

PiC code KARAT simulations of Coherent THz Smith-Purcell Radiation from diffraction gratings of various profiles

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Abstract. Generation of coherent THz Smith-Purcell radiation by single electron bunch or multi-bunched electron beam was simulated for lamellar, sinusoidal and echelette gratings. The dependences of the CSPR intensity of the corrugation gratings depth were investigated. The angular and spectral characteristics of the CSPR for different profiles of diffraction gratings were obtained. It is shown that in the case of femtosecond multi-bunched electron beam with 10 MeV energy sinusoidal grating with period 292 μm and groove depth 60 μm has the uniform angular distribution with high radiation intensity.

1. Introduction

One of the actual problems of modern accelerator physics is the development of compact sources of THz radiation. Currently there are new applications of coherent THz radiation. The basis of modern THz radiation sources are powerful and bulky gas lasers or compact semiconductor laser systems.

In this paper, we investigate the possibility of developing a compact tunable monochromatic THz CSPR source based on electron accelerator with femtosecond bunched beam. A 10 MeV multi-bunched electron beam with a THz repetition frequency is formed in RF gun with photocathode by a femtosecond laser.

CSPR is generated when a charged particle passes near the diffraction grating. This radiation is described by the dispersion relation, also called Smith-Purcell relation:

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

where λ is wavelength, d is grating period, n is diffraction order, β is charged particle velocity in units of speed of light, and θ is radiation angle.

There are a number of theoretical and experimental studies of the CSPR generation by multi-bunched electron beams. Using multi-bunched beam allows generation of narrow-band CSPR in super-radiance regime [1,2]. The radiation frequency can be tuned changing the repetition rate of the femtosecond laser pulse in RF gun [3]. In addition, it is possible to change the angle of radiation generation by changing the repetition frequency of micro-bunches. For example, the generation of radiation perpendicular to the grating plane simplifies the radiation output from the installation and recording of its characteristics. Since the radiation is formed on the diffraction grating, its size and the radiation angle will define the spatial size of the wave packet.



The generation of CSPR by THz multi-bunched electron beam from diffracting gratings with an arbitrary profile is a very complex task for which modern numerical simulation methods should be used.

2. Simulation of CSPR characteristics

2.1. Particle-in cell code KARAT

In the present paper, the numerical simulation of the CSPR generation was carried out by PiC-code KARAT [4]. The code allows taking into account the effect of the grating profile on spatial and spectral characteristics of the CSPR and choosing the optimal diffraction grating. KARAT is a fully electromagnetic code based on the particle-in-cell (PiC) method. It has been designed to simulate the dynamics of charged particle beams in their own and external electromagnetic fields in complex geometry. In particular, code KARAT performs well in modeling of the generation of different types of polarized radiation, such as diffraction, transition, Cerenkov radiation and Smith-Purcell radiation [5]. There are 1D, 2D and 3D versions of the code. In all cases, it takes into account the three components of the electromagnetic fields and moments. A finite difference scheme with overstepping on the rectangular shearing grid is used to solve Maxwell's equations.

2.2. Simulation parameters

Numerical simulation of the CSPR generation was carried out for the four types of diffraction gratings (figure 1):

- echelette grating with 45 degrees blaze angle (prof. 1);
- echelette grating with 30 degrees blaze angle (prof. 2);
- sinusoidal grating (prof. 3);
- lamellar grating (prof. 4).

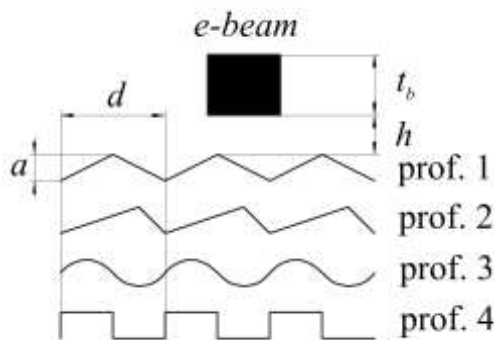


Figure 1. The profiles of diffraction gratings.

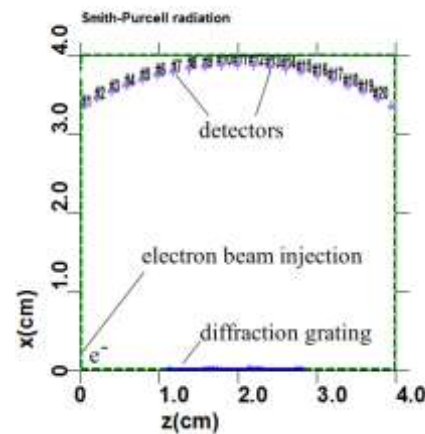


Figure 2. Simulation geometry.

