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First indication of the coherent unipolar diffraction radiation generated by relativistic electrons

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Abstract: As is generally known, the integral of the electric field strength over all time for usual (bipolar) radiation is zero. The first demonstration of the possibility of unipolar radiation generation has been considered theoretically by Bessonov in 1981 [E.G. Bessonov, *Zh. Eksp. Teor. Fiz.* **80** (1981) 852]. According to this work, the unipolar radiation (or strange electromagnetic waves) is radiation for which the integral of the electric field strength over the entire duration of a pulse differs significantly from zero. Later, several theoretical papers devoted to this phenomenon have appeared in the literature, where authors investigated mainly synchrotron radiation. However, despite the critical interest, the experimental investigations ignored this effect. In this paper we present results of the first experimental investigation of the unipolar radiation generated by a relativistic electron beam. To detect the unipolar radiation the detector that is sensitive to the selected direction of the electric field strength has been elaborated and tested. We used a designed detector to observe the coherent backward diffraction radiation appearing when a bunched electron beam travels in the vicinity of a flat conductive target. The asymmetry of the electric field strength of the coherent backward diffraction radiation has been demonstrated.

Keywords: Polarisation; Microwave Antennas; Microwave radiometers

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Contents

1 Introduction

Radiation of relativistic electrons is usually presented as bipolar radiation. It means that the integral of the electric field strength over the entire duration of a pulse is zero, i.e., $\int_{-\infty}^{\infty} E(t)\,dt = 0$. This is probably due to the fact that the radiation is considered mainly in the Fourier representation, when it operates with its harmonic decomposition. The first mention of unipolar radiation belongs to Bessonov [1], who theoretically investigated unipolar pulses named as "strange electromagnetic waves", which satisfy the condition $\int_{-\infty}^{\infty} E(t)\,dt \neq 0$. After a detail theoretical study of generation process of unipolar radiation produced by relativistic electrons in a magnetic field the author formulated a criterion of unipolarity. The Fourier component of electric field can be written as $E_\omega = \int e^{i\omega t} E(t)\,dt$. One can show that if $\int E(t)\,dt = 0$, then in classical (non-quantum) approximation $E_{\omega\to 0} = 0$, and vice versa. Thus, the relationship $\frac{E_{\omega\to 0}}{\int |E(t)|dt}$ in indicated approximation can be regarded as a normalized criterion for radiation unipolarity. This work caused a stormy theoretical study of this problem.

The possibility of a unipolar pulse generation in nonlinear media in terahertz and optical electromagnetic ranges was considered theoretically in number of articles [2–9]. In [10] the possibility of unipolar pulse radiation in the context of Cherenkov radiation when medium is excited by ultrashort pulses at superluminal velocity was considered. Also, the existence of unipolar subcycle solitonic solutions of Maxwell-Bloch equations has been considered in [11–14].

The possibility of generating a unipolar radiation of relativistic electrons in a magnetic field has been theoretically shown in [1, 15, 16]. However, experimental studies devoted to the emission and detection of unipolar radiation did not carried out.

In this paper we present the results of the first experimental investigations of the unipolar backward coherent diffraction radiation generated by relativistic electrons, which travel in the vicinity of a plane conducting target. Diffraction radiation is the radiation of electrons moving near an edge of target without crossing it. In [17, 18] one may find the theoretical consideration of the backward diffraction radiation (BDR) of relativistic electrons from a conducting semiplane. These conditions are very close to our experimental one. In [17] the authors obtained the solution for

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the BDR vector potential in Fourier presentation (a schematic view of radiation geometry shown in figure 1):

$$A_x(R) = \frac{2\pi e^{i\omega R}}{R} j_x(k_0, q_0),$$

where R is the distance from the target to the observation point. In system, where $x = R\sin\psi\cos\varphi$, $y = R\sin\psi\sin\varphi$, $z = R\cos\psi$, $k_0 = -\omega\sin\psi\cos\varphi$, $q_0 = -\omega\cos\psi$, ψ is the axial angle between an observation direction and the z axes. Expression for current $j_x(k, q)$ has complicated view and one may find it in [17]. The vector potential A_x corresponds to the horizontal component of polarization. After the back Fourier transform we obtain the expression for the time dependence of the horizontal polarization component of the electric field strength of BDR

$$E_x(t) = \int_{-\infty}^{\infty} e^{i\omega t}\omega \cdot A_x(R)\, d\omega.$$

This dependence for experimental conditions (see paragraph 2.1) is shown in figure 2.

