START-TO-END SIMULATION ON TERAHERTZ SUPERRADIATION OF ULTRASHORT ELECTRON BUNCH IN AN UNDULATOR*

Xiaolu Su, Lixin Yan[†], Dan Wang, Zhen Zhang, Yingchao Du, Wenhui Huang, Chuanxiang Tang,
Department of Engineering Physics, Tsinghua University, Beijing 100084, China

Abstract

The narrowband, intense and frequency-tunable THz radiation can be generated by letting an ultrashort electron bunch pass through an undulator. Start-to-end simulation of terahertz radiation from electron bunch in an undulator is studied in this paper. GPT code is used to track particle distribution from the photocathode RF gun to the entrance of the undulator and Genesis 1.3 is applied to simulate the radiation. The simulation results agree well with theoretical predictions.

INTRODUCTION

The scientific and engineering phenomena lying in the terahertz (THz) spectral region has become one of the most exciting areas today [1]. Terahertz sources based on relativistic electrons has various emission mechanisms, such as free electron laser (FEL) [2], coherent transition radiation (CTR) [3], coherent synchrotron radiation (CSR) [4], Cerenkov radiation [5] and Smith-Purcell radiation [6], which include both narrowband and broadband THz sources [7].

When the electron bunch length is much shorter than the radiation wavelength, the radiation is coherent. The total emitted radiation field is proportional to the electron number and the radiation power is proportional to the square of the number [8]. The superradiation would increase power and energy by many orders of magnitude. The energy spectrum of coherent radiation is expressed in

$$\frac{d^2 I}{d\omega d\Omega} = \frac{d^2 I_{sp}}{d\omega d\Omega}[\mathrm{N} + \mathrm{N}(\mathrm{N}-1)\,\mathrm{F}(\omega)], \quad (1)$$

where $\frac{d^2 I_{sp}}{d\omega d\Omega}$ is the energy spectrum of a single electron, $\omega = 2\pi c / \lambda$ is the angular frequency of the emit-

ted light, N is the number of electrons in a bunch, $\mathrm{F}(\omega)$ is the bunch form factor defined as the square of the Fourier transform of the particle distribution within the bunch. For a Gaussian distribution bunch with rms bunch length σ_t, the form factor is:

$$\mathrm{F}(\omega) = \exp[-(\omega\sigma_t)^2]. \quad (2)$$

In this paper, we perform start-to-end(S2E) simulation of terahertz superradiation from an ultrashort electron bunch in an undulator. The simulation parameters are based on Tsinghua Thomson scattering X-ray(TTX) source [9], which is shown in Figure 1. A modified version of the BNL/KEK/SHI type 1.6 cell photocathode radio-frequency (RF) gun and a 3 m SLAC-type traveling wave accelerating section are used to generate ultrashort, high-brightness beams. A Ti:sapphire laser system provides ultraviolet driving laser for the photocathode RF gun. A magnetic chicane following the accelerating section is used to compress the electron bunch to less than 100fs. GENERAL PARTICLE TRACER (GPT) code [9] and Genesis 1.3 [10] are respectively used to simulate the beam dynamics and the undulator radiation.

SIMULATION PROCESS

The process of the S2E simulation in this paper is similar to Ref. [11]. The detailed process is illustrated in Figure 2. The electron beam is tracked from the photocathode RF gun to the chicane with GPT, accelerated off the maximum accelerating phase and compressed by chicane. The particles are dumped at the exit of chicane and analysed to get some statistic parameters of the bunch, such as bunch emittance, transverse beam size, energy spread. Usually Genesis will regenerate macroparticles based on these statistical characteristics. However, if there is a
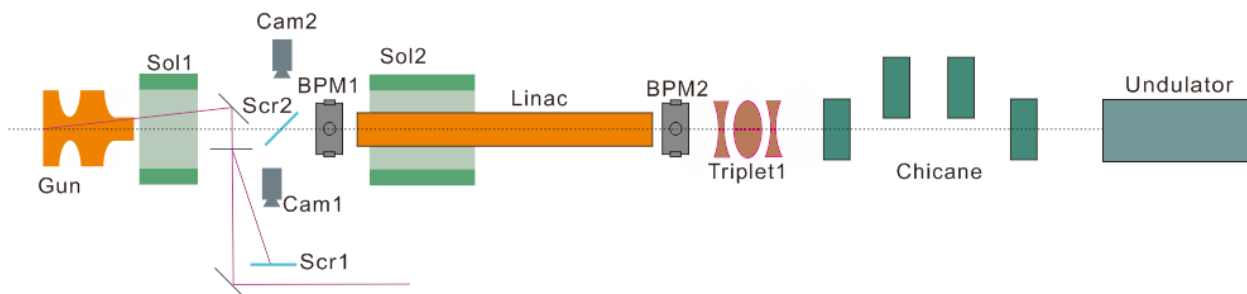

Figure 1: Schematic of the TTX beamline for Terahertz superradiation in an undulator.

