OPTIMUM OF TERAHERTZ SMITH-PURCELL RADIATION GENERATED FROM PERIODICAL ULTRASHORT BUNCHED BEAM*

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Abstract

In this paper, the radiation characteristics of terahertz (THz) Smith-Purcell radiation generated from the ultrashort electron beam are analyzed with the help of three-dimensional (3D) particle-in-cell (PIC) simulation. For obtaining the intense THz radiation, the grating parameters including the groove width, depth and that of ultrashort electron beam are optimum. At optimum radiation system, the radiation power is obtained by the PIC simulation. On the other hand, the band width of train bunches is compared with that of single bunch. Through this study, we observe that the radiation power is enhanced and the band width can be adjusted with the train bunches.

INTRODUCTION

The THz wave has some unique characteristics resulting in varieties of applications to far-infrared spectroscopy, medical and industrial imaging, biomedical research and material science [1-3]. The various schemes for generating the THz waves have been employed, such as QCL [4], ultrafast laser pulses [5] and the vacuum electron devices [6]. At the present time, an intense interest has been raised in the Smith-Purcell devices, for which is a promising alternative in development of a tunable, compact, powerful of THz radiation source, since J.Urata et al. [7] and A.Bakhtyari et al. [8] observed the superradiant Smith-Purcell emission in the THz regime by the electron beam passing through the single rectangular grating in experiment.

Up to now, the terahertz SP radiation can be generated from different electron beam, such as the continuous, bunched and ultrashort beam. The terahertz radiation SP radiation produced from the continuous beam is required satisfaction of start current, and the bunched beam is realized by some methods, such as two section grating, wiggler, etc. However, the THz SP radiation can be directly produced from the ultrashort beam because of the bunch length less than ps. With the help of ultrashort beam, the THz SP radiation device can be developed into compact and tuneable source. For obtain the intense THz SP radiation, the optimum parameters of SP gratings are studied with the numerical analyzes and PIC simulations in this paper.

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PHYSICAL MODEL

It is well known that Smith-Purcell (SP) radiation is emitted when an electron passes near the surface of a periodic metallic grating [9]. The radiation wavelength λ observed at the angle θ measured from a direction of surface grating is determined by

$$\lambda = d(1/\beta - \sin\theta)/|n| \tag{1}$$

where d is the grating period and β is electron relativistic speed, n is the order of the radiation. For the single electron passing over the grating, its radiation power per solid angle in a single grating period is given [10]:

$$\frac{dW_n}{d\Omega} = \frac{e^2 n^2}{2d\varepsilon_0}\frac{\cos^2\theta\cos^2\varphi}{[1/\beta - \sin\theta]^3}|R_n|^2 \exp[-z_h/\lambda_e] \tag{2}$$

in which $\lambda_e = \lambda_n \dfrac{\beta\gamma}{4\pi\sqrt{1+\beta^2\gamma^2\cos^2\theta\sin^2\varphi}}$

$\gamma = 1/\sqrt{(1-\beta^2)}$. θ, φ are the longitudinal and horizontal angles between the electron and z-direction, respectively. $|R_n|$ is the grating efficiency factor. It is closely related to the grating's geometry profile, the distance between the electron beam and grating surface, electron energy as well as the observation angle and the radiation order n. The numerical calculation of $|R_n|$ can be found in many reported papers.

When a single beam bunch with electron numbers N_e passing near a single grating period, the radiation power per solid angle is given as:

$$\left(\frac{dW_n}{d\Omega}\right)_{N_e} = \frac{dW_n}{d\Omega}\left[N_e S_{\mathrm{inc}} + N_e^2 S_{\mathrm{coh}}\right] \tag{3}$$

where S_{inc} and S_{coh} are incoherent and coherent factor of the SP radiation and can be represented as:

$$S_{\mathrm{inc}} = \int_h^\infty dz Z(z) e^{-z/\lambda_e} \tag{4}$$

$$S_{\mathrm{coh}} = \left|\int_h^\infty dz Z(z) e^{-z}\tilde{Y}(k_y)\tilde{X}(\omega)\right|^2 \tag{5}$$

Normally, the coherent radiation can be generated while the bunch length less than radiation wavelength, and its radiation energy or power is proportional to N_e^2 . Otherwise, the inherent radiation is produced, and the energy is linear N_e . In this paper, we consider periodical bunched beam passing over three different grating profiles shown in Fig.1, such as rectangular, sine and triangular grating. The SP radiation power generating from N_b periodical bunches can be represented as:

$$\left(\frac{dW_n}{d\Omega}\right)_{\text{total}} = \left[\frac{dW_n}{d\Omega}\right]_{N_e} \left|\sum_{n=1}^{N_b} \exp\left[i2\pi n\,\omega/\omega_0\right]\right|^2 = \left[\frac{dW_n}{d\Omega}\right]_{N_e} \left[\frac{\sin(\pi N_b\,\omega/\omega_b)}{\sin(\pi\,\omega/\omega_b)}\right]^2 \quad ,(6)$$

in which $\omega_b = 2\pi\,c_0/\lambda_b$, λ_b is the period lengths of bunches. By the PIC simulation, we can see the radiation is modulated by the periodical bunches.