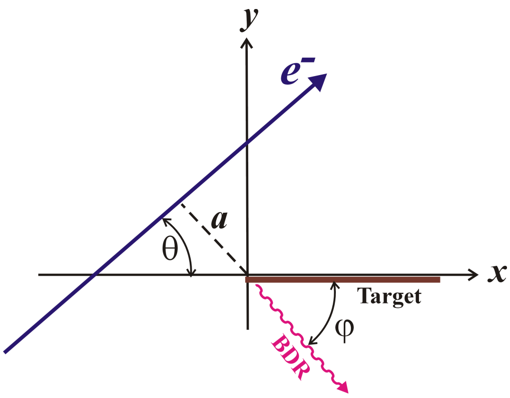

Figure 1. Geometry of interaction (figure 1 from [17]).

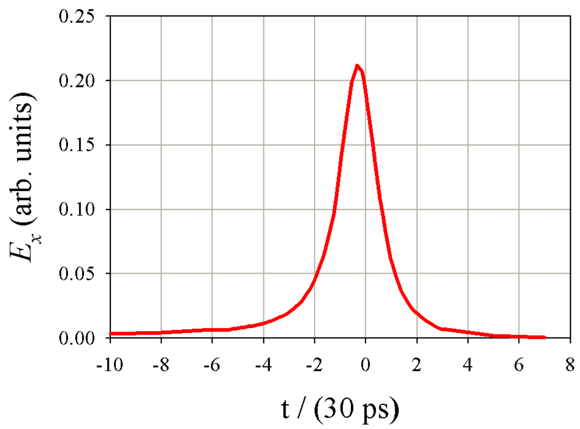

Figure 2. The time dependence of the horizontal polarization component of the BDR electric field strength.

As is seen from figure 2 the BDR is strongly unipolar.

On the other hand, in the pseudo-photon approximation [19, 20] the BDR of relativistic electrons from a conducting target is the reflection of the electronfield from the target. For the BDR geometry (figure 3) the horizontal polarization component of the reflected electric field of electrons keeps the same direction and we can expect that BDR is unipolar.

2 Experimental setup

2.1 Layout of experiment

The experiment was carried out using the relativistic electron beam extracted from the microtron in Tomsk Polytechnic University. The beam parameters are listed in table 1.

Under these conditions, radiation from the electron bunch at wavelengths $\lambda > 9$ mm ($\nu \leq 33.3$ GHz) is coherent [21]. Since the process of radiation generation is coherent, the intensity of

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radiation increases by a factor of N_e, where N_e is electron number in a bunch, and can be measured by existing detectors at room temperature.

Table 1. Beam parameters.

Electron energy	6.1 MeV ($\gamma = 12$)
Macro-pulse (train) duration	4 µs
Bunch length	$\sigma_z = 3 \pm 1$ mm
Bunch population	10^8
Bunches in train	10^4
Distance between bunches	$\Lambda = 114$ mm
Extracted beam size	4×2 mm

The measurement time is determined by the pulse duration $\tau = 4$µs of the electron beam, which corresponds to the wavelength $\lambda = 2\pi c\tau = 7.2$ km, however, since we measure only the coherent radiation from the electron bunch, the minimum wavelength of the measured radiation is determined by the longitudinal bunch form factor and is equal $\lambda_{\min} \sim 9$ mm.

