

# TERAHERTZ SMITH-PURCELL RADIATION GENERATED FROM THE PERIODICAL ULTRASHORT ELLIPTICAL BUNCHING BEAM\*

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## Abstract

In this paper, the terahertz (THz) Smith-Purcell (SP) radiation generated from the periodically elliptical ultrashort (sub-picosecond) electron beam is presented and that of characteristic is analyzed with the help of three dimensional (3D) particle-in-cell (PIC) simulation. The radiation power and energy are obtained by the PIC simulation and the radiation characteristics generated from train bunches are compared with that of single bunch. The transverse profiles and emittances including the flat, circular and elliptical bunching beams are studied by the tracker code of Parmela. Through this study, we observe that the radiation power is enhanced and the band width can be adjusted through the train bunches.

## INTRODUCTION

As is well known, 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]. The various schemes for generating THz waves have been employed, such as QCL[2], ultrafast laser pluses[3] and the vacuum electron devices[4]. 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*[5] and A.Bakhtyari *et al*[6]observed the superradiant Smith-Purcell emission in the THz regime by the electron beam passing through the single rectangular grating in experiment.

Smith-Purcell (SP) radiation is emitted when an electron passes near the surface of a periodic metallic grating [7]. The radiation wavelength  $\lambda$  observed at the angle  $\theta$  measured from a direction of surface grating is determined by

$$\lambda = \frac{D}{|n|} \left( \frac{1}{\beta} - \cos \theta \right), \quad (1)$$

Where  $D$  is the grating period,  $\beta c$  is the electron velocity,  $c$  is the speed of light, and the integer  $n$  is the spectral order.

In present study, the THz characteristics of Smith-

Purcell radiation generated from the ultrashort single and train elliptical bunches beam are studied with the help of three-dimensional PIC simulations. The emittances of three profiles including the flat beam, rounded beam and elliptical beam are analyzed with the PIC simulation Parmela.

## ELLIPTICAL BEAM DYNAMIC

### Physical Descriptions

For the satisfied THz application, it is necessary to improve the performance of THz radiation source. As for the THz SP one, the electron beam is an important part, the remarkable enhancement of THz radiation performance can be expected when the high brightness beam and ultrashort bunching beam is obtained, for example, the high current density, low emittance and mild beam profile, especial the low emittance. In normal SP THz source, the grating profile is planar grating[8], and the beams are employed the flat beam and round beam, as shown in Fig.1(1) and Fig.1(2). Because the flat beam with the large interaction region can enhance the radiation, then it is mostly used. As mentioned in Ref.[9], V.Kumar and K.-Je Kim analyzed the three-dimensional emittance requirement of Smith-Purcell backward oscillator, and recently, Kim and his co-worker present a novel way to relax the requirement emittance of flat beam through the focusing of a wiggler and solenoid magnetic field, etc. In the Ref [10], Li and his co-authors presented a method of sidewall to reduce the start current of SP backward oscillator, he analyzed the beam-wave interaction through the round beam, and the transverse field can confine the beam on the top of grating.

For considering the relax emittance and the enlarge interaction region of beam with grating, a beam with an elliptical profile is presented, as shown in Fig. 1(3). To analyze the effects of transverse profile, the current, current density and the transverse area region of flat,

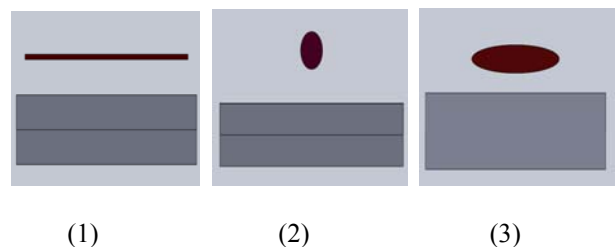


Figure 1: Three Profiles of beam, (1) flat beam, (2) rounded beam, (3) elliptical beam.