02 Photon Sources and Electron Accelerators

T15 Undulators and Wigglers

narrow spike distribution in the beam current profile, which can be generated by the upstream chicane compression, the resampled method does not apply, not representing the real longitudinal distribution. Here a modified method is used to simulate the superradiation in an undulator with Genesis when the bunch length is much shorter than the radiation wavelength. The statistic parameters are used as input parameters of Genesis steady-state mode and the output macroparticles are used as the particle file of a slice. The particle phase of the dumped file is modified according to the radiation wavelength as well as the particle longitudinal distribution from GPT simulation. Then the initial longitudinal distribution of the beam can be reserved in Genesis. In addition, as the bunch length is much shorter than the radiation wavelength, time-dependent simulation does not work in this case. With the dumped slice and modified slice mentioned above, we perform steady-state simulation for one undulator period and then dump the particle and field distribution files. Slippage is manually added to the radiation field and then they are imported as the input for the next period simulation. The outputs of every undulator period are recorded and used for post procedure of radiation spectrum and energy.
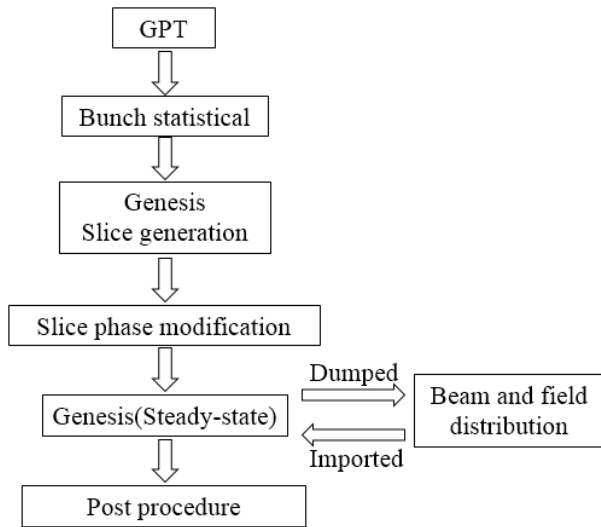

Figure 2: The process of the S2E simulation of ultrashort bunch in an undulator.

SIMULATION RESULTS

The typical simulation parameters used in GPT is shown in Table 1. The parameters are based on the experimental setup of TTX beamline. In these simulations, the linac phase is set 30 degrees off the maximum accelerating phase to produce energy chirp before chicane compression. The chicane current can be varied to control bunch compression from under-compression to over-compression. The rms bunch length could be compressed to tens of femtoseconds with proper chicane settings.

A planar undulator with adjustable gap is used in the simulation. The main parameters of the undulator and electron bunch are listed in Table 2. The resonant fre-

quency vs magnetic gap with different bunch energy is shown in Figure 3. The resonant frequency covers 0.1-20THz with proper beam energy and undulator gap.
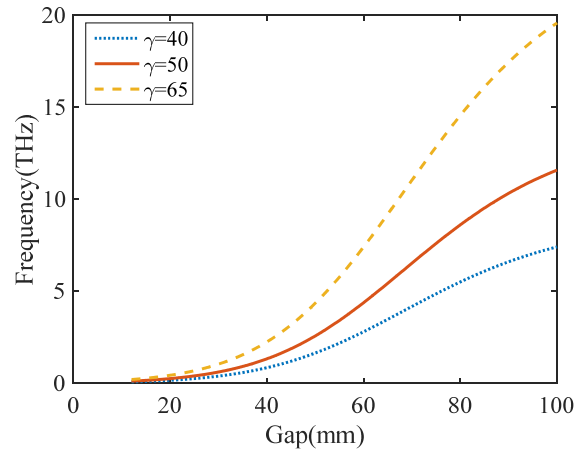

Figure 3: Resonant frequency vs magnetic gap with different bunch energy.

Table 1: GPT Simulation Parameters

Parameter	Value
Laser duration(quasi flattop)	8 ps
Laser spot size on cathode	500 μm(rms)
Peak field on cathode	110 MV/m
Phase of rf gun	25 degrees
Thermal emittance	0.9 mm-mrad/mm
Peak field in linac	11 MV/m
Charge	700pC

Table 2: Radiation Simulation Parameters

Parameter	Value
Undulator period	100mm
Undulator Gap	12-100mm
Undulator parameter[*]	0.54-10.88
Number of Undulator periods	15
Beam energy(γ)	65
Rms bunch length	20fs

We scan the resonant frequency while keeping the bunch energy and length constant and present the corresponding total emission energy in Figure 4. The simulation results are in agreement with the theoretical predictions [12]. At low resonant frequency, the emission energy is limited by diffraction effect and for high resonant frequency, the limiting factor is smaller form factor. With constant bunch parameters and undulator gap, the relation between total radiation energy and bunch charge is shown in Figure 5. The simulated results and theory calculation agree well and both are close to the quadratic fit, which means that the total radiation energy is proportional to the

---

[*] $K = \dfrac{eB_{rms}}{mck_u}$, $B_{rms} = B_{peak}/\sqrt{2}$ for planar undulator.

