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Coherent forward and backward diffraction radiation of relativistic electrons in a dielectric targets

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Abstract. During the interaction of the relativistic electrons field with a dielectric target various types of electromagnetic radiation, such as Cerenkov radiation, diffraction radiation, transition radiation can be generated. In this report we present the results of experimental studies of the diffraction radiation generated by relativistic electrons in a dielectric target at the interface vacuum-insulator and insulator-conductor in the millimeter wavelength range. The experimental results show that the component of the diffraction radiation of relativistic electrons at the interface insulator-conductor, for any significant refractive index of insulator, is suppressed. The analysis of the results from different points of view was done.

1. Introduction

The interaction of relativistic particles with the material of the dielectric target can generate various types of electromagnetic radiation, such as Cerenkov radiation (ChR), diffraction radiation (DR), the transition radiation (TR). The nature of the radiation depends essentially on the characteristics of the materials that define the properties of the boundary between the media. In the case of perfect dielectrics, the main characteristic is a real part of the permittivity or refractive index. DR, by definition, is a radiation generated when the particles move near the target. It should be noted, that ChR might be generated, when particles move close to a target, not crossing it. For example, in [1] the forward DR and ChR in such conditions were simultaneously registered.

It is shown in [2] that TR and DR are of the same nature – radiation generated due to polarization of the target material by the electromagnetic field of moving electron. In the case of DR, only part of the electron field crossing the target is involved in the process of target material polarization. The theoretical analysis and experimental research on planar dielectric TR targets are well known [3, 4]. In this case, mainly TR on the upstream and downstream surface of the target is considered. The resulting radiation has characteristic properties, depending on the thickness of the target, its dielectric constant, and the electron energy [5]. The theoretical model of the generation of TR and DR for a charged particle moving near the edge of the screen of finite size and a finite conductivity with frequency dispersion has been developed in [6, 7].

In the case of relativistic electrons, usage of pseudo-photon approximation [8] is useful for an intuitive understanding of the processes during an interaction of the electron field with a substance. In [9] this viewpoint is called "the virtual photon method". In this case, the longitudinal component of the electron field is negligible (i.e., the field is nearly transversal), and the speed is nearly equal to the light speed. So, the field of the electron in the interaction with the matter has locally nearly the same properties as the radiation field. During an interaction, a target "can not distinguish" the electron field from radiation field and gives the same response. From this point of view, DR and TR represent refraction and reflection of an electron field at the interface of target substance.

Next, we consider radiation produced during the passage of an electron through a dielectric plate of finite thickness as well as radiation produced during the moving of an electron near edge of a target. For definiteness hereinafter the surface at the side of the electron source will be called an upstream surface, and the opposite surface will be called a downstream surface. Moreover, forward radiation will be called a radiation in semisphere in the direction of the electron motion, and the backward radiation will be called a radiation in the semisphere towards the electron source. In case of DR electrons are not scattered by the target material. This simplifies the procedure of the experiment and does not require taking into account the calculations of scattering. Therefore, we focus our attention at the DR in a dielectric targets.

Intuitively, if we screen the downstream surface of the flat dielectric target (figure 1) using a conductive plate, which is a mirror in the investigated wavelength range, then a backward DR (pseudo-photon field of the electron, reflected from the mirror) on the border between two media (insulator-metal) can be generated.

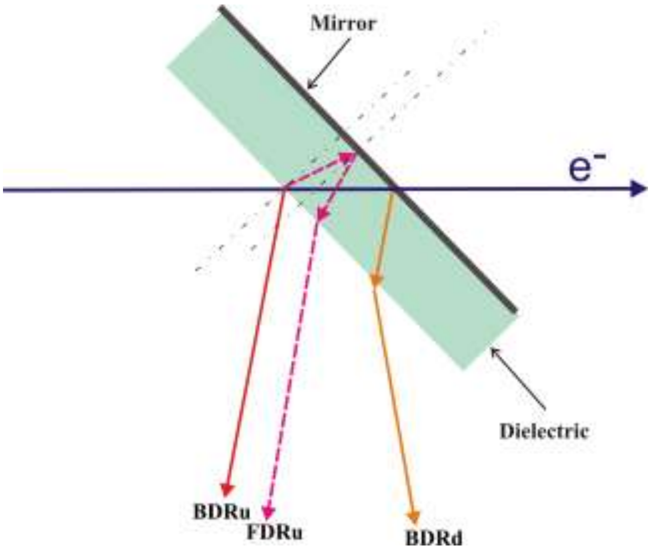

Figure 1. Scheme of DR components separation on the planar dielectric target.

