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SUPERRADIANT EMISSION OF ELECTRON BUNCHES BASED ON CHERENKOV EXCITATION OF SURFACE WAVES IN 1D AND 2D PERIODICAL LATTICES: THEORY AND EXPERIMENTS*

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Abstract

We report of the experiments on Cherenkov generation of 150 ps superradiance pulses with a central frequency of 0.14 THz, and an extremely high peak power up to 70 MW. In order to generate spatially coherent radiation in shorter wavelength ranges (including THz band) in strongly oversized waveguiding systems, we propose a slow wave structure with double periodic corrugation (2D SWS). Using quasi-optical theory and PIC simulations, we demonstrate the applicability of such 2D SWS and its advantages against traditional 1D SWS. Proof-of-principle experiments on observation G-band Cherenkov superradiance in 2D SWS are currently in progress.

INTRODUCTION

In recent years, significant progress was achieved in generation of high-power ultrashort microwave pulses based on superradiance (SR) of electron bunches extended in the wavelength scale. In this process, coherent emission from the entire volume of the bunch occurs due to the development of microbunching and slippage of the wave with respect to electrons.

The SR pulses with the highest peak power were obtained for the Cherenkov mechanism when electrons interact with the backward wave propagating in slow-wave structures (SWS). In the Ka-band, peak power exceeding 1 GW was obtained [1, 2]. In these experiments, an electron bunch interacts with a synchronous spatial harmonic of the lowest TM-polarized volume mode of periodically corrugated waveguide with an oversize factor $D/\lambda \approx 1$ (D is the mean diameter and λ is the radiation wavelength). However, in the shorter wavelength bands, the use of single-mode SWS is becoming more complicated due to strict requirements for transportation of the high-current electron beams and increase of the Ohmic losses.

Advancement of vacuum electronic devices into sub-THz and THz frequency ranges calls for oversized beam-wave interaction space due to the fact that that the dimensions of the beam guiding systems can not be reduced lower than the millimeter scale. Thus, in order to provide coherent THz radiation from the spatially extended beams, excitation of surface modes existing in 1D and 2D corrugated systems appears to be attractive [3-6].

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In this paper, we present recent results of theoretical and experimental studies of SR emission based on excitation of surface waves by extended bunches. Using oversized 1D slow-wave structures allows for a significant increase of total current and, correspondingly, the output radiation power. Based on SR of electron bunches in a cylindrical corrugated waveguide, 150 ps short-pulse SR emission with a central frequency of 0.14 THz, and an extremely high peak power reaching 50-70 MW were obtained in the joint effort by the Institute of Electrophysics RAS and IAP RAS.

Further increase of the frequency or of the aimed radiation power requires the increase of the transverse dimensions of the interaction space, which, in turn, leads to the loss of the mode control over the azimuthal coordinate. The problem of mode synchronization over this coordinate can be solved by using the SWS with 2D corrugation. Proof-of-principle experiments are in progress based on the RADAN accelerator. We present here the results of 3D numerical simulation of Cherenkov SR emission in the 3mm wavelength range in an oversized cylindrical waveguide with 2D corrugation of the wall. A SR pulse with a duration of 0.5 ns and an output power of ~ 70 MW was obtained.

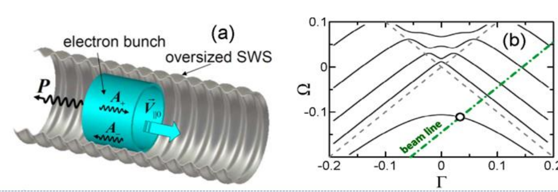

Figure 1: a) Scheme of SR pulse generation with excitation of a surface wave in an oversized periodically corrugated waveguide. b) Dispersion characteristics of the corrugated waveguide and an electron beam.

SIMULATION AND EXPERIMENTS ON GENERATION OF SURFACE-WAVE SR PULSES IN 1D LATTICES

Cherenkov SR of electron bunch exciting the surface wave in an oversized 1D corrugated cylindrical waveguide (Fig. 1a) can be considered within quasi-optical approach [3]. In this case the radiation field near a shallow corrugation is presented as a sum of two counter-propagating TM polarized wavebeams:

$$H_\varphi = \mathrm{Re}(A_+(z,r,t)e^{i\bar{\omega}t-ikz} + A_-(z,r,t)e^{i\bar{\omega}t+ikz}), \quad (1)$$

