SUPERRADIANT SMITH-PURCELL RADIATION IN THE TERAHERTZ-WAVE REGION FROM BUNCHED ELECTRON BEAMS*

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Abstract

This paper presents an analysis of a possible method of producing the bunches and obtaining the coherent THz radiation. With the help of a two-dimensional particle-in-cell (PIC) simulation, the simulation proposes a model with two sections consisting of a square-toothed grating with a flat conducting roof above it and an open grating. In the first section, an initially continuous beam interacting with TM modes is bunched by using an external signal. In the second section, the coherent THz radiation is produced by the well bunched beam interacting with the open grating. The strongest radiation is at 120^0 and at frequency 266.5GHz.

INTRODUCTION

In recent years, there is a substantial interest in development of coherent radiation sources, especially to the coherent THz radiation. An important source of radiation in the THz region is Smith-Purcell(SP) radiation[1].

It is well known that the SP radiation may occur at angles θ measured from the direction of the electron beam and order n such that $\lambda = L(1/\beta - \cos\theta)/|n|$, where L is the grating period, βc the electron velocity, and c the speed of light. The coherent SP radiation has been observed in the THz region from experiments. One example is the Dartmouth experiments [2] with an initially continuous beam. The other is the MIT experiments [3] using the beam already bunched when it reaches the grating. The bunched beam from a linac operating at 17.14Ghz delivers pulses of duration 1ps. Quite recently, the PIC code simulations related to the coherent and superradiant SP radiation are performed by Li et al [4], Donohue and Gardelle, respectively [5,6]. In their simulations, the Dartmouth experiment and MIT experiment have been presented. These simulations are able to clearly observe coherent SP radiation at harmonics of imposed bunching frequency. Those results support the viewpoint of Andrews and Brau [7]. In the theoretical side, Kumar and Kim have performed a detailed 2D analysis in which the SP free-electron laser is treated as a BWO [8]. And a thorough discussion of the radiation emitted by prebunched beams has been given recently by Gover [9].

We know it is necessary for generating coherent SP radiation that the bunches are short comparing with the radiation wavelength. However, for the short electron bunches high quality electron accelerator which is expensive is needed. The bunches are unstable both in time and along the grating for the bunching of the initially continuous beam by an evanescent wave that is operating in backward wave region.

In this paper, with the help of a two-dimensional PIC simulation we discuss and analyze a new method of making the bunches and obtaining the coherent THz radiation. The simulation proposes a model with two sections consisting of a square-toothed grating with a flat conducting roof above it and an open grating. In the first section, an initially continuous beam interacting with TM modes is bunched by using an outer incoming signal. The electron-wave interaction is operating in the travelling-wave region, which resembles a Cerenkov amplifier. Due to the Mechanism for TWT, the bunches are relative stable compared with what is operating in backward wave region. In the second section, the coherent THz radiation is produced by the well bunched beam interacting with the open grating.

DETAILS OF THE NUMBER ANALYSIS

Geometry and parameters of the simulation

The simulations are carried out using the PIC code CHIPIC[10]. It is a finite-difference, time-domain code for simulating plasma physics process. Our simulations use a 2D PIC code in this paper. The geometry is given in Fig. 1. The basic structure consists of a grating bounded above by a roof and an open grating .The surface of the grating and the roof are assumed to consist of a perfect conductor whose rectangular groove are parallel and uniform in the z direction. A sheet electron beam propagates along the x-direction. It is a perfect beam produced from a small cathode located at the left boundary of the simulation. The drive signal is also

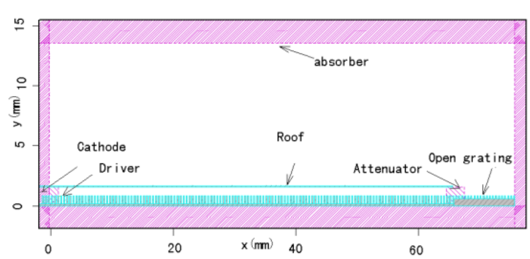

Figure 1. Simulation geometry.

