RESEARCH ON A TERAHERTZ COHERENT TRANSITION RADIATION SOURCE BASED ON ULTRASHORT ELECTRON BEAM *

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Abstract

In this paper, the characteristics of terahertz coherent transition radiation generated from the interaction of cylindrical electron bunch with a finite target are analyzed through the numerical calculation, and the radiation characteristics are investigated by the particle-in-cell (PIC) three-dimensional simulations. The simulation results of field distributions are in good agreement with that of the theoretical calculations.

INTRODUCTION

The THz sources, a currently active research area, are of importance in varieties of applications [1,2] in the far-infrared spectroscopy, medical and industrial imaging, biomedical research and material science. Various schemes for generating THz waves have been employed, such as QCL[3], ultrafast laser pluses and the vacuum electron devices. Recently it has been reported that the ultrabroadband terahertz radiation based on coherent transition radiation can be generated from the short electron bunches [4].This intense THz source offers unique opportunities for studying a variety of science matters including nonlinear optical phenomena.

Coherent radiation occurs at wavelengths longer than, or comparable to, the bunch length of the electron beam, with an intensity that scales with N^2, where N is the number of electrons in the bunch, and typically ranges from 10^8–10^9 for an electron accelerator. The radiation pulse created by such a bunch can be subpicosecond in time and therefore contains coherent spectral content up to a few THz, the radiation of single-cycle can reach ~100 μJ .In this paper, THz CTR produced from picosecond ultrashort relativistic electron bunches is analyzed, the characteristics of THz CTR are studied with the help of three-dimensional PIC simulation

PHYSICAL MODEL

We consider a single electron moving toward a finite target consisting of Titanium foil, which is considered as a perfect conductor, then $\varepsilon \to \infty$, the electric distribution expression of TR generated from the finite size of target can be given [5]:

$$E_x(\theta,\omega) = \frac{e}{(2\pi)^{3/2}\varepsilon_0 c}\frac{\exp(ikR)}{R}\cdot\frac{\beta\sin\theta}{1-\beta^2\cos^2\theta}[1-T(\theta,\omega)] \quad (1)$$

in which

$$T(\theta,\omega) = \frac{\omega a}{c\beta\gamma}\cdot J_0(\frac{\omega}{c}a\sin\theta)K_1(\frac{\omega a}{c\beta\gamma}) + \frac{\omega a}{c\beta^2\gamma^2\sin\theta}\cdot J_1(\frac{\omega}{c}a\sin\theta)K_0(\frac{\omega a}{c\beta\gamma}) \quad (2)$$

θ is the observation angle and a is the radius of target , c , β and γ is the speed of light in vacuum, relative velocity and relativistic mass factor, respectively.

The radiation electric field Ex with observation angle θ can be obtained:

$$E_x(\theta) = \int_0^\infty E_x(\theta,\omega)d\omega \quad (3)$$

And magnetic field component $B(\theta)$ can be given as:

$$B(\theta) = E(\theta)/c \quad (4)$$

From the Fourier component of field Ex, the spectral energy as a function of observation angle θ and radiation frequency can be represented as:

$$\frac{d^2W_s}{d\omega d\Omega} = \frac{e^2}{4\pi^2\varepsilon_0 c}\cdot\frac{\beta^2\sin^2\theta}{(1-\beta^2\cos^2\theta)^2}\cdot[1-T(\theta,\omega)]^2 \quad (5)$$

As mentioned above, the coherent transition radiation (CTR) is generated when the bunch length is less than or comparable to the radiation wavelength. The radiation intensity is increased in factor of N^2, otherwise, that is enhancement of N in case of incoherent, in which N is numbers of electron in the bunch. The radiation energy of CTR generated from the ultrashort beam is expressed as:

$$\frac{d^2W}{d\Omega d\omega} = N^2F^2\frac{d^2W_s}{d\Omega d\omega} \quad (6)$$

in which F is a formation factor. When the bunch shape is Gaussian, the distribution function is depicted as:

$$f(z,\sigma_z) = \frac{1}{\sqrt{2\pi}\sigma_z}\exp(-z^2/2\sigma_z^2) \quad (7)$$

And the formation factor from FFTs of (7) is given as:

$$F(\omega) = \exp\left(-\frac{1}{2}(\frac{\omega}{c}\sigma_z)^2\right) \quad (8)$$

The radiation magnetic field Bz as a function of radius for foil target a and observation angle θ is shown in

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Fig.1. Seen from Fig.1, the Bz is symmetry relative to θ. The intensity of Bz is almost kept a constant when the radius of target excesses a certain value. It is necessary to employ an enough large radius of target for reducing the effect on radiation field.