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propagation and mutual coupling of which is described by two non-uniform parabolic equations:

$$\frac{\partial A_+}{\partial z}+\frac{\partial A_+}{c\partial t}+\frac{i}{2k}\frac{\partial}{\partial r}\left(\frac{1}{r}\frac{\partial\left(rA_+\right)}{\partial r}\right)=i\alpha\delta\left(r-r_0\right)A_- +$$

$$+\frac{iI_0}{\bar{\omega}S_b}f\left(z-v_0t\right)\frac{\partial}{\partial r}\left(\psi\left(r\right)J\right), \quad (2)$$

$$-\frac{\partial A_-}{\partial z}+\frac{\partial A_-}{c\partial t}+\frac{i}{2k}\frac{\partial}{\partial r}\left(\frac{1}{r}\frac{\partial\left(rA_-\right)}{\partial r}\right)=i\alpha\delta\left(r-r_0\right)A_+,$$

The amplitude of the RF current J is found from the electron motion equations. Synchronous interaction of electrons with forward partial waves leads to development of self-bunching and formation of powerful SR pulse.

Simulations show that the most optimal conditions for SR emission correspond to excitation of the backward surface wave near the Bragg frequency (π- regime, Fig.1b). For parameters of an electron bunch formed by an accelerator RADAN (electron energy of 300 keV, a total current of 2 kA, a bunch duration of 500 ps) and a corrugated waveguide with the mean radius of 3.75 mm, corrugation period of 0.825 mm, and corrugation depth of 0.36 mm the operating frequency in the resonant point is of 0.14 THz ($D/\lambda \approx 3.5$). In this case the power of generated SR pulse emitted in $-z$ direction achieves ~200 MW for pulse duration of ~200 ps (Fig. 2a). As it is seen in Fig. 2b the instant spatial structure of the partial wave corresponds to formation of the evanescent surface wave with the field amplitude exponentially decaying from the corrugation.

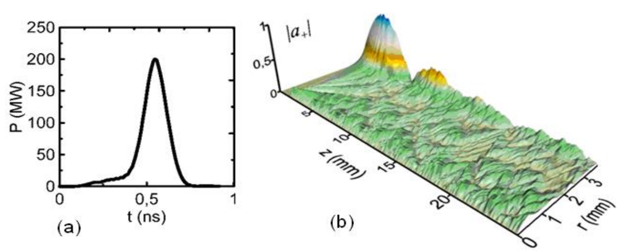

Figure 2: SR emission with excitation of the backward surface wave: a) generated SR pulse, b) structure of the forward partial wave.

Based on the theoretical analysis, experiments on observation of the sub-terahertz SR pulse generation were carried out in IEP RAS (Ekaterinburg). Photo of the experimental set-up is shown in Fig. 3a,b. A typical oscilloscope trace of generated SR pulses with a duration of about 150 ps and a rise time of 100 ps reconstructed in the "power-time" coordinates is presented in Fig. 3c. Frequency measurements using a set of cut-off waveguide filters show that the pulse spectrum has a central frequency in the interval 0.13-0.15 THz. The peak power of generated SR pulses was estimated by integrating the detector signal over the directional pattern and achieved of 50-70 MW, that strongly exceeds the value obtained in the previous sub-terahertz experiments [4] with single-mode waveguides.

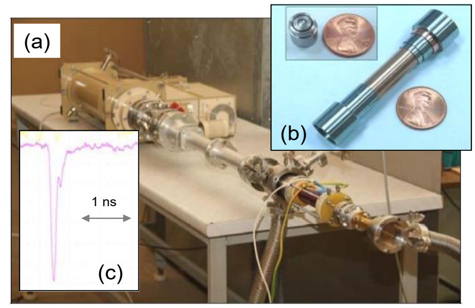

Figure 3: Photo of the experimental set-up (a), corrugated waveguide and coaxial reflector (b) used for observation of SR with excitation of a surface wave. (c) Oscilloscope trace of the 0.14 THz SR pulse with duration of 150 ps and peak power up to 70 MW.

SIMULATION OF HIGH-POWER CHERENKOV SR PULSE GENERATION IN 2D SLOW-WAVE STRUCTURES

However, at larger oversize factors, the transverse mode selection problem arises, that leads to deformation of the radiation pattern of a Cherenkov SR generator. A promising method to solve this problem in highly oversized systems is based on using slow wave structures in the form of cylindrical waveguide with two-dimensional corrugation of its walls, 2D SWS [5,6]. Similar structures were proposed [7] for transverse synchronization of radiation and provision of distributed feedback (DFB) in free electron masers (FEM) based on sheet [8] or tubular [9] electron beams. Due to formation of azimuthal wave fluxes, such structures ensure synchronization of the radiation of a tubular electronic bunch of large diameter. The distinguishing feature of Cherenkov devices exploiting 2D DFB is that in this case, unlike FEM, the 2D structures can play the role of SWS and of a synchronizer simultaneously. Recent experiments [6] at IAP RAS based on the SATURN accelerator has proven the viability of surface wave oscillators with 2D SWS operating in steady state oscillation regime.

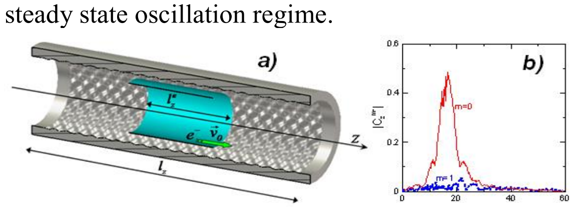

Figure 4: Simulations of 90 GHz SR pulse generation with excitation of azimuthally symmetric surface wave in a cylindrical 2D SWS: a) geometry of the interaction space; b) temporal dependence of the amplitudes $\left|\hat{C}_z^{m-}\right|$ of modes with different azimuthal indices (in the framework of a quasi-optical approach).

In order to demonstrate the effectiveness of the proposed approaches we carried out the simulations of SR pulse generation in 3-mm wavelength band (90 GHz) with parameters of experiment to be conducted at the Institute of Elecrophysics. We assumed that the surface

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wave is excited by a hollow cylindrical electron bunch with electron energy of 300 keV, the total current of 2 kA, a bunch duration of 1 ns, the mean injection radius of 7.5 mm, and the beam width of 0.2 mm. These parameters can be obtained using high-current accelerators, namely RADAN accelerator [3]. Interaction takes place in 2D SWS with mean diameter D = 17.2 mm, period of corrugation 2.7 mm and corrugation depth 1.1 mm (Fig.4a). For the chosen radiation frequency, the oversized factor is of $D / \lambda \approx 5.7$. The total length of SWS was 6 cm.

First simulations were carried out based on the quasi-optical theory developed in [10]. In the frame of this approach the electromagnetic field near the 2D corrugated surface is presented as a sum of four components (compare to Eq.(1)), two of them propagate in longitudinal $\pm z$ directions and two others in azimuthal directions. Evolution of all components is described by a set of coupled parabolic equations. This set is complemented by the averaged motion equations for electrons and also by the corresponding boundary conditions. The results of simulations are presented in Fig. 4b. As it is seen, the radiated field includes mainly the azimuthally symmetric harmonic $m=0$ at almost all stages of the SR pulse formation. In fact, it is provided by the presence of azimuthal wave fluxes in the 2D periodic structure which leads to synchronization of radiation from different parts of the electron bunch during the SR pulse formation. As a result, the amplitude and phase distributions are close to azimuthal symmetry.

Conclusions obtained in the framework of the averaged quasi-optical approach are confirmed by the results of PIC modeling using the CST PIC code. Figure 5 presents the results of PIC modeling for the parameters of the 2D SWS and an electron bunch mentioned above. One can see that at the central frequency of about 90 GHz, peak output power of SR pulses reaches 70 MW for the pulse duration of ~0.5 ns with azimuthally symmetric output pattern. The surface wave is formed by the modes with radial indices n = 1, 2, and 3, while the amplitudes of asymmetric modes (e.g., $TM_{1,1}$) are negligibly small. It should be noted that use of a 2D SWS ensures the formation of a reproducible azimuthally symmetric structure of the output radiation even at certain deviations of the relativistic tubular bunch axis from the waveguide axis.

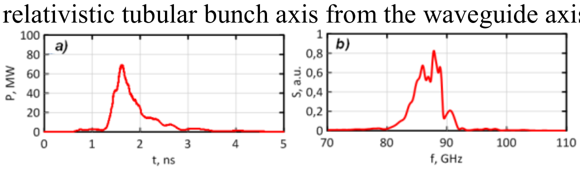

Figure 5: 3D simulations of 90 GHz SR pulse generator with 2D SWS: a) temporal dependence of the output radiation power; b) the spectrum of the output signal.

Thus, the results of our model analysis demonstrate good prospects of using the regime of surface-wave excitation in highly oversized 2D corrugated SWS for the generation of SR pulses in the millimeter waveband. It should be noted that, similarly to SR in single-mode waveguides, optimization of the profile of 2D corrugation would provide a significant increase in the peak power of output radiation at fixed energy characteristics of the electron bunch. It is also of interest to analyze the possibility of using 2D periodic SWS for SR pulses generation in the short-wavelength part of the millimeter band. Experimental investigations in this direction are currently planned on the basis of the RADAN electron accelerators.

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