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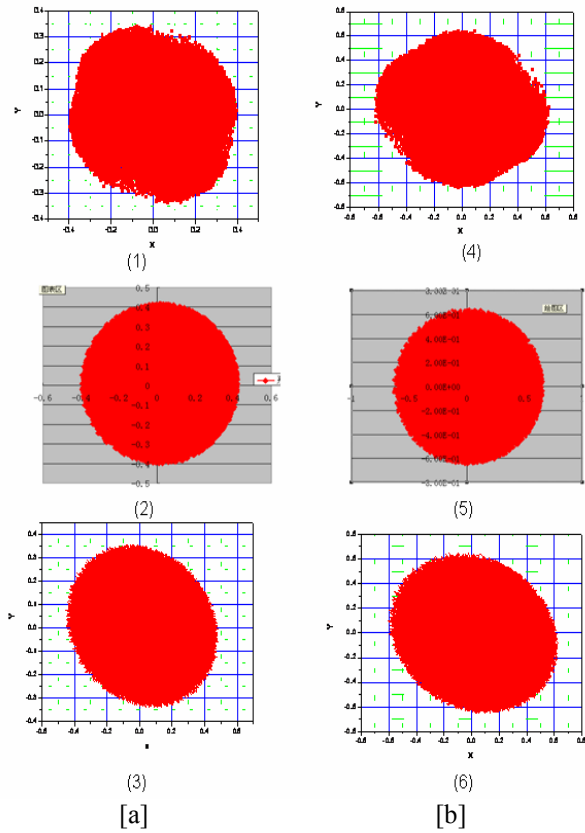


Figure 2: Particles Transverse distribution (1) and (4) flat, (2) and (5) round, (3) and (6) elliptical: [a] @ z=16cm, and [b] @ z=71cm.

round and elliptical beam are same, the only difference is the transverse profiles.

*Beam Dynamic Characteristics*

For generating the coherent THz Smith-Purcell radiation, the ultrashort length of electron bunching and the low emittance are very important. To compare the quality of high brightness, the emittance and profile before entering the grating system are analyzed by Parmela [11]. It is a versatile multi-particle code that transforms the beam, represented by a collection of particles, through a user-specified linac and/or transport system, and it includes options for 2-D and 3-D space-charge calculations. In present simulation, the initial distributions including the flat, round and elliptical beam are shown in Fig. 2. It shows that the flat beam in the transverse plane is degraded and it is turned into an irregular profile, however, that of round and elliptical beam is kept as well as the initial shape. We can deduce that the profile of flat beam will severely distorted as the increasing of beam transport distance.

In the beam transport system, the distance from the cathode surface to solenoid exit system is z=15cm, the Fig.3[a] shows that the particles in phaspace distribution  $P_x-x$  z=16cm, it means that the particle has drift a distance of 1cm. From Fig. 3[a], in which Fig.3(1) and 3(4), 3(2)and 3(5), 3(3)and 3(6) represent the flat beam, round beam and elliptical beam, respectively. Obviously,