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Table 1. Parameters of the simulations

Parameters	First section	Second section
Beam energy	120 kV	
Current	200 A	
Beam thick	0.4 mm	0.4mm
Beam -grating distance	0.1 mm	0.1mm
Grating period	0.5mm	0.5mm
Grating groove depth	0.625mm	0.2mm
Grating groove width	0.25mm	0.3mm
Number of period	135	20
External magnetic field	2T	
Drive signal	2kW	
Mesh size	$(50um)^2$	$(50um)^2$

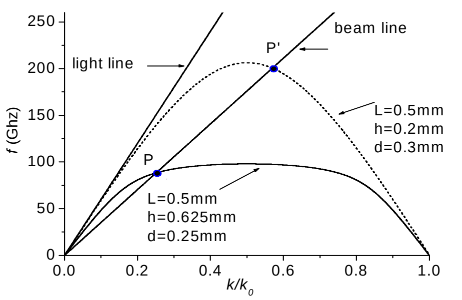

Figure 2.Dispersion relation for the grating

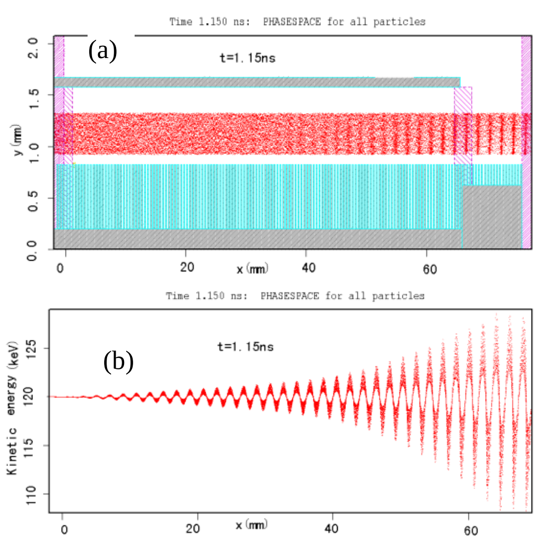

Figure 3. Phase-space distribution (a) density of electrons in the x-y plane at 1.15ns.Bunching is evident.(b) kinetic energy-*x* density at the same time

imposed on the left, which provides a 2kW power to the device. The beam-wave interaction and radiation propagation happen in the vacuum box. The boundary is enclosed with absorbers. At the end of the first section, there is an attenuator, which prevents most of the electromagnetic wave reaching the second section from perturbing the bunching and interpreting the coherent radiation. The grating parameters we choose have a period L=500*um*, a width of slots d=0.25*mm*, and a depth h=0.625 *mm*. The distance from the tops of the teeth to the roof is 0.75 *mm*. We assume a beam voltage of 120kV, a current of 200A, a beam thickness of 0.4mm, and beam-grating distance 0.1*mm*, external magnetic field B_x=2T. The main parameters of the grating and electron beam are summarized in Table 1.

Description of our idea

In fig. 2, the solid line shows the lowest order TM mode dispersion relation for the grating with a roof, and the dash line for open grating. Due to the choice of parameters, the lowest-order TM mode will be resonant with the beam in the neighborhood of 90-100GHz. At the operating point P, the group velocity is positive, which means electron-wave interacts at the traveling-wave region, as in the traveling-wave tube (TWT). The working process of the device is explained as follows. By using an initial injected signal with frequency 88.5GHz, the electron beam interacts with TM mode electromagnetic wave through the first section, and gets density bunching. The bunching wavelength will be the same as the spatial wavelength of the operating point P .In the second section in order to clearly observe coherent SP radiation at harmonics of the bunching frequency, we varied the parameters of the grating. In fig.2, the point P' is the operating point. Then the operating point frequency of the evanescent wave is different from the bunching frequency.

Through the second passage, which also acts a drift tube, the well bunched beam interacts with the grating, and the coherent radiation is produced.

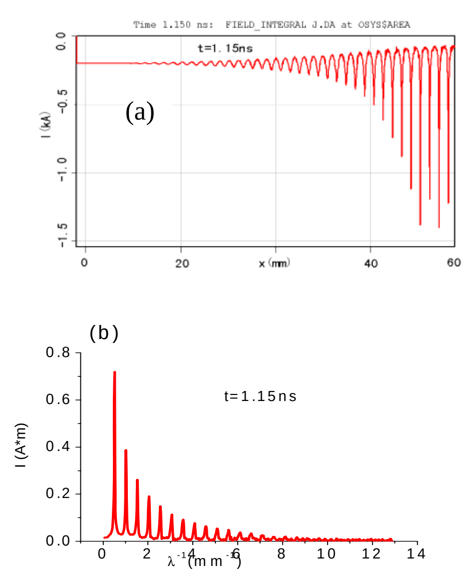

Figure 4. Space dependence of current (a) current I(x), (b) corresponding FFT.

