation. When b equals to 0, the DR becomes TR.

Considering only the fundamental mode of the undulator radiation, the single electron spectrum $U_{e,UR}$ is:

$$\frac{d^2U_{m,UR}}{d\Omega d\omega} = \frac{e^2\gamma^2K^2}{4\pi\varepsilon_0 c\left(1+K^2/2\right)^2}\cdot M_u(\omega)\cdot|JJ|^2, \tag{4}$$

where

$$M_u(\omega) = \frac{\sin^2\left(\pi N_u\left(\omega-\omega_1\right)/\omega_1\right)}{\sin^2\left(\pi\left(\omega-\omega_1\right)/\omega_1\right)},$$

$$JJ = J_0\left(\frac{K^2}{4+2K^2}\right) - J_1\left(\frac{K^2}{4+2K^2}\right),$$

ISBN: 978-3-95450-210-3 doi:10.18429/JACoW-FEL2019-TUP015

J is bessel function, and $K = 0.934 \cdot B_0[\mathrm{T}] \cdot \lambda_u[\mathrm{cm}]$ is called *undulator parameter*, $\lambda_1 = \frac{\lambda_u}{2\gamma^2}\left(1 + K^2/2\right)$, is the center wavelength of the fundamental mode, N_u is the period number of the undulator.

Considering a bunch charge of 100 pC, an RMS bunch length of 200 fs, an undulator period of 5 cm, and an undulator period number of 10, the different radiation energy spectrum can be calculated. The results are shown in Fig. 5. The super-radiation will be ultrafast, high-energy, and high-repetition. The pulse energy is mostly more than 100 nJ, and the peak power is more than 25 kW. The peak power of CTR is more than 1 MW. When the CTR radiation is focous within a diameter of 1 mm, the peak electronic field would be about 0.5 MV/cm.

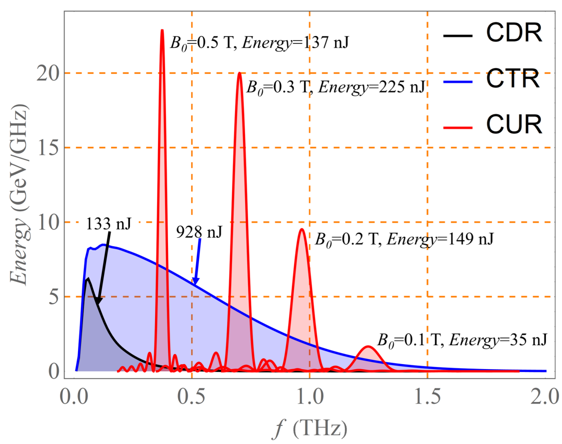

Figure 5: The radiation energy spectrum with different radiation types.

Simulations using the SPECTRA code [14] were performed with these parameters and the result is presented in Fig. 6. The peak frequencies of radiation under different magnetic fields are consistent with the theoretical calculations, but with wider bandwidth. The reason is because the off-axis frequency is not the same as the frequency on the axis, and is included in simulation.

MULTI-COLOR PUMP-PROBE DESIGN

To build a multi-color pump-probe system, it is important to make sure the synchronization between the pump and the probe. Because the CDR/CTR and CUR are generated by the same beam bunch, they are synchronized naturally. The jitter is mostly caused by the trajectory difference between micro-pulses. In addition, the drive laser itself and THz induced by the ultra-fast laser can be the pump beam, too. The multi-color pump-probe system is shown in Fig. 7.

SUMMARY

This paper has briefly introduced a super-radiation system based on the CAEP THz FEL facility. The coherent diffraction/transition radiation (CDR/CTR) and coherent undulator radiation (CUR) can be synchronized naturally. And these

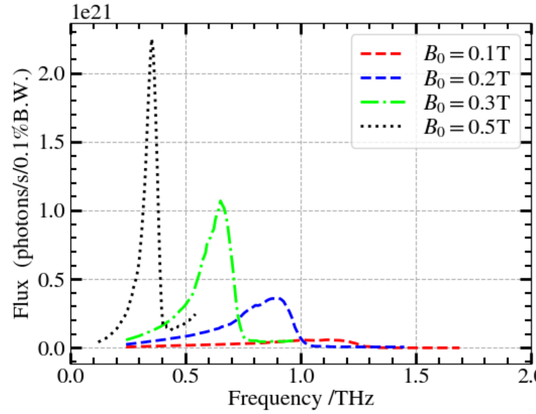

Figure 6: The super-radiation spectrum calculated by SPECTRA.