During the passage of relativistic electrons above the target, in geometry shown in figure 1, the following radiation components can be generated:

a) backward DR from the upstream surface of the target (BDRu);

b) forward DR from the upstream surface (FDRu), which is reflected from a mirror, refracted on the upstream surface, and propagates out of the target;

c) backward DR at the insulator-metal border (BDRd), which is also refracted at the upstream surface and propagates out of a target;

d) ChR, which is reflected from the mirror and by the refraction on the upstream surface of the target will be released.

This geometry is interesting because all of these components can be measured in the same conditions. However, it should be noted that BDRu and FDRu have the same direction and cannot be separated in the angular distribution.

But, if we use not a flat target, but a dielectric wedge (figure 2), we can separate these components.

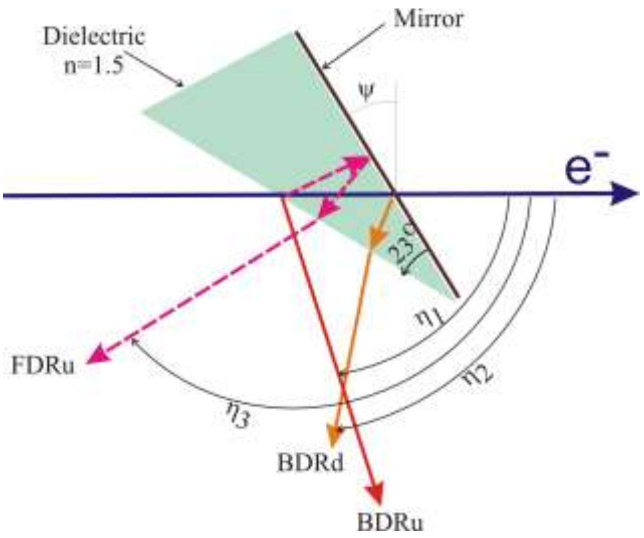

Figure 2. Scheme of separation of the DR components from the dielectric wedge.

The exact theoretical solution of this problem for the described geometry of DR target, which can be used in the experiment, is very difficult due to a complicate border conditions. The goal of the experiment, which will be described below, is to measure and compare the intensity of DR components a, b and c.

2. Experiment

The experiment was performed on the extracted electron beam of microtron PTI TPU with the following parameters: electron energy – 6.1 MeV, macro-pulse duration – $4\,\mu s$, the macro-pulse frequency $1-8$ Hz, the characteristic length of the electron bunch in the Gaussian approximation $\sigma_z = 2.4$ mm, the bunch population $Ne = 10^8$, the number of bunches in macro-pulse – 10^4, the cross-section of the extracted beam – 4×2 mm, the angular divergence of the extracted beam – 0.08 rad.

Under these conditions for $\lambda > 9$ mm radiation of electron bunch is coherent [10]. Because of the coherency the radiation intensity increases by *Ne* times (i.e. for the specified bunch population it is by 8 orders) in comparison with incoherent radiation, making it available for the measurement using existing detectors operating at room temperature. For radiation registration, we used broadband detector DP-21M, manufactured in Semi-conductive Devices Research Institute (Tomsk, Russia) on the basis of a broadband antenna with a threshold diode. The detector ensures the detection of radiation at room temperature with a sensitivity of approximately 0.3mV/W in wavelength region $\lambda = 0.5-25$ mm with accuracy $\pm 15\%$.

To suppress the accelerator RF system background the beyond cut off waveguide with diameter 10 mm was mounted on the detector, which attenuates a radiation having a wavelength $\lambda > 17$ mm. Thus, the spectral range of the measurement is $\lambda = 9-17$ mm.

The angular characteristics of the radiation were measured using the parabolic telescope (figure 3) which is a detector, located at the focus of a parabolic mirror, placed on the rod. The rod may be rotated around an axis passing through the center of the radiating face of the wedge. In this case, the measured angular radiation characteristics coincide with the characteristic measured in the far field zone [11] for comparison with theoretical calculations.