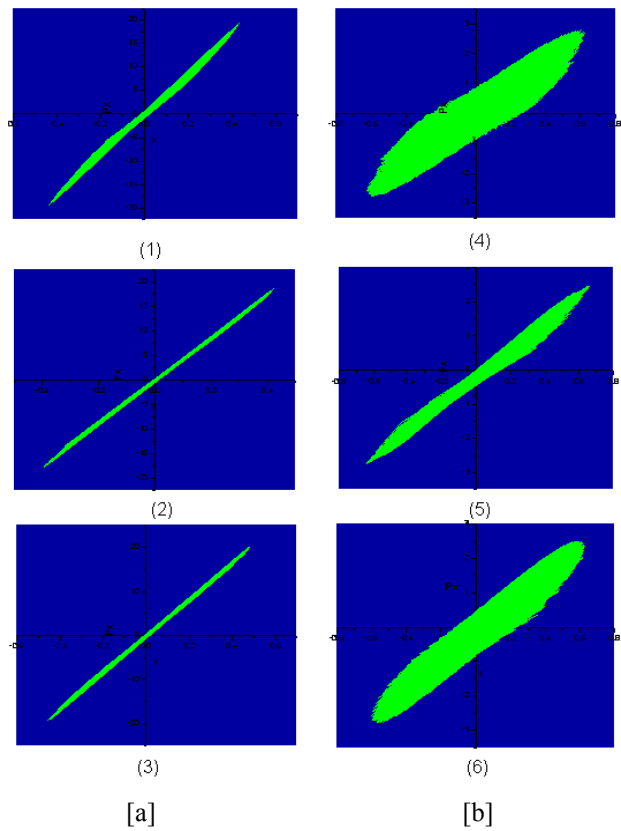


Figure 3: Transverse phase space distribution: (1) and (4) flat, (2) and (5) round, (3) and (6)elliptical: [a]@ z=16cm, and [b]@z=71cm.

the distributions of round and elliptical are located the phase elliptical area, and the distribution area of flat beam in the phase elliptical is larger than that of round and elliptical beam. It shows that the brightness of flat beam can be turned into worse than that of other beams.

When the beam transport locates at z=71cm, the particles distribution in phasespace are shown in Fig. 3 [b]. Obviously, the phase-space area of flat beam is largest, and that of circular beam is smallest. It shows that the flat beam brightness is degraded, and the circular beam is kept well.

The emittance versus transport distance including the three profiles are shown in Fig. 4, in which Fig.4(1), 4(2) and 4(3) represent the flat beam, circular beam and elliptical beam, respectively. From the pictures of Fig. 4, the emittance of circular is lowest, and the flat beam is largest. The transverse profiles of circular beam in x and y-direction are the same, the growth of emittance in the two directions are uniform, resulting in the growth rate in x and y-direction is slow. As for the flat beam, the size of transverse profile in x and y-direction is unequal and the growth of emittances are nonuniform, leading to the growth rate of emittance is larger than that of circular beam. However, the elliptical beam in transverse profile give attentions to the characteristics of circular and flat beam. The long axis of elliptical is same as that width of flat beam, and the short axis is half that radius of circular beam, then the area of elliptical is equal to that of circular

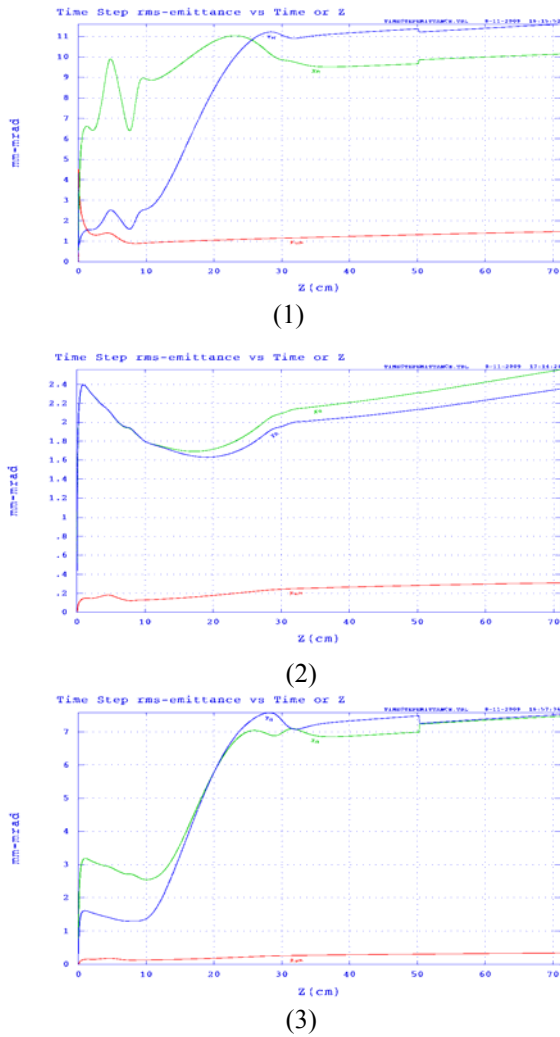


Figure 4: Transverse emittance versus transport distance: (1) flat beam, (2) round beam, (3) elliptical beam.

beam. The growth rate is located at the middle of circular and flat beam.