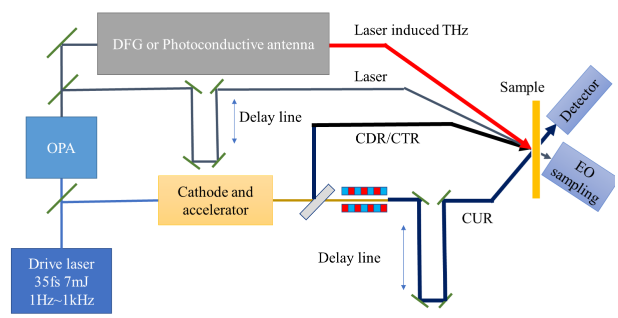

Figure 7: Schematic diagram of multi-color pump probe system.

super-radiation source can be ultra-fast with high repetition and CEP stable. The simulation and calculation indicate that the radiation duration can be less than 200fs rms, and the pulse energy can reach almost 1 μJ, which makes the peak field be about 0.5 MV/cm. Combined with the drive laser, OPA system and laser induced THz, a multi-color pump-probe system can be estabilished, which will greatly expand the application of CTFEL facility.

REFERENCES

[1] Y.-H. Dou, X.-J. Shu, and Y.-Z. Wang, "3d-simulations of transverse optical modes of the free electron laser resonator with hole output coupling," *Communications in Computational Physics*, vol. 1, no. 5, pp. 920–929, 2006.

[2] P. Li, Y. Jiao, W. Bai, H. B. Wang, X. H. Cui, and X. K. Li, "Start-to-End Simulation of CAEP FEL-THz beamline," *High Power Laser and Particle Beams*, vol. 26, pp. 213–217, 2014.

[3] H. Wang, K. Li, M. Li, D. Wu, D. Xiao, and X. Yang, "A GaAs photoemission DC gun for CAEP high-average-power THz FEL," *Proceedings of FEL 2014*, 318–321, paper TUA03, 2014.

[4] D. Wu *et al.*, "Studies on factors affecting the life-time of high average current GaAs photocathode," in *Proceedings of SAP2014*, Lanzhou, China, 2014, 12–15, paper WEAMH6.

ISBN: 978-3-95450-210-3 doi:10.18429/JACoW-FEL2019-TUP015

[5] X. Luo *et al.*, "Design and fabrication of the 2x4-cell superconducting linac module for the free-electron laser," *Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment*, vol. 871, pp. 30–34, 2017, ISSN: 0168-9002. DOI: 10.1016/j.nima.2017.06.058

[6] K. Zhou *et al.*, "Progress of the 2×4-cell superconducting accelerator for the CAEP THz-FEL facility," in *Proceedings of the 18th International Conference on RF Superconductivity*, Lanzhou China, Jul. 2017. DOI: 10.18429/JACoW-SRF2017-MOPB037

[7] M. Li *et al.*, "First lasing of CAEP THz free electron laser," *High Power Laser Particle Beams*, vol. 29, no. 10, p. 1, 2017.

[8] M. Li *et al.*, "Experimental study on the stimulated saturation of terahertz free electron laser," *Acta Physica Sinica*, vol. 67, no. 8, p. 84 102, 2018.

[9] T. Kampfrath *et al.*, "Coherent terahertz control of antiferromagnetic spin waves," *Nature Photonics*, vol. 5, no. 1, p. 31, 2011. DOI: 10.1038/nphoton.2010.259

[10] T. Kampfrath, K. Tanaka, and K. A. Nelson, "Resonant and nonresonant control over matter and light by intense terahertz transients," *Nature Photonics*, vol. 7, no. 9, p. 680, 2013. DOI: 10.1038/nphoton.2013.184

[11] S. Kovalev *et al.*, "Selective THz control of magnetic order: new opportunities from superradiant undulator sources," *Journal of Physics D: Applied Physics*, vol. 51, no. 11, p. 114 007, 2018. DOI: 10.1088/1361-6463/aaac75

[12] H. A. Hafez *et al.*, "Extremely efficient terahertz high-harmonic generation in graphene by hot dirac fermions," *Nature*, vol. 561, no. 7724, p. 507, 2018. DOI: 10.1038/s41586-018-0508-1

[13] S. Casalbuoni, B. Schmidt, P. Schmüser, and B. Steffen, "Far-infrared transition and diffraction radiation," DESY, Tech. Rep., 2005.

[14] T. Tanaka and H. Kitamura, "SPECTRA: a synchrotron radiation calculation code," *Journal of Synchrotron Radiation*, vol. 8, no. 6, pp. 1221–1228, 2001. DOI: 10.1107/S090904950101425X