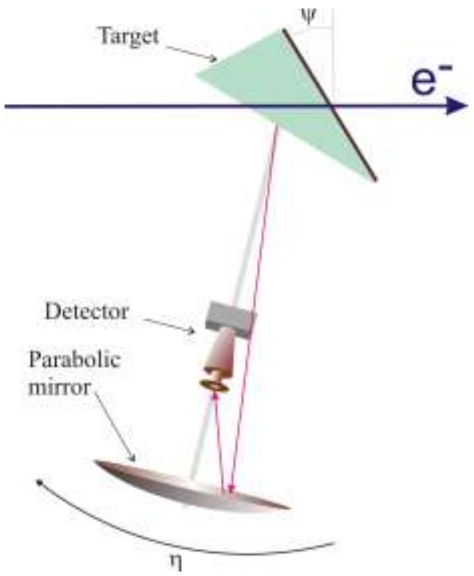

Figure 3. Scheme of the experiment.

The angular resolution of a telescope is 0.035 radians. If the measurement of the angular distribution with this resolution is performed in the horizontal plane (in the plane of figure 3), we will register only the vertical component of the radiation polarization. So we can eliminate the contribution of ChR in the angular dependence, because this component of ChR propagates in a vertical plane at the Cherenkov angle in respect the horizontal plane. Thus, we can measure the radiation characteristics of only components DR, types a, b and c.

For investigation we chose the wedge from paraffin with the opening angle of 23 degrees and with the refractive index of n = 1.5. The size of the diagonal of the wedge was 200 mm. The refractive index of this target was measured using a beam from millimeter wavelength emitter. The target has been tested on absorption of radiation in investigated wavelength region. It was found that absorption is less than 5%. Impact-parameter of the target was 15 mm. Orientation of the wedge is chosen so that the peaks of all three components of the angular distribution of the radiation separated. For this purpose, using the pseudo-photon point of view, the emission angle η from the target for each radiation component as a function of the target orientation angle ψ was calculated (figure 4).

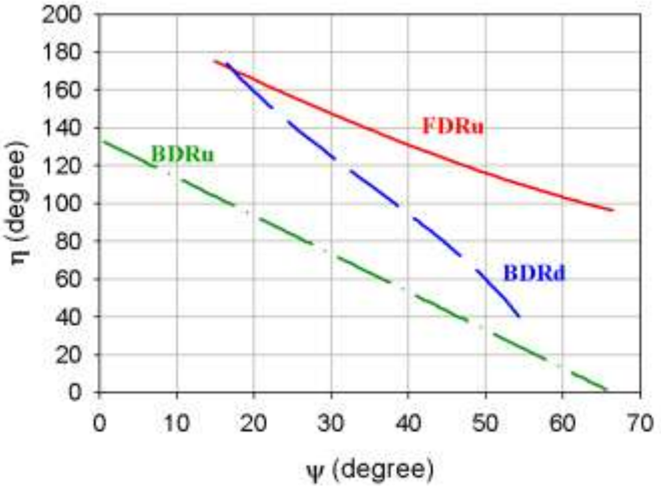

Figure 4. Calculated dependences of a propagation angle η of DR components on orientation angles ψ of the target.

Technically the range of observation angles η is limited between $95° - 145°$.

TR and DR are special cases of polarization radiation, which is a radiation of target material, polarizing by a Coulomb field of a relativistic electron. In case of DR in contrast to TR, only part of electron field takes part in polarization of target material, but the process of radiation is the same. The same nature of TR and DR for conductive targets has been shown convincingly in [2]. So we can suppose the same similarity for radiation in dielectric targets. Unfortunately, no analytical solutions using appropriate theoretical models of DR for combined dielectric–metal targets with geometry used in our experiment were in theory considered. Therefore we use for estimations the exact solution from [4] for forward and backward TR in dielectric targets. These estimates showed that for $n = 1.5$ the intensity of backward radiation is negligible in comparison to the forward radiation. So we will not be interested in the radiation component BDRu (see figure 2) and we chose for the measurement the target orientation angles $\psi = 35°$ and $\psi = 40°$. In this case both FDRu and BDRd may be observed in the same η - scan in our limits of $\eta = 95° - 145°$.

Figure 5 shows the measured angular dependences of the radiation intensity for these angles of orientation.