square of the electron number in the bunch. The comparisons between simulation and theory verify the modified method to simulate superradiation of an ultrashort electron bunch in an undulator, which can be used further to simulate more complex cases, such as bunch train superradiation. The total radiation energy of ultrashort bunch superradiation in an undulator can be up to several mJ per pulse and the peak power can reach several GW. The spectrum of the radiation at different undulator periods is shown in Figure 6, the narrowband characteristic is determined by undulator radiation mechanism.
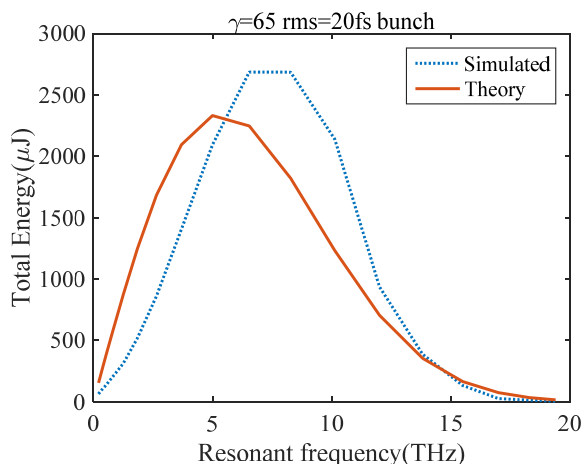

Figure 4: Comparison of total radiation energy vs resonant frequency (magnetic gap) between simulated and theoretical results.
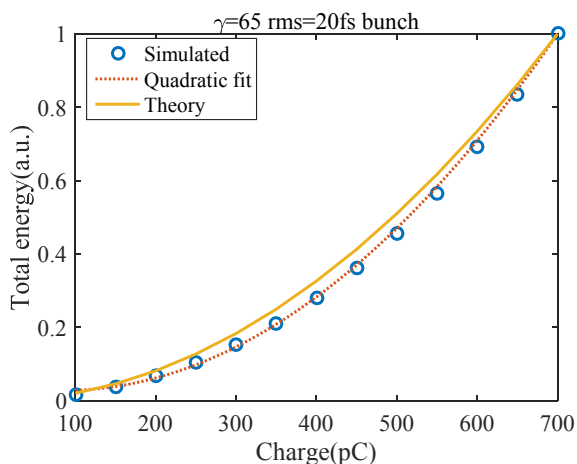

Figure 5: Total radiation energy vs charge with constant bunch property and resonant frequency (magnetic gap).
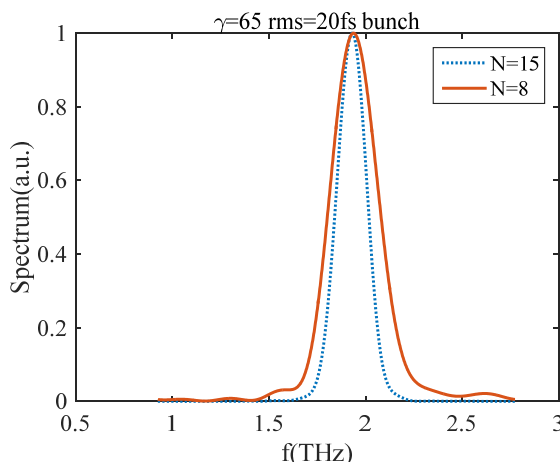

Figure 6: Spectrum of the THz radiation at different undulator periods.

CONCLUSION

In this paper, the superradiation of ultrashort bunch in an undulator is simulated from start to end. A modified method is used to simulate the superradiation with Genesis and the simulation results agree well with theoretical predictions. The total THz radiation energy can reach up to several mJ, which makes it be a promising source for high-power narrow-band THz radiation. The experimental measurement will be implemented at Tsinghua Thomson scattering X-ray (TTX) beamline recently.

ACKNOWLEDGEMENT

REFERENCES

[1] Shumyatsky, P. *et al.*, 2011 J. Biomed. Opt. 16 033001.

[2] Williams, G. P. Rev. Sci. Instrum., 2002, 73(3): 1461-1463.

[3] Casalbuoni, S. *et al.*, Phys. Rev. ST Accel. Beams, 2009, 12(3): 030705.

[4] Abo-Bakr, M. *et al.*, Phys. Rev. Lett., 2003, 90(9): 094801.

[5] Cook, A. M. *et al.*, Phys. Rev. Lett., 2009, 103(9): 095003.

[6] Korbly, S. E. *et al.*, Phys. Rev. Lett., 2005, 94(5): 054803.

[7] Carr, G. L. *et al.*, Nature, 2002, 420(6912): 153-156.

[8] Gover, A. Phys. Rev. ST Accel. Beams, 2005, 8(3): 030701.

[9] Du, Y. *et al.*, Rev. Sci. Instrum., 2013, 84(5): 053301. http://www.pulsar.nl/gpt

[10] Reiche, S. Nucl. Instrum. Methods Phys. Res. A, 1999, 429(1): 243-248.

[11] Yan, J. *et al.*, Nucl. Instrum. Methods Phys. Res. A, 2010, 615(3): 249-253.

[12] Gover, A. *et al.*, Phys. Rev. ST Accel. Beams, 2005, 8(3): 030702.