Gratings period $d = 292 \mu\text{m}$ provided the generation of THz radiation at an angle $\theta \sim 90^\circ$ to the direction of motion of the electron beam. The number of grating periods $N_p = 60$. A groove depth a was varied from 0 to $300 \mu\text{m}$. The bunch repetition rate $\gamma_b = 1 \text{ THz}$, number of bunch N_b from 1 to 16, electron energy $E_e = 10 \text{ MeV}$ and beam current $I_b = 75 \text{ A/cm}$. The number of electrons per micro-bunch $N_e \approx 3 \cdot 10^7$. The longitudinal distribution of electron bunch corresponds to a Gaussian distribution with $\sigma = 55 \text{ fs}$. In the transverse direction, the electron bunch has a uniform distribution and a thickness of $t_b = 300 \mu\text{m}$. The impact parameter $h = 150 \mu\text{m}$.

The basic geometry is shown in Figure 2. The dimensions of the simulated region were 40×40 mm with grid spacing of $\Delta x = 10 \mu\text{m}$ transversely and $\Delta z = 10 \mu\text{m}$ longitudinally. Diffraction grating is located at the bottom of the simulated region. The electron beam is injected in a direction parallel to the diffraction grating through the left boundary. The spectral characteristics of the radiation and the spatial and angular dependences are recorded at a maximum distance from the grating.

3. Simulations results

3.1. The dependence of the CSPR intensity of the multi-bunched beam on the diffraction gratings grooves depth

It is known that for a rectangular diffraction grating the dependence of the CSPR intensity of the grating corrugation depth has a periodic character [6]. For sinusoidal, echelette and lamellar diffraction gratings in the groove depth range from 0 to $300 \mu\text{m}$ code KARAT simulation was carried out.

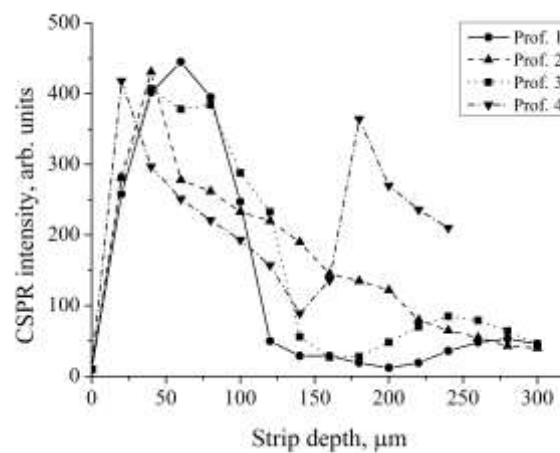


Figure 3. Dependence of the CSPR intensity of the multi-bunched beam on the diffraction gratings grooves depth.

Figure 3 shows the dependences of the radiation intensity of the corrugation depth for all studied diffraction gratings. It is seen that the periodic dependence is observed only for a lamellar grating. The electromagnetic wave enters grating groove gaps and then is reflected from the bottom of the grating and emitted back into space. Because interference of the electromagnetic waves depends on the groove depth, there is a periodic character of the radiation intensity. In sinusoidal and echelette gratings, the groove gaps are narrowed to the base which leads to deterioration of propagation of electromagnetic waves in them. Radiation with different frequencies penetrates into gaps at different depths. The interference conditions are disturbed leading to suppression of radiation with increasing groove depth.

Based on these dependencies, we can conclude that for the generation of THz radiation by diffraction gratings with a period $d = 292 \mu\text{m}$ groove depth a should be chosen equal to $60 \mu\text{m}$.

3.2. The angular distribution of CSPR by single electron bunch

PiC code KARAT simulation of the CSPR by single electron bunch for four types of gratings was carried out. The depth of the corrugation of the diffraction gratings is chosen on the basis of the results obtained above and was $a = 60 \mu\text{m}$. The angular distribution was recorded in the range of angles from 60 to 120 degrees (figure 2) where the 90 deg corresponds to the perpendicular drawn through the grating center and 120 deg towards the rear with respect to the motion of the beam electrons.

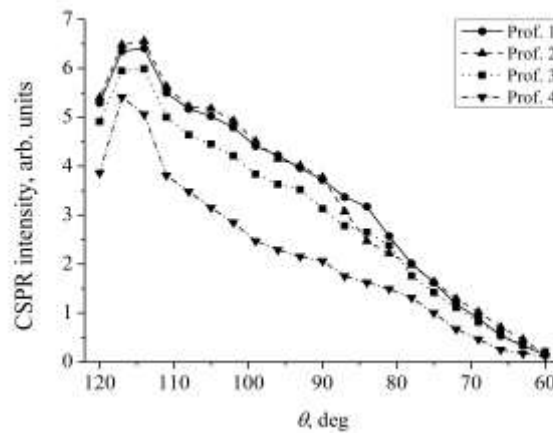


Figure 4. Angular distribution of CSPR by single electron bunch.