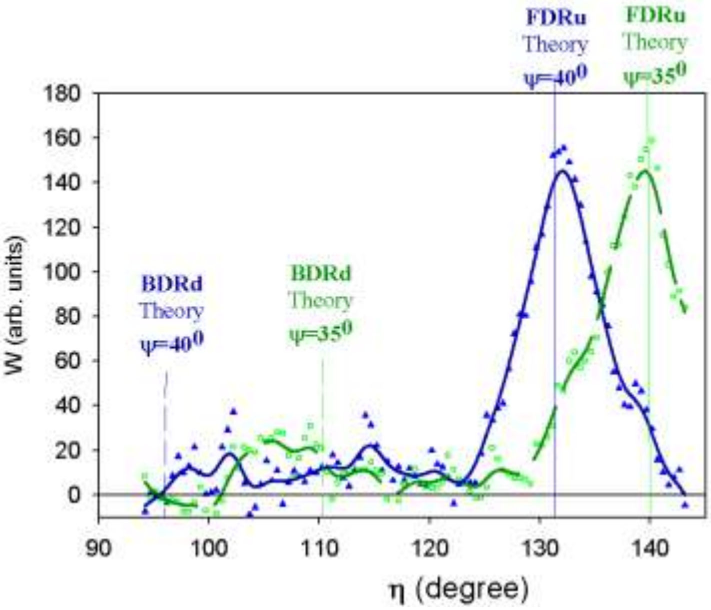

Figure 5. The experimental dependence of the radiation intensity W on the observation angle η for different angles ψ of the target orientation. Dots are the experimental values and lines represent the smoothed experimental data. Vertical lines represent calculated positions of the peak maximum.

These results show that the component BDRd is practically absent outside the statistical error. That is, the pseudo-photon electron field in the investigated spectral range is not reflected from the mirror. This result is totally unexpected and requires careful analysis.

3. Discussion

As was mentioned above, no solutions using appropriate theoretical models of DR for combined dielectric–metal targets with geometry used in our experiment were in theory considered. Using the approximation of similarity of TR and DR mentioned above, we attempt to use for the qualitative analysis of these results the expression (2.35) from [4] for the backward transition radiation at the interface between two semi-infinite media:

$$W(\theta_1)=\frac{q^2v^2}{\pi^2c^3}\sin^2\theta_1\cos^2\theta_1\sqrt{\varepsilon_1}\left|\varepsilon_2-\varepsilon_1\right|^2$$
$$\times\left|\frac{\left[1-\left(v^2/c^2\right)\varepsilon_1+\left(v/c\right)\sqrt{\varepsilon_2-\varepsilon_1\sin^2\theta_1}\right]}{\left[1-\left(v^2/c^2\right)\varepsilon_1\cdot\cos^2\theta_1\right]\left[1+\left(v/c\right)\sqrt{\varepsilon_2-\varepsilon_1\sin^2\theta_1}\right]\left(\varepsilon_2\cos\theta_1+\sqrt{\varepsilon_1\left(\varepsilon_2-\varepsilon_1\sin^2\theta_1\right)}\right)}\right|^2.$$

Here all the notations are the same as they were in the source. We are interested in the case where the second medium is an ideal metallic mirror, i.e. $\varepsilon_2\to\infty$. Then, this expression takes the form:

$$W(\theta_1)=\frac{q^2}{\pi^2c}\frac{\beta^2\sqrt{\varepsilon_1}\sin^2\theta_1}{\left|1-\beta^2\varepsilon_1\cos^2\theta_1\right|^2},\tag{1}$$

where $\beta=v/c$.

In the vacuum $(\varepsilon_1=1)$ from (1) we obtain the expression for the TR:

$$W(\theta_1)=\frac{q^2}{\pi^2c}\frac{\beta^2\sin^2\theta_1}{\left|1-\beta^2\cos^2\theta_1\right|^2}.$$

On the other hand for $n_1=(\beta\cos\theta_1)^{-1}$, the expression (1), where $n_1=\sqrt{\varepsilon_1}$ is a refractive index, has a pole of Cherenkov radiation, generated in the target and reflected from the mirror. Analyzing the angular distribution of radiation from (1) we can see that at the insulator-metal transition the TR will be generated only if $1\le n_1<(\beta\cos\theta_1)^{-1}$ (we do not consider here a negative refractive index). For our experiment this condition reduces to $1\le n_1<1.003$. That is, our target with $n_1=1.5$ in these conditions may generate at the metal-insulator transition in the studied spectral range Cherenkov radiation only, which is suppressed in the experiment due to selected polarization of detected radiation. As the principle of reflection of electron field from conductive screen for right angle of incidence and for an inclined angle of incidence of electrons is the same, we may expect that for inclined angle of incidence of electrons the backward TR will be also negligible. Hence, given the same nature of generation of TR and DR, it can be argued that the experimental results are consistent with the classical theory.