The 3D energy distribution as a function of frequency and observation angle □ is shown in Fig.2, in which the Gaussian distribution of electron bunch moves towards the target with 0° incidence angle. It shows that the radiation energy, which is symmetry at the direction of observation angle, is focused on the lower frequency and it is decreased with the increment of frequency. The main energy locates at the low frequency less than 1.0THz.

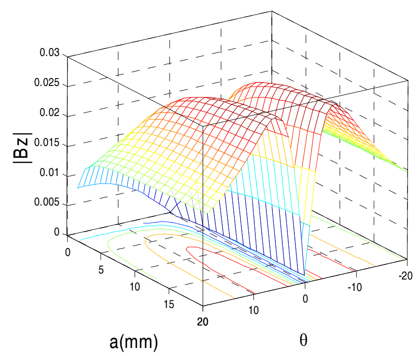


Figure 1: Magnetic field distribution of electron bunch varieties with frequency and observation angle θ at 0° incidence angle.

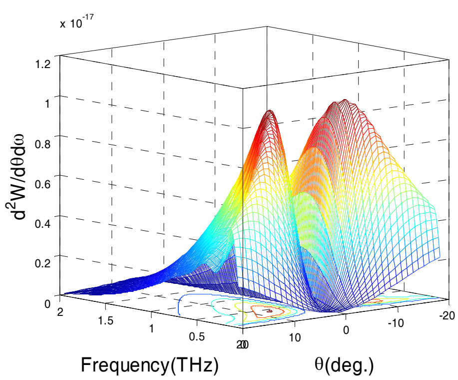


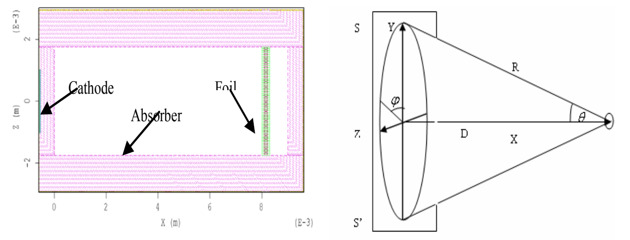
Figure 2: Radiation energy varying with frequency and observation angle θ.

SIMULATION DESCRIPTIONS

The PIC simulations are carried out with a code of CHIPIC [6]. It is a finite-difference, time-domain code for sufficiently simulating plasma physics process. With the help of 3-dimensional PIC simulation, the characteristics of transition radiation including the radiation power and field distribution as well as the interaction processes of electron bunches with the target can be observed. During the simulation, the command of 'foil' and 'film' is used when the target is perfect conductor and dielectric material, respectively.

The simulation geometry is shown in Fig. 3(a). The target is located at the right, and electron beam is emitted from the left disk consisting of perfect conductor. The electron bunching propagation happens in the vacuum area, which is enclosed by a special region called *free space* in PIC, where the incident electromagnetic waves and electrons can be absorbed. The operation area is divided meshes with rectangular cell (□x=0.02mm) in the radiation area and another one with mesh size is just thickness of foil in the *x*-direction, the *y* and *z*-direction mesh size is uniform (δy=δz =0.02mm).

During the simulations, the bunch shape in the longitudinal direction is Gaussian distribution and the total charge is 0.36nC, the length of bunch (RMS) is 0.5ps. The bunch energy is 5MeV.



(a) (b)

Figure 3: (a) Simulation Geometry, (b) Observation Plane.

SIMULATION RESULTS

For observation the characteristics of radiation field, we set the detectors in θ directions and azimuth φ per degree located at y-plane at z=0, *i.e.* S-S' plane, shown in Fig. 3(b). The contour of Bz in XY plane is given in Fig.4. It shows that the intensity of Bz is symmetry about the center of cathode, the amplitude can reach 0.025Tesla which is in agreement with that in Fig.1.

The frequency of radiation field through the Fourier

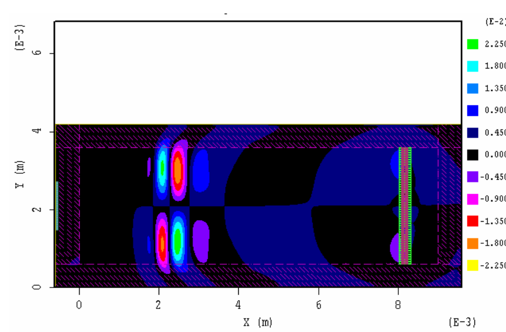


Figure 4: Contour of Bz.

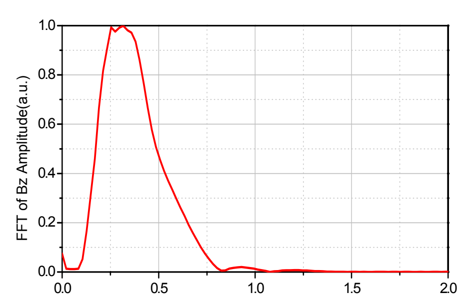


Figure 5: FFTs of Radiation Field Bz.

