FEASIBILITY OF THZ SOURCE BASED ON COHERENT SMITH-PURCELL RADIATION GENERATED BY FEMTOSECOND ELECTRON BUNCHES IN SUPER-RADIANT REGIME*

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Abstract

We report about starting of a new project devoted to investigation of THz radiation generation based on coherent Smith-Purcell radiation of a bunched electron beam with THz repetition rate. In this report we present the first simulations of the radiation characteristics and discuss the future plans.

INTRODUCTION

Research and development of the new compact radiation sources especially in the THz region is one of the most import tasks of the modern accelerator physics. The THz region is very important for the development of the practical applications in various fields, e.g. material science, biomedical imaging and homeland security. Nowadays the THz radiation is generated mostly by the large accelerator complexes such as light sources and FELs or by the compact semiconductor devices [1]. The light sources generate up to tens watts of power that is useful for material science but is not so useful for biomedical applications where "lower powers with high signal-to-noise ratio are preferable to simply high power" [1]. The compact semiconductor devices are better with respect to signal-to-noise ratio but the power, monochromaticity and the radiation frequency tuning are the points need to be improved.

The recent development of accelerator and laser technologies makes it possible to create a compact accelerator-based powerful monochromatic THz source with the tunable radiation frequency. A short (hundreds of femtoseconds) electron bunch of the accelerator may generate the powerful coherent radiation in a various processes e.g. transition radiation or Smith-Purcell radiation (SPR). In the case when electron bunches have THz repetition rate the radiation spectrum changes and the power increases significantly . Such radiation generation regime is often called the "super-radiance" [2] or the "frequency-locked radiation" [3].

In Refs. [3, 4] authors measured the spectral-angular characteristics of coherent SPR (CSPR) generated by the multibunch beam. SPR is generated when a charged particle travels in a vicinity of the surface of a periodic structure, i.e. a diffraction grating. Due to the periodicity involved in the radiation generation, this kind of radiation obeys a characteristic dispersion relation which relates the observation wavelength λ and the radiation angle θ, the so called Smith-Purcell relation:

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

with d the grating period, n the diffraction order, and β the charged particle velocity in units of speed of light. The authors of Refs. [3, 4] demonstrated the significant change of the radiation spectrum with the change of the bunch repetition rate. In Ref. [5] authors showed that it was possible to generate the tunable THz radiation changing the repetition rate of the laser pulses that were used to generate the electron beam. The electron beam had the same structure as the laser pulse and generated coherent transition radiation in the super-radiant regime.

In this paper we present our new project devoted to investigation of CSPR generation by 10 MeV multibunch electron beam in the super-radiance regime. We plan to generate the multibunch electron beam using the femtosecond laser with the tunable repetition rate of the pulses. As a first step we carried out the numerical simulation of CSPR characteristics in order to show that the multibunch electron beam generates the radiation with better characteristics than the single bunch.

RADIATION GENERATED BY MULTIBUNCH BEAM

It is well known that in the case when the radiation wavelength is longer than the bunch length the radiation intensity is increased quadratically with the bunch population. The total radiation power $\frac{dW_{tot}^2}{d\omega d\Omega}$ generated by the single short bunch may be written as (neglecting transverse form-factors):

$$\frac{d^2W_{tot}}{d\nu d\Omega} = \frac{d^2W_e}{d\nu d\Omega} N_e \left(1 + (N_e - 1)\,|f_z|^2\right) \qquad (2)$$

where $\frac{dW_e^2}{d\omega d\Omega}$ is the radiation generated by the single electron, N_e is the bunch population, $|f_z|^2$ is the longitudinal form-factor that is the Fourier transform of the longitudinal distribution of the electrons in the bunch.

In the case of radiation generated by the multibunch beam the total radiation intensity is modified and the following dependence on the number of bunches N_b and on the distance between the bunches λ_s appears:

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$$\frac{dW_{tot}^2}{d\nu d\Omega} = \frac{dW_e^2}{d\nu d\Omega} N_e \left(1 + (N_e - 1)\frac{\sin^2\left[\frac{N_b \pi \nu \lambda_s}{\beta c}\right]}{\sin^2\left[\frac{\pi \nu \lambda_s}{\beta c}\right]} |f_z|^2\right) \tag{3}$$

From Eq. (3) one may see that the radiation power is intensified at the frequencies that correspond to the bunch repetition rate and its harmonics and is suppressed at the other frequencies. One may also see that the radiation intensity in the spectral peak maximum increases quadratically with the number of bunches. However, the integral over the whole spectrum increases linearly with the number of bunches. The spectral line width decrease with the number of bunches as N_b^{-1}.

