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Coherent diffraction and Cherenkov radiation of relativistic electrons from a dielectric target in the millimeter wavelength range

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ABSTRACT

The coherent diffraction radiation (DR) and Cherenkov radiation (ChR) emitted by bunched electron beam of 6.1 MeV passing near a flat dielectric target have been observed in the millimeter wavelength range. The simple geometry of experiment allows testing different theoretical approaches, which consider the process of simultaneous emission of DR and ChR from dielectric targets. Properties of the radiation have been experimentally investigated in far-field zone. The angular distribution of the observed radiation at various tilt angles of the target in respect to the electron beam have shown the effect of interference between DR and ChR. The comparison of experimental results with the theoretical calculations based on the approach of polarization currents has been done.

1. Introduction

Diffraction radiation (DR) and Cherenkov radiation (ChR) may be described via universal theoretical approach, which is expounded in papers [1–4]. DR is an important process of the electron energy loss, in particular when it occurs in particle accelerators. DR is emitted by a charge particle moving through an aperture or near an edge of interface between media with different dielectric properties [5]. Another type of radiation, which can be emitted by a charged particle under the same condition, is ChR. In conventional case ChR appears while a charged particle moves in a medium with a velocity v exceeding the light speed c/n in this medium, i.e., by the condition $\beta n > 1$, where $n = \sqrt{\varepsilon}$ is a refractive index of the target, ε is a dielectric permittivity and $\beta = v/c$. The ratio $\beta n = 1$ is called the Cherenkov threshold which is defined for a dielectric medium of an infinite extent, and the condition $\beta n > 1$ is called Cherenkov criterion. In the case where $\beta n < 1$, the radiation is not emitted. For a medium of infinite volume, the Cherenkov emission is confined to the surface of cone with the half-angle Θ_{Ch} (the angle between a direction of observation and the electron trajectory) determined by the equation

$$\cos\Theta_{Ch} = 1/n\beta. \quad (1)$$

On the other hand, according to the papers [6–8], the ChR can appear when an electron traveling in the vicinity of a dielectric target. For high-energy electrons with the Lorentz factor $\gamma \gg 1$, the characteristic transverse dimension of the electron electromagnetic field has macroscopic scale. Thus, the dynamic polarization of a target may occur on a distance less then $\gamma\lambda$ (where λ is the observed wavelength). Under these conditions, one can observe the simultaneous generation of DR and ChR. This fact was confirmed in the experimental paper [9], where the authors first observed and described the case of the simultaneous generation of forward DR and ChR, when the relativistic electron beam moves near the triangular prism made out of Teflon. Unfortunately, the authors does not demonstrate the comparison of obtained results with theoretical predictions.

In this paper, we adduce the experimental and theoretical results of the process of simultaneous generation of DR and ChR emitted by 6.1 MeV electron beam passing near a dielectric screen in the millimeter wave range. The simple geometry of the experiment is very useful for comparison the different theoretical models, which widely used for estimation DR and ChR properties from a dielectric target. In particular we use the approach of polarization currents [1–4] for the comparison of experimental results with theoretical calculations.

2. Experiment

The experiment was carried out on an extracted electron beam from the microtron at Institute of Physics and Technology, Tomsk

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Polytechnic University, with energy of accelerated electrons of 6.1 MeV and electron beam current 25 mA. Beam parameters of the microtron allow using the coherent properties of radiation in the millimeter wavelength range for the research of DR and ChR. Namely, in this range, the radiation intensity is increased by 8 orders (proportionate to the number of electrons per bunch N_e), and it become available for its measurement by use of existing detectors. The extracted electron beam parameters are listed in Table 1.

The experimental setup is schematically shown in Fig. 1. The electron beam extracted through 50 μm beryllium foil was used. As the source of DR and ChR, we used Teflon (PTFE) target with $n = 1.41 \pm 0.01$ measured using the method described in the paper [10]. The height a, thickness b and length of the target are 260, 40 and 260 mm, respectively. Electrons passed near the center of the edge of dielectric target T. The target T was placed at a distance $h = 20$ mm from the beam, for Lorenz factor $\gamma = 12$ and wavelength $\lambda > 8$ mm the impact factor h can be chosen from the condition $h \leqslant \gamma\lambda \approx 120$ mm . The screen T can be oriented at the angle ψ with respect to the beam trajectory. Clockwise rotation of target corresponds to the positive angle ψ (see Fig. 1).

The pre-wave region is determined by the radiation formation length $\gamma^2\lambda$ [11], under the experimental conditions it was 1.4 m. To prevent the effect of the pre-wave region, the radiation angular distributions were measured by the parabolic telescope, which consisting of the detector placed at the focus of the parabolic mirror about the axis coinciding with the point of intersecting the beam with the target. The angular resolution of the telescope is determined by the relation between the aperture of the beyond-cutoff waveguide and the focal distance of the parabolic mirror. In the case under consideration the telescope angular resolution is 2.6°. According to the paper [12], the spectral–angular characteristics of radiation detected in this scheme are in a good agreement with the radiation characteristics in the far-field region.

The emitted radiation from the target was detected using DP-20M detector. The detector is based on a wide-band antenna, high-frequency low barrier Shottky diode and preamplifier. The average sensitivity of the detector in the radiation wavelength 3–16 mm is approximately equal to 0.3 mV/W [13]. The measured region was limited by coherent threshold in the smaller wavelengths and by the beyond-cutoff waveguide that passes wavelengths lower 25.5 mm used to decrease accelerator RF background. The intensity of coherent radiation was measured as a function of the observation angle θ with the step of 1°. The angle $\theta = 0°$ corresponded to the direction of the electron beam. The detector signals for 20 successive pulses were averaged for each θ position.