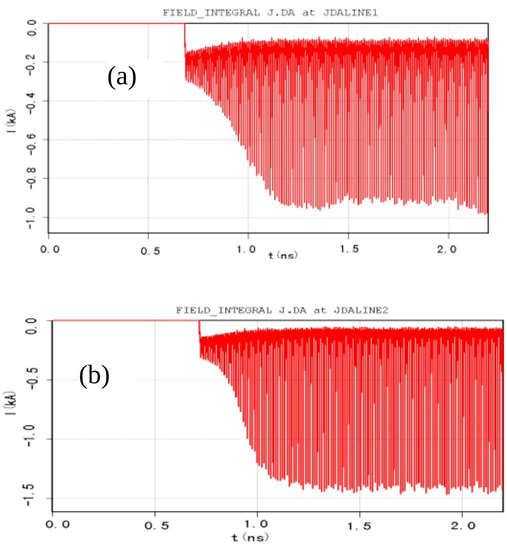

Figure 5. (Color) Current as a function of time: (a) at end of the first section .(b) at the center of the open grating .

SIMULATIONS RESULTS

Electron bunching

In this simulation, the main goal of the first section is not gaining the maximum output power of the beam-wave interaction, but obtaining the well stable bunches. Hence, by using of an outer injected wave, choosing a reasonable period numbers, an initial continuous beam travels through the first section and gets velocity modulation and density bunching, then passes through the open grating and the stable bunches are generated. The bunching can be clearly observed as a function of both space and time. In fig.3, we observe the beam bunching: phase-space plots at time 1.15ns and energy modulation of the electron .We note that the mean energy loss is about 5keV of the beam energy. The spatial modulation of the current displayed in fig.4 increases with *x*, and the period of the modulation is 1.94*mm*. The beam is well bunched at the downstream of the first of passage. We note that the bunching is relative stable along the open grating. In fig.4 (b) shows the bunching is nonlinear when it becomes strong. In fig.5 the beam current is a function of time, for locations at the end of the first of the passage and the center of the open grating. One clearly sees the bunching current is stable in time after time about 1ns. This is an advantage compared to the bunching of the initially continuous beam by an evanescent wave that is operating in backward wave region. In fig.5(b), the bunching current shows the beam is well bunched at the center of the open grating compared with that at the downstream of the grating with roof displayed in fig.5(a). It shows that the open grating also resembles a drift tube.

Coherent terahertz radiation

Here we analyze the radiation from the periodic bunching interacting with the open grating. The results of the simulation are given in fig.6, and three radiations are clearly observation. It has be shown that the dominant radiation is with the frequency of third harmonic of bunching wave, 88.5GHz peaked at the angle of about 120 deg which corresponds to the SP radiation angle. While the other two radiation are with the frequency of the fourth and fifth harmonics ,respectively, and also corresponds to the SP radiation angle. From the contour plot of fig.7 we can observe that the dominant third harmonic radiates at the angle of about 120^0, in agreement with that shown in fig.6.Of course, due to the interacting of the beam-wave which reduces the value of the particle velocity, the discrepancy appears somehow for the simulation data for the radiation angle compared to the theoretical value.

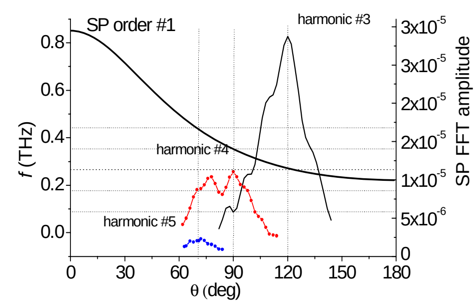

Figure 6. Radiation frequency and the peak of FFT amplitude of B_z as a function of angle, detected at the distance 10.58*mm* from the grating center.

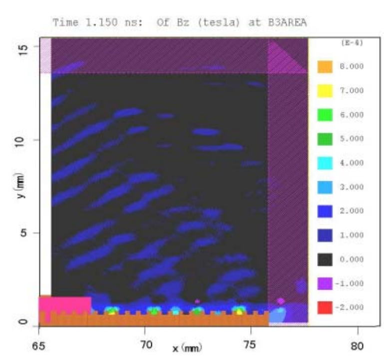

Figure 7. (Color) Contour plot of B_z for coherent radiation

CONCLUSIONS

We have presented results of the coherent THz radiation through the simulations of electron bunching of continuous beam interacting with an open grating. The results show that the bunching is stable in time and along the grating. The strongest radiation is at 120^0 and at frequency 266.5GHz at the simulation parameters. The coherent radiations are emitted at frequencies that are integer multiples of the bunching frequency, and at the corresponding SP angle.

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