SIMULATION OF CSPR CHARACTERISTICS

Simulation of CSPR characteristics was carried out using particle-in-cell electromagnetic code KARAT [6]. It is aimed primarily at the solution of non-stationary problems of electrodynamics having complicated geometry and involving dynamic of relativistic electrons and nonrelativistic ions. In particular, KARAT is well suited to the simulation of high-current electron devices such as vircators, free-electron lasers, gyrotrons, etc. A finite difference scheme with overstepping on the rectangular shearing grid is used to solve Maxwells equations. The electric field is corrected with the help of Boris method. The schemes unique feature is a special grid shear that provides fulfillment of the boundary conditions without any extrapolation. In addition, the code has several features useful for modeling phenomena associated with charged particle beam devices. One may adjust the code for potential approximation of electromagnetic problems. The code KARAT has been compared to analytic solutions and applied successfully to many physical problems. The results have been found in reasonable agreement with laboratory experiments [6]. For our simulation we used two dimensional version of the code. However, in this case all case three electromagnetic field components and three momentum components are taken into account.

The "screen shot" of the simulated CSPR generation process that gives an idea of the simulation scheme is shown in Fig. 1. The simulation was carried for the following beam parameters: electron energy $E_e = 10\,\text{MeV}$, bunch repetition rate $\nu_b = 1\,\text{THz}$, beam current $I_b = 75\,\text{A/cm}$, impact-parameter $h = 150\,\mu\text{m}$, number of bunches $N_b = 6$. The bunch had a Gaussian longitudinal distribution with the rms $\sigma_z = 55\,\text{fs}$, and the uniform transverse distribution with the beam thickness $t_b = 300\,\mu\text{m}$.

As a first step we simulated radiation characteristics for the different grating profiles: the lamellar grating with the period equal to $d = 272\,\mu\text{m}$ and the echelette-type grating with the same period. According to our simulation the echelette-type grating was better for generation of CSPR by the multibunch beam because the high order modes are suppressed. The optimal blaze angle of the grating was equal to 30 degrees. The following simulations were carried out for echelette-type grating with the period equal to $272\,\mu\text{m}$, 30 degree blaze angle, number of periods is equal to $N_p = 64$.

Fig. 2 shows CSPR power spectrum for different number of bunches in the train measured at the point #1 (see Fig. 1). The insert in Fig. 2 shows the radiation in the neighborhood of 1 THz frequency in more details. In Fig. 2 one may see that CSPR spectrum consisted of the main peak at the frequency 1 THz that coincided with the bunch repetition rate and the collateral peak at the frequency 0.9 THz. Such double peak structure arose because of the choice of the observation point that is rather close to the grating. However, one may see in the insert of Fig. 2 that the collateral peak intensity was suppressed with increase

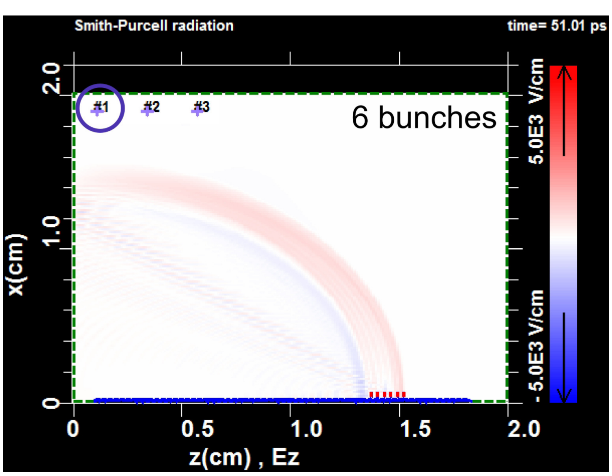

Figure 1: "Screen shot" of the simulated CSPR generation process. The radiation was generated by 6 bunches (shown as the red dots) and was measured at the numbered points.