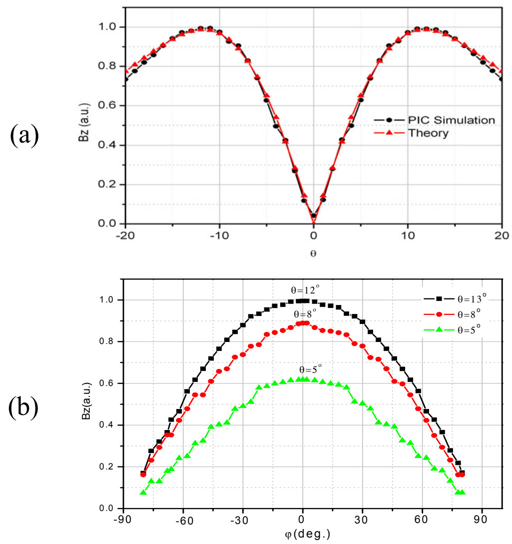


Figure 6: Radiation Field Bz versus (a) observation angle θ, (b) azimuth φ.

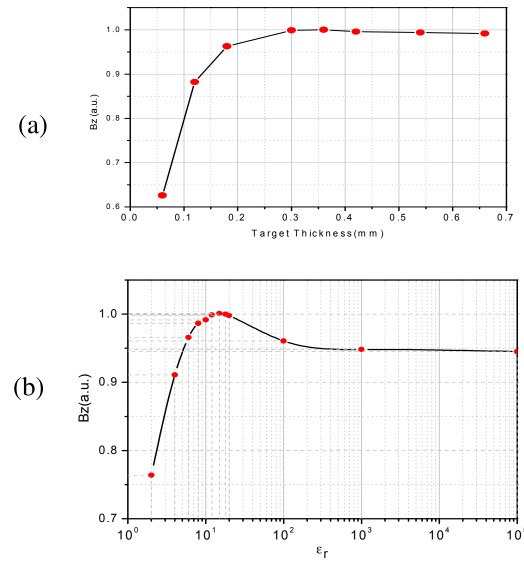


Figure 7: Radiation Field Bz versus (a) thickness and (b) ε_r of target.

transforms (FFTs) is shown in Fig.5. The width of frequency is up to 1.5THz and the low frequency is absent because the sizes of mesh and bunch are not enough small and the size of target is finite. The main radiation energy locates at frequency of 0.1THz to 0.8THz and we can extract the energy through the filter.

To analyze the characteristics of Bz varying with θ we set some detectors in the XY plane with interval 1° and radius r=7.5mm relative to the center of foil. We pick the peak of magnetic field with θ, the results are shown in Fig.6(a). Obviously, the radiation field is symmetry in terms of observation angle, and the maximum field locates at the 13°. The ideal radius of target is infinite and the observation point is as far as possible. During the simulation, the size of target and the observation distance is finite as the limitation of computer capacity, resulting in the difference of simulation results with that of theoretical ones.

The peak intensity of Bz varying with azimuth φ is shown in Fig.6(b). Obviously, the amplitude of radiation field Bz is symmetrical angle φ, and the amplitude of Bz is increased with □ when it is less than maximum observation angle. This result is in agreement with Fig.6(a).

The effects of target thickness *d* and relative dielectric constant ε_r on THz CTR are studied with PIC simulations, the results are shown in Fig. 7(a) and 7(b), respectively. Fig.7 (a) shows that the radiation intensity Bz is increased when *d* is less than a critical value 0.3mm. It is because that the electron bunching can sufficiently interact with target as the increasing of *d*, resulting in the enhancement of radiation efficiency. However, it almost keeps invariable when *d* excesses the optimum value for the radiation field generated from the interaction of electron bunching with the target is saturated. From Fig. 7(b), we can easily find the optimum dielectric constant ε_r is about 15. The intensity of Bz is increased when ε_r is less than an optimum value 15. It is because that the polar current density is increased as the increasing of ε_r, resulting in the enhancement of radiation intensity. However, the polar current density reaches a saturation when ε_r moves towards infinite, the radiation intensity can keep a constant. We can deduce the radiation intensity Bz can keep a constant when ε_r is infinite. In the preparing experiment, the titanium foil would be used as a target.

CONCLUSIONS

In this paper, the THz CTR generated from a ultrashort beam bunch is analyzed. With the help of PIC simulation, the characteristics of radiation magnetic field in the observation angle and azimuth direction are observed. The simulation results are in good agreement with theoretical calculations. Through the simulation, we obtain the radiation center frequency is about 322GHz, the critical thickness is about 0.3mm and the optimum relativity dielectric constant ε_r is about 15. The THz CTR experiment is under performance.

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