For experimental analysis, were used absorbing screens A-I and A-II [14] (see Fig. 1). The absorber properties were checked both with a photon beam from the source of wavelength $\lambda = 6$ mm and with the measurement of reflected radiation from electron beam, according to the scheme shown in Fig. 2. In Fig. 3 curve 1 is the backward DR angular distribution from a conductive target without absorber and curve 2 is the angular distribution for the same target covered by the absorber. As we can observe, no radiation photons reflection can be registered. The test with the photon beam showed that all photons were absorbed within experimental accuracy $\sim 3\%$.

Table 1
The parameters of extracted electron beam.

Maximum energy (MeV)	6.1
Duration of a burst (μs)	4
Bunch length (mm)	2
Number of electrons per bunch	6×10^8
Bunch period (ps)	380

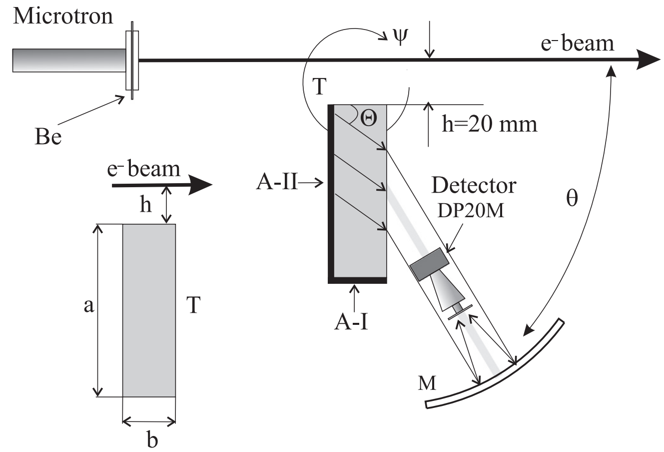

Fig. 1. The schematic diagram of the experiment and used target. Be – foil window; T – PTFE target, M – parabolic reflector, A-I and A-II are the absorbing screens. The trajectory of the beam is shown by the solid line.

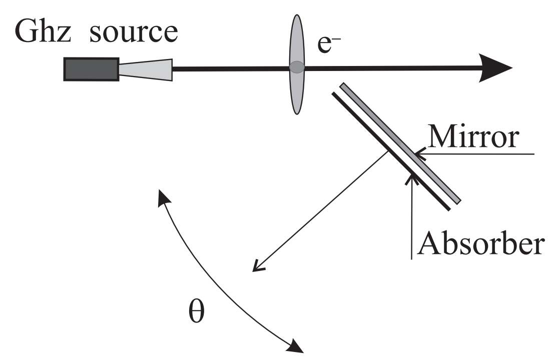

Fig. 2. The scheme of the absorber test.

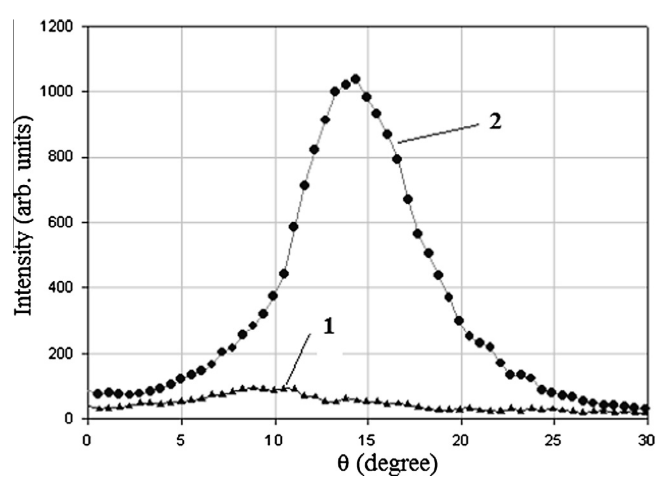

Fig. 3. The radiation intensity angular distribution, measured in the absorber test (see Fig. 2); 1 – backward DR from conductive target without absorber, 2 – radiation from the same target covered by absorber.

The theoretical calculations of the angular distributions of DR and ChR were obtained by the method of polarization currents [1–4]. The method is based on that the source of the radiation field is the polarization current density induced inside the medium by external field of the particle. Note that the authors of papers [1–3] for the theoretical calculation use the thin target approximation $a \gg b$, this means that the transverse dimensions a of

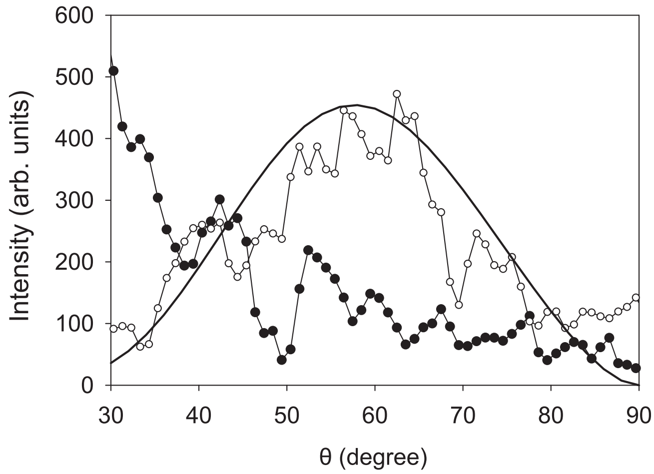

Fig. 4. The radiation angular distribution from the Teflon target for the angle $\psi = 0^\circ$.