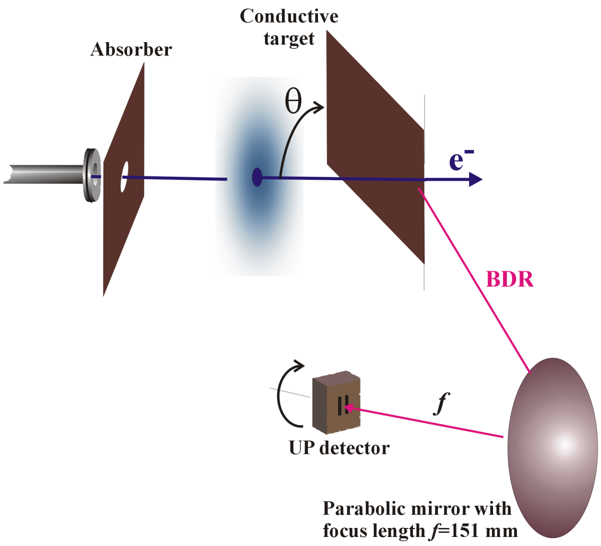

Figure 3. Layout of experiment. Detector is placed in the focus of parabolic mirror.

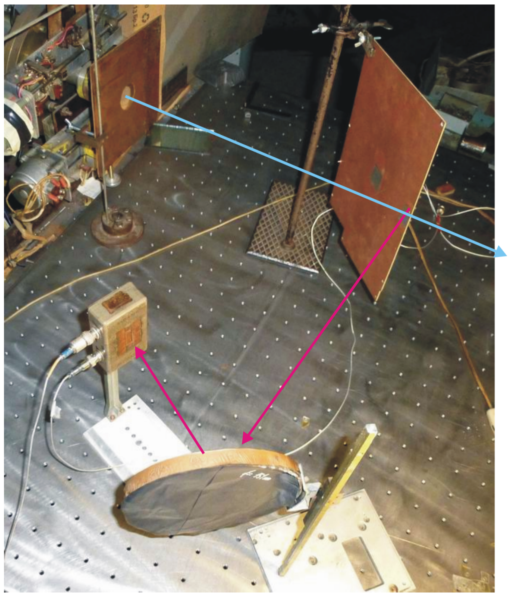

Figure 4. Photograph of experimental setup.

The layout of the experiment and a photograph of experimental setup are shown in figure 3 and 4 respectively. The detector is placed in the focus of the parabolic mirror with focus length $f = 151$ mm to provide the measurement of angular distribution of radiation in the far field zone (see [22]). The target could be rotated around its vertical edge for a radiation orientation dependence measurement (so-called θ-scan, where θ is the angle between target surface and electron beam direction). The impact-parameter a (the shortest distance from the edge of the target to the centre of electron beam) is 16 mm. The transversal beam size near the target is $\sigma_{\mathrm{BS}} = 15$ mm. The measurements were carried out at the angle $\psi = 90°$. The distance from the target to the parabola is 300 mm and $11\,mm < \lambda < 14$ mm. In this case, the formation length $l_f \sim \lambda/2\pi \approx 2$ mm, which is much less than the distance from the target to the parabola. To suppress intensity of transition radiation from the extraction window an absorber was used.

2.2 Detector

To measure unipolar radiation, a detector (see figure 6) based on the well-known technique applied for the surface current measurement in strip-line beam position monitors [23] has been developed. The scheme of detector is shown in figure 5. Surface currents induced by radiation in different directions are dispensed by microwave diodes to different channels: channel No 1 and channel No 2.

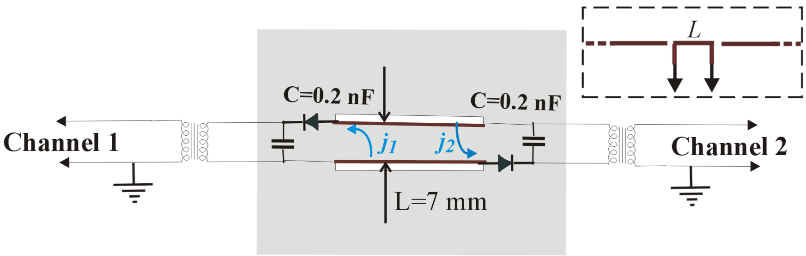

Figure 5. Scheme of detector. In insertion the profile of strip is shown.

Figure 6. Image of detector.

The spectral efficiency of the developed detector according to [23] is shown in figure 7, where $\nu_0 = \frac{c}{4L} = 10.7$ GHz and c is the speed of light. Spectral range of detection equals $\Delta\nu_{\mathrm{FWHM}} = 10$ GHz. In the current experiment the measurements of the radiation orientation dependence were carried out for two positions of the detector, which are demonstrated in figure 8. Thus, different directions of the electric radiation field are detected by different channels.