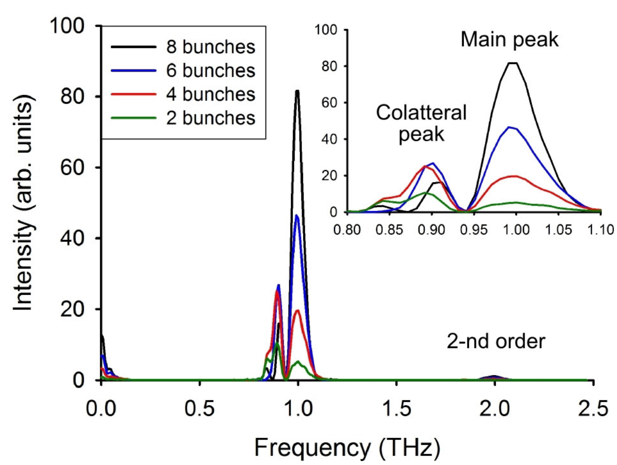

Figure 2: CSPR power spectrum for the different number of bunches in the train measured at the point #1. The insert shows the radiation in the neighborhood of1 THz frequency in more details

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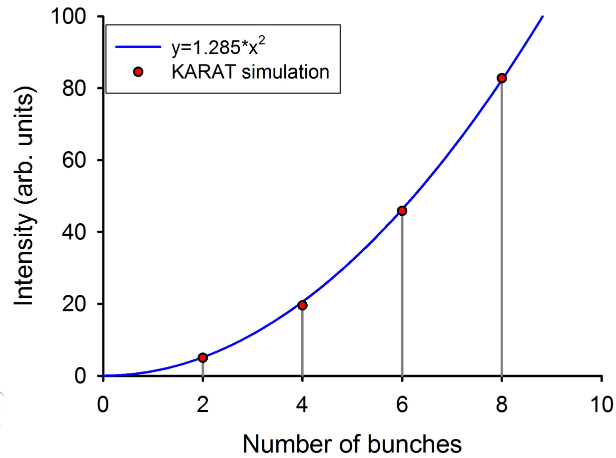

Figure 3: Dependence of the main spectral peak maximum on the number of bunches

of the number of bunches. We would like to point that the optimal choice of the bunch repetition rate that should coincide with the maximum intensity of CSPR allows to increase the radiation power. One may also see in Fig. 2 that there is the second radiation harmonic at the frequency equal to 2 THz. However, the intensity of this radiation harmonic is suppressed as it was mentioned above.

Fig. 3 shows the dependence of the main spectral peak maximum intensity on the number of bunches that increased quadratically. The solid line in Fig. 3 shows the fit by the function $y = 1.285x^2$. However, the integration of the whole spectrum resulted in the linear increase of the radiation power with the number of bunches. Such dependence confirms our theoretical calculation of the coherent radiation generated by the multibunch beam.

LUCX ACCELERATOR

We plan to carry out our experimental investigation of THz CSPR generated by the femtosecond multibunch beam using LUCX facility at KEK (Tsukuba, Japan). LUCX - laser undulator compact x-ray project, is a multipurpose linear electron accelerator. A total length of the accelerator is equal to 12.5 m. A new, 3.6 cell RF gun with a high mode separation and a high Q value is installed to produce a multi-bunch high quality electron beam with up to 1000 bunches, a 0.5-nC bunch charge, and 10-MeV beam energy which is accelerated to 30 MeV by the normal conductivity 3-m S-band accelerating structure [7]. Recently the upgrade plan involving replacement of the 3 m structure by 1 m 12-cell mode-separated booster and introducing new femtosecond Ti-Sapphire laser system for RF Gun has been released [8]. The accelerator parameters are listed in Tab. 1.

CONCLUSION AND OUTLOOK

CSPR characteristics generated by the multi-bunch electron train were simulated for the different number of bunches with THz repetition rate and for the different gratings. Simulation results clearly show that Smith-Purcell radiation is generated in the coherent mode i.e. the radiation intensity increases quadratically with the bunch population. The power spectrum of the radiation has the strong maximum at the frequency that corresponds to the bunch repetition rate. The intensity of the maximum scales quadratically with the number of bunches. However, the radiation intensity integrated over the whole spectrum scales linearly with the number of bunches that coincides with theoretical estimations.

Table 1: LUCX 2012 upgrade beam parameters at SPR chamber

Energy	10 MeV,
Intensity	0.4 nC/bunch
Number of bunches	1000
Number of microbunches	6
Bunch spacing	2.8 ns
Microbunch spacing	$\geq$ 100 fs
Bunch length	10 ps
Repetition rate	up to 12.5 train/sec
Normalized emittance	$5 \times 5\,\pi$ mm mrad

According to the simulations the echelette-type grating is better for generation of CSPR because of suppression of the higher harmonics in the radiation spectrum. The optimal blaze angle of the grating is equal to 30 degrees.

As a first step we plan to carry out experimental test of the grating efficiency using the present-day configuration of LUCX accelerator. The machine configuration allows generating CSPR with the frequencies of the order of 100 GHz. Such test planned to be carried out during the autumn 2012 allows to define the optimal grating parameters for THz radiation generation after the upgrade of LUCX accelerator.

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