The problem of Maxwell's equations is that we may obtain in some cases the accurate final decisions, but these solutions do not provide information about the physics of the processes occurring in the interaction of relativistic particles with matter (in a sense – "black box"). For example, in [14] is shown the solution of Maxwell's equations for evolution of electromagnetic field generated by a relativistic electron downstream to the conductive screen. However, no information about a nature of this radiation may be extracted from this solution.

As mentioned, the pseudo-photon method may be useful for the intuitive understanding of the processes taking place in the interaction of an electron field with a substance. According to this approach the field of the electron in the interaction with the matter has locally nearly the same properties as the radiation field. A forward DR and TR on the upstream surface of the target is a refraction of the electron field on this surface. So the direction of propagation of an electron field like a direction of propagation of usual plane waves in the medium with a refractive index $n_1>1$, is different from the direction of the electron velocity. Hence it follows logically, that the field of electron and the electron itself are separated, and the electron moves without some part of its Coulomb field in the investigated spectral range. The separate electron field propagates further in the form of real photons. This field is reflected from the mirror, refracted on the upstream surface of the target, and will be registered as FDRu. The similar case of separation of an electron field and an electron itself, when electrons are scattered for large angles, is considered in the work of E.L. Feinberg [12], which introduces the concept of "half-naked electron" (electron deprived of part of its Coulomb field). This view is also used in [15, 16]. In this case, at the input of the insulator-metal transition (downstream face of the target) in the geometry shown in figure 2, the electron become "half-naked" in the investigated spectral range, and cannot generate backward DR on this transition. That is, the radiation BDRd should be absent, as is observed in the experiment.

In this paper we considered the problem of interaction of electron Coulomb field with combined dielectric-metal target from two points of view: classical viewpoint and pseudo-photon viewpoint. There is no contradiction between these points of view and experimental results. However the pseudo-photon point of view allows us to understand more in detail the processes occurring in the interaction of relativistic electrons with matter. In [12] the interpretation of the processes based on "half-naked electron" is considered as a possible, but not the only interpretation of the mechanism of interaction of a charge field with the substance. However, in [13, 14] was shown that opposite interpretation of these phenomena is baseless. Thus, the interpretation based on the concept of "half-naked electron" is the only one.

The importance of this concept in consideration of the interaction of the Coulomb field of relativistic charged particles with matter is that this viewpoint raises a number of questions about the nature of the charge and its Coulomb field and it can be considered as an example for the application of this approach to other types of interactions (such a strong interactions in [12]).

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References

[1] Naumenko G A, Potylitsyn A P, Shevelev M V and Popov Yu A 2011 *JETP Lett.* **94** 258
[2] Potylitsyn A P 1998 *Nucl. Instrum. and Methods* B **145** 169
[3] Denisov S P 1997 *Soros. Obrazov. Zh.* **3** 124
[4] Ginzburg V L and Tsytovich V N 1990 *Transition Radiation and Transition Scattering* (Bristol: Adam Hilger)
[5] Ter-Mikaelian M L 2001 *Phys.-Usp.* **44** 571
[6] Karlovets D V and Potylitsyn A P 2009 *JETP Lett.* **90** 326
[7] Karlovets D V 2011 *J. Exp. Theor. Phys.* **113** 27
[8] Ter-Mikaelian M L 1972 *High Energy Electromagnetic Processes in Condensed Media* (New York: Wiley-Interscience)
[9] Jackson J D 1998 *Classical Electrodynamics*, 3rd ed (New York: J. Willey & Sons)
[10] Aleinik A N, Aryshev A S, Kalinin B N *et al* 2002 *JETP Lett.* **76** 337
[11] Kalinin B N, Naumenko G A, Potylitsyn A P *et al* 2006 *JETP Lett.* **84** 110
[12] Feĭnberg E L 1979 *Sov. Phys. Usp.* **22** 479
[13] Naumenko G A, Potylitsyn A P, Shevelev M V, Soboleva V V and Bleko V V 2013 *JETP Lett.* **98** 593
[14] Naumenko G A, Popov Yu A and Shevelev M V 2012 *J. Phys: Conf. Ser.* **357** 012005
[15] Shul'ga N F and Syshchenko V V 2000 *J. Phys. of Atomic Nuclei* **11** 2018
[16] Artru X and Ray C 2007 *Proc. SPIE: Int. Conf. on Charged and Neutral Particles Channeling Phenomena II* vol 6634 (Rome, Italy) p 66340Y-1