Figure 4 shows the angular distribution of CSPR by single electron beam for the four types of diffraction gratings. Figure 4 shows the angular distribution of the radiation intensity for the frequency corresponding to the observation angle. Dependencies increase monotonically with increasing angle of observation. In this case the radiation intensity for a lamellar grating is the lowest. The maximum intensity has the echelette grating. The results agree well with the radiation intensity depending on the grating corrugation depth for multi-bunched electron beam.

3.3. The angular distribution of CSPR by multi-bunched electron beam

The angular distribution of the CSPR by multi-bunched beam is significantly different from the case when single bunch passes near the diffraction grating. For multi-bunched beam as a result of constructive interference a set of plane waves is produced, in our case, propagating perpendicular to the grating with a frequency of 1 THz (figure 5).

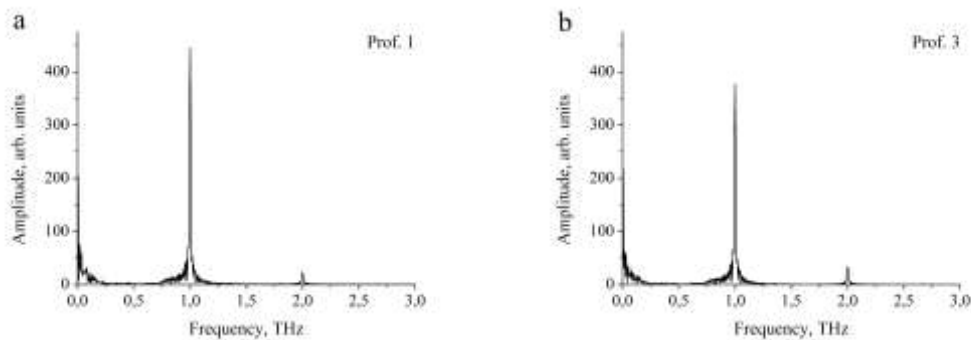


Figure 5. CSPR power spectrum for echelette (a) and sinusoidal (b) diffraction gratings for $a = 60 \mu\text{m}$.

PiC code KARAT simulation of CSPR generation by multi-bunched electron beam consisting of 16 micro-bunches for the diffraction gratings of different profile was carried out. The depth of the corrugation gratings $a = 60 \mu\text{m}$. Figure 6 shows the angular distribution of the CSPR intensity. In this case, CSPR consists of planar wavefronts formed due to constructive interference between successive bunches. The transverse dimensions of the planar wavefronts are determined by the geometrical dimensions of the grating. It should be noted that the efficiency of CSPR generation from the echelette grating is almost two times higher than that for the lamellar grating.

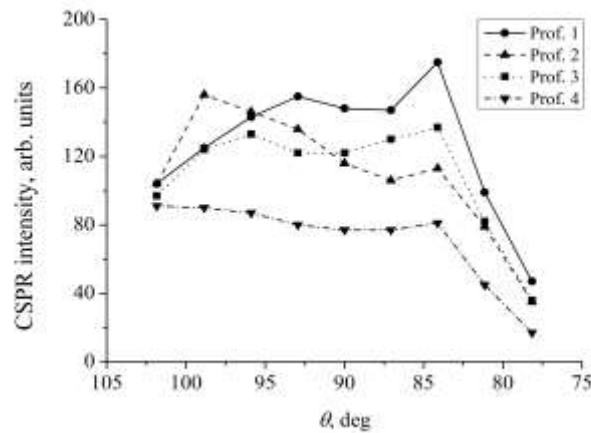


Figure 6. Angular distribution of CSPR by multi-bunched electron beam.

In addition, the shape of the angular distribution depends on the gratings profile. Since the angular distribution for a sinusoidal grating is most uniform at a sufficiently high average intensity. At the same time, the angular distribution for echelette gratings is not symmetric with a significant amplitude difference depending on the observation angle.

4. Conclusion

Numerical simulation by PiC-code KARAT allowed a direct comparison of the efficiency of the CSPR generation from four types of diffraction gratings for single electron bunch and for multi-bunched electron beam. The analysis of the spatial and angular characteristics of radiation leads to the conclusion that the optimal grating for further investigations is the sinusoidal grating with a period $d = 292$ mm and a depth of corrugation $a = 60$ mm.

Uniform angular distribution and high intensity of radiation are undoubted advantage over diffraction gratings with echelette profile and, especially, gratings with a lamellar profile.

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