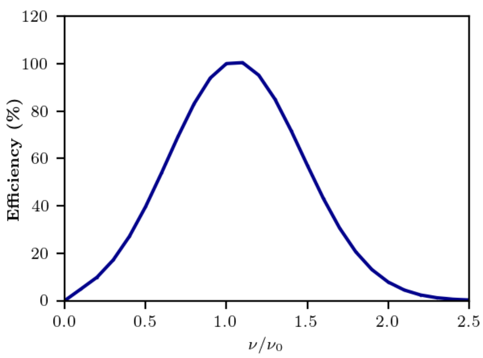

Figure 7. Spectral efficiency of detector

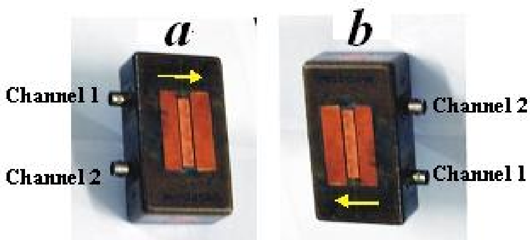

Figure 8. Indication of the detector position.

3 Measurement results

Using technique described we measured the θ-scans from channels No 1 and No 2 for the ***a*** and ***b*** detector positions as shown in figure 8. The examples of the θ-scan obtained after background suppressing are shown in figures 9 and 10. The background was measured without a conductive target for each position of the detector. In figure 11 the θ-scan of the radiation intensity with indication of statistical errors (see figure 10a), and the similar scan without a target (i.e. background) is shown. One can see in figures 9, 10 that the channels No 1 and No 2 demonstrate opposite results for the ***a*** and ***b*** detector positions. Obtained results suggest that the induced currents and, hence, the strength of the electric field of radiation have an allotted direction.

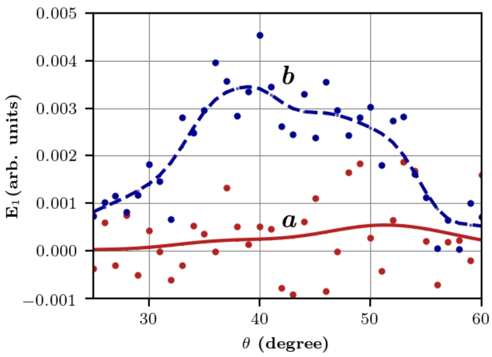

Figure 9. The θ-scan from channel 1 for the ***a*** and ***b*** detector positions (see figure 11). The solid and dashed lines are the smoothed experimental data.

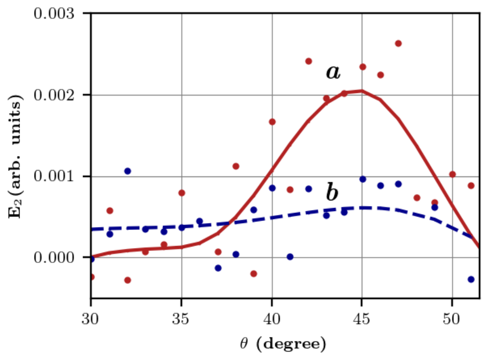

Figure 10. The same as in figure 9 but for channel 2.

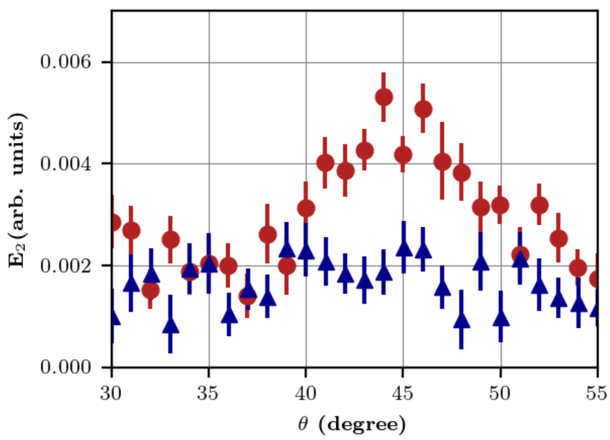

Figure 11. The θ-scan from channel 2 (red circles) for the ***a*** detector position (see figure 8 and 10) with indication of statistical errors, and the similar dependence of the background (blue triangles).