According to the beam profile and emittance growth, the elliptical beam is employed in the next simulation studies.

### PIC SIMULATION

#### Descriptions of Simulation Geometry

The PIC simulation is performed with the code of CHPIC [12], which is a finite-difference and time-domain code for simulating processes that involve interactions between space charge and electro-magnetic fields. The geometry for PIC simulation is shown in Fig.5, respectively. A grating with rectangular profile is located above of the bottom. The grating is considered as a perfect conductor and discarding the grating losses, in which the grooves with width  $w$  are parallel and uniform in the  $z$ -direction. The closed sides are six special regions (called *free space* in PIC language). is 30 grids about 3mm. The elliptical beam is produced by the “cold cathode” located at the left boundary of the simulation box.

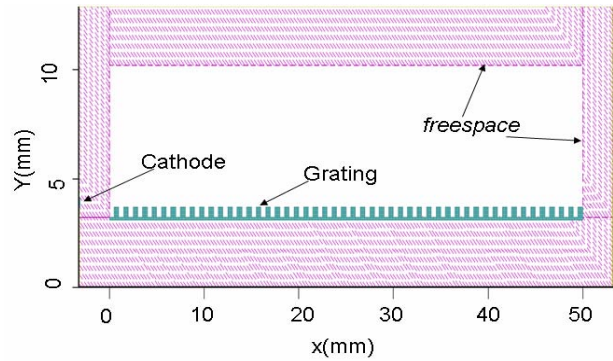


Figure 5: Simulation Geometry.

#### Descriptions of Simulation Parameters

The main parameters of the grating and electron beams are summarized in Table 1. The period of perfect grating with a rectangular profile is 1.0mm, and the width of slot is 0.5mm, and the depth of groove is 0.5mm. As for the three-dimensional PIC simulation, the width of grating plane  $w$  is 5.0mm, and the parameters about the rectangular grating are displayed in Fig.6.

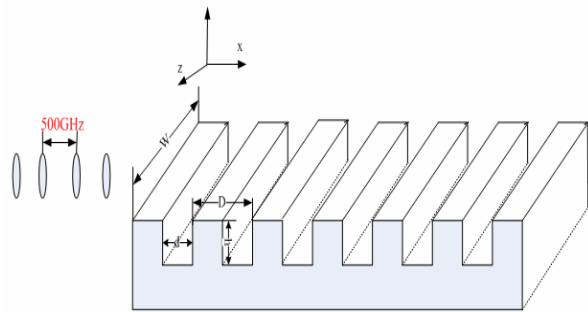


Figure 6: Three-dimensional grating profile.

Table 1: Parameters for PIC Simulation

Parameters	Value
D	1.0mm
h	0.5mm
W	5.0mm
d	0.5mm
E	40MeV
I	1000A
$R_a$	0.25mm
$R_b$	1.0mm
$\delta_z(\text{rms})$	0.1ps

As for the single elliptical bunching beam, the short axis  $R_a$  is 0.25mm, and the long axis  $R_b$  is 1.0mm. On the other hand, the current is 1000A, and the energy of electrons is about 40MeV. For the train bunching beam,

consisting of four bunches, the repetition frequency is 500GHz. The other parameters are the same as single bunching.

As to the diagnostics, CHPIC allows us to observe a variety of physical quantities such as electromagnetic fields as functions of time and space, power outflow, and electron phase-space trajectories, etc. We can set the relevant detectors anywhere in the simulation area.