In the following subsection, the grating parameters are optimum by the numerical analyzes, then the THz SP radiation characteristics of single and periodical bunches in the optimum grating systems are investigated with the help of 3D PIC simulation.

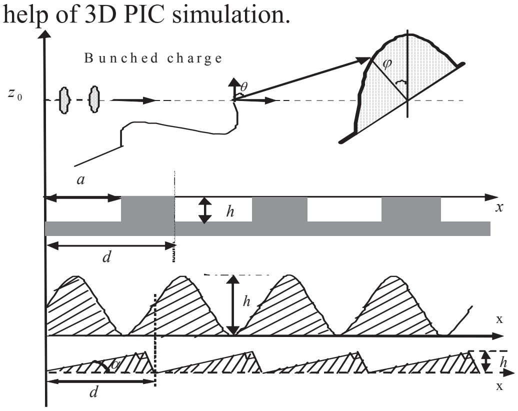


Figure 1: General view of Smith-Purcell procession and the coordinate system with different grating profiles.

NUMERICAL CALCULATIONS

In order to develop a high performance SP THz source, the power spectrum should be optimized. The first step is chosen the proper grating profile by comparing different efficiency factors. Based on the experiment plans, the THz SP experiment will be performed at the Tsinghua University Accelerator Laboratory, the ultrashort bunching beam energy is from several MeV to 50MeV, then the grating parameters at this conditional are analyzed.

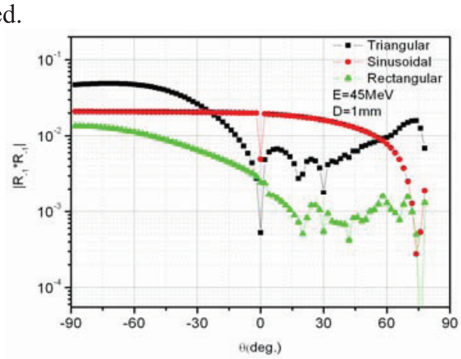


Figure 2: Efficiency factors of different grating profiles at beam energy 45MeV.

Figure 2 gives the efficiency factors of different grating profiles when the beam energy is 45MeV, from which the triangular grating efficiency factor at high energy range is higher than the other two. For the triangular grating, the efficiency factor is calculated at different beam energy, shown as in Fig.3. Seen from it, $|R_n|$ is decreased as the beam energy becomes increasing.

For obtaining the optimum triangular grating parameters, the grating efficiencies versus depth are described in Fig.4. It shows that the efficiency factor at the observation angle -90° to 0° is smooth, and at the range of the 0° to 90° is different each other. On the other hand, the efficient factor at h/D=0.1 is larger than that of grating depth.

Based on the calculations, the optimized grating and beam parameters are shown in Table 1. On these conditions, SP Power distributions versus observation angles and frequency in the rectangular and triangular gratings are compared, as shown in Fig.5, from which we can observe that there is an intense SP radiation locating at an optimum angle and radiation frequency ranges.

Figure 6 gives the radiation power generating from the periodical bunches. In Fig.6, the spectrum is modulated by equation (6) and the SP power at the integer multiple of the periodical bunches repetition frequency is strengthen, which are 0.5THz, 1THz, etc in this condition. In this way, frequency-locking SP radiation can be achieved if there is a good modulated electron beam source with suitable repetition. Table 1 gives the parameters of single bunch numerical calculation.

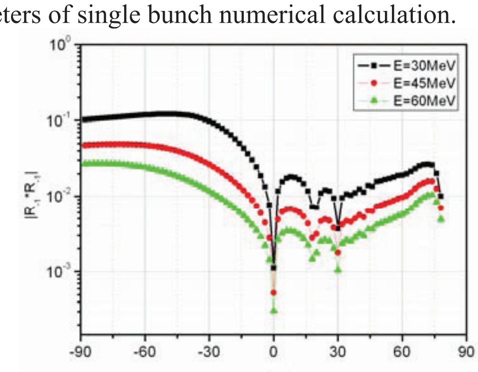


Figure 3: Triangular grating's efficiency factor versus the beam energy at the relative high energy range.

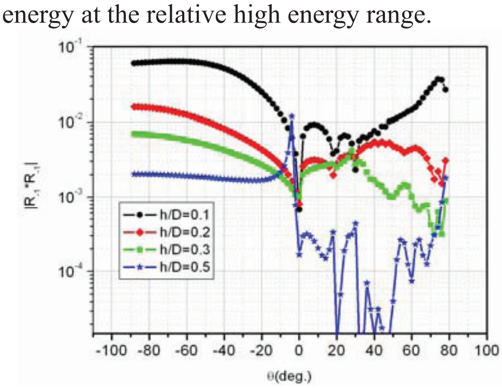
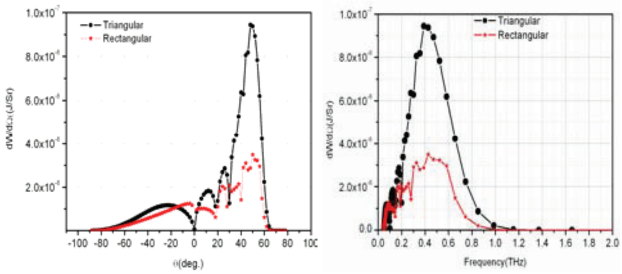


Figure 4: Triangular grating's efficiency factor versus the grating depth.

Table 1: Numerical Calculation and PIC Parameters

Parameters	Values
Grating period length	1mm
Grating depth	0.1mm
Bunch distribution	Gaussian
Beam energy	40MeV
Beam Charge	0.5nC
Longitudinal bunch length (FWHM)	1.0ps
Transverse bunch size (FWHM)	0.5mm



(a) (b)

Figure 5: Power distribution versus angle θ (a) and Frequency (b) of different grating types.

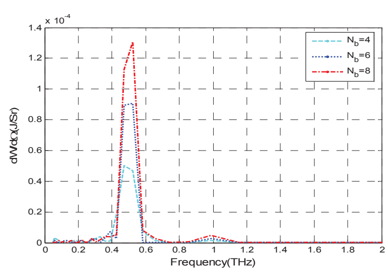


Figure 6: Power distribution from periodical bunches at repetition frequency 500GHz pass above the grating.

PIC SIMULATION

The PIC simulations are carried out with a code of CHIPIC [11]. It is a finite-difference, time-domain code for sufficiently simulating plasma physics process. Ultrashort bunch length 0.1ps and h/d=0.1 are chosen, the periodical bunches repetition frequency is 500GHz, the other parameters are given in table 1.

Figure 7 shows the layout of the simulation. The cathode is located at the left side. The cell is surrounded by material called 'absorber' which can absorb electromagnetic wave. The observation plane is on the left of grating excluding the cathode profile.

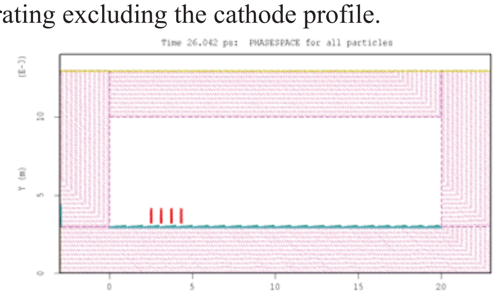


Figure 7: Layout of the simulation.

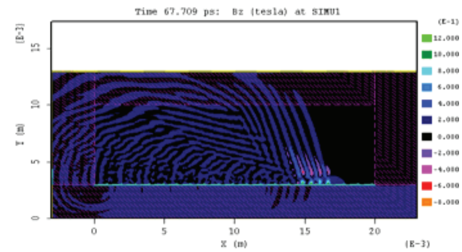
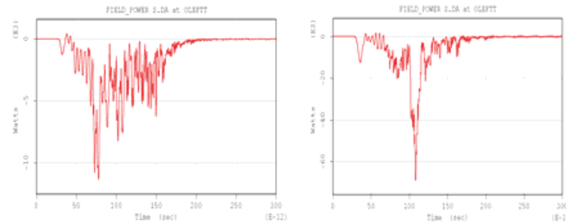


Figure 8: Contour of magnetic field Bz.

Figure 8 gives the contour of B_z when the periodical bunches passing through the cell, from which the backward SP wave can be obviously observed.



(a) (b)

Figure 9: Radiation Power (a) single bunch (b) Periodical bunches.

Figure 9 shows the observed power produced by a single bunch and periodical bunches. Obviously, the remarkable enhancement of radiation power is obtained compared with that of single bunch. This result is good agreement that reported in [12]. In this PIC simulation, we observe that high repetition periodical bunches can adjust the SP radiation frequency.

CONCLUSIONS

In this paper, the optimum grating parameters for THz SP is performed by the numerical analyzed, including the grating profiles, depth, observation angle, etc. On the other hand, the THz SP radiation of power generated from single and periodical bunches are compared with the help of 3D PIC simulation, furthermore, the SP radiation frequency can be adjusted by chosen the periodical bunches repetition frequency. This study will help the THz SP experiment performed in Tsinghua University.

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