Thus, we can state that the unipolarity effect of BDR is observed.

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4 Conclusion

In this paper we demonstrated that BDR is unipolar radiation (possibly, partially unipolar). The detector developed provides the possibility of detection of the unipolarity effect of radiation. Our next steps will be to assume:

a) Optimization of the parameters of the unipolar radiation detector. We should note that it is necessary to modify the detector including full matching of its elements such as antenna characteristics, microwave diodes and signal registration circuitry, as well as providing pre-amplification of the signal, in future experiments;

b) In [1, 15, 16] authors theoretical studied synchrotron radiation and demonstrated that it is unipolar. Thus, experimental investigation of unipolarity of synchrotron radiation is waited for;

c) According to [24], Cherenkov radiation can be generated when an electron beam passes near a dielectric target. This geometry is very similar to the geometry of diffraction radiation and we may expect that Cherenkov radiation could also be unipolar. The investigation of this effect will be carried out experimentally;

d) From fundamental point of view the particular interest is the analysis of the bremsstrahlung unipolarity. According to [25], to calculate the radiation field in the low-frequency approximation, one can use the expression for the Liénard-Wiechert potentials:

$$\vec{E} = \frac{e}{c^2} \frac{1}{\left(R - \frac{\vec{v}\vec{R}}{c}\right)^3} \vec{R} \times \left(\left(\vec{R} - \frac{\vec{v}R}{c}\right) \times \vec{a}\right),$$

where e is the electron charge, $\vec{R}$ is the radius of the observation vector, $\vec{v}$ is the electron velocity, and $\vec{a}$ is the electron acceleration in the field of the nucleus, which for $\gamma \gg 1$, where γ is the Lorentz factor, takes the form: $\vec{E} \approx -\frac{e\gamma^4}{Rc^2}\vec{a}$. Obviously, $\vec{a}$ is determined by which side and at what distance from the nucleus the electron moves. The last parameters can be fixed by using the bremsstrahlung photon tagging system (see figure 12).

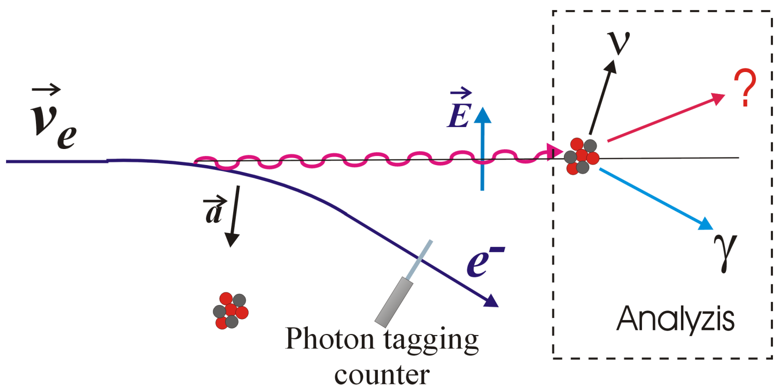

Figure 12. Scheme of the system of marking of bremsstrahlung photons and their analysis.

In this approximation, the direction and modulus of the vector $\vec{a}$ will be fixed and the radiation field will be unipolar. In this experiment the problem of determination of unipolarity bremsstrahlung radiation will arise. The problem is that in the quantum approximation the notion of photon unipolarity is absent, but as was shown above, in classical approximation a bremsstrahlung can be unipolar. If this fact takes place, then using the unipolar bremsstrahlung in a reaction which can be sensitive to the unipolarity, one can obtain an unexpected and unexplained asymmetry of reaction products in frame of quantum approximation. For the suggested experiment it is necessary for analysis to find a reaction which will be sensitive to unipolar radiation. In principle, we can consider the Tomson or the Compton scattering, if we can find the classical or quasi-classical approximation of this reaction. Observation of this effect has fundamental importance.

Acknowledgments

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