### Simulation Results

Recently, Li and coworkers [13] have addressed the superradiant SP radiation with the help of 2D or 3D PIC simulations. They studied the evanescent wave, electron beam bunching and radiation gain, the loss of grating, etc. In present work, we focus on the enhancement of THz SP radiation by elliptical bunching beam.

The radiation power produced by the single flat, circular and elliptical bunching beam is shown in Fig. 7. Obviously, the radiation power of elliptical and rectangular/flat beam is very closely, and it is larger than that of circular bunching beam. It is because that the interaction regions of flat and elliptical bunching beam are larger than that of circular beam, resulting in the enhancement of radiation power. For the flat and elliptical bunching beam, the emittance of former is larger than that of latter, *i.e.*, the beam brightness is worse than the latter, then radiation power is larger than of flat beam.

According to the elliptical beam radiation characteristics, the train bunches are consisted of four elliptical bunching beams. The repetition rate is 500GHz, and the longitudinal shape is Gaussian distribution with a standard  $\delta z(\text{rms})=0.1\text{ps}$ . The power spectrum including the left and right observation plane is shown in Fig.8. From the power spectrum, the radiation power can be obtained the maximum at the  $n$ th times of repetition frequency. The real harmonics frequency is lower than the repetition frequency, resulting from the space charge effect. The peak of power spectrum is about four times that of single bunching, the result is well agreement with that reported in ref.[14]. On the other hand, the peak of left radiation spectrum is larger than that of right. It shows that such Smith-Purcell radiation based on gratings is operated at the backward mode. The radiation power spectrum shows that the THz Smith-Purcell radiation can be obtained through the adjustment of repetition rate.

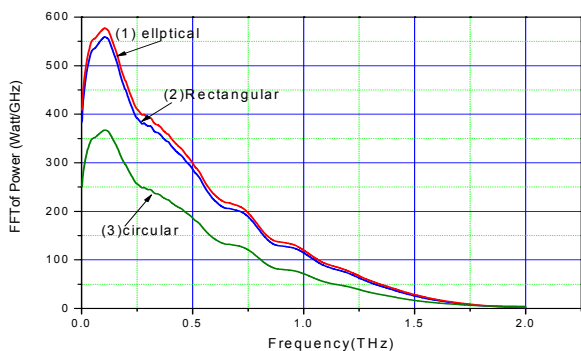
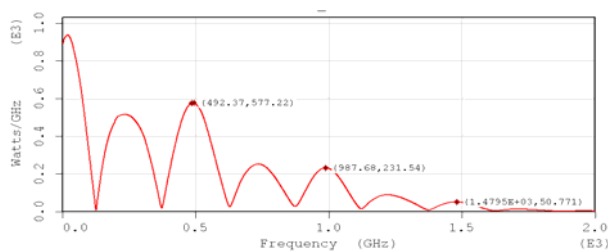
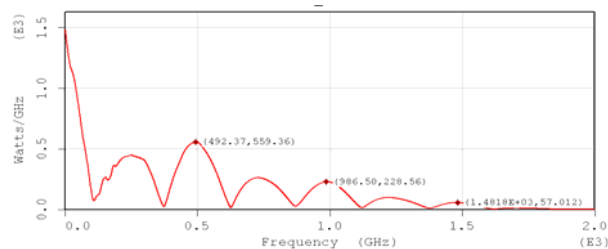


Figure 7: Radiation power on the left observation plane.



(1)



(2)

Figure 8: Radiation power spectrum (1) left (2) right.

## CONCLUSIONS

In this study, the THz Smith-Purcell radiation generated from the ultrashort periodical elliptical bunching beam is presented. The beam dynamic and radiation characteristics are analyzed by the three-dimensional PIC simulation with the code of Parmela and CHPIC, respectively. The results show that the growth of emittance for elliptical is between the flat and circular bunching beam, and the radiation power can be valid enhancement. On the other hand, the THz SP radiation can be obtained by the adjusted of repetition rate. The THz SP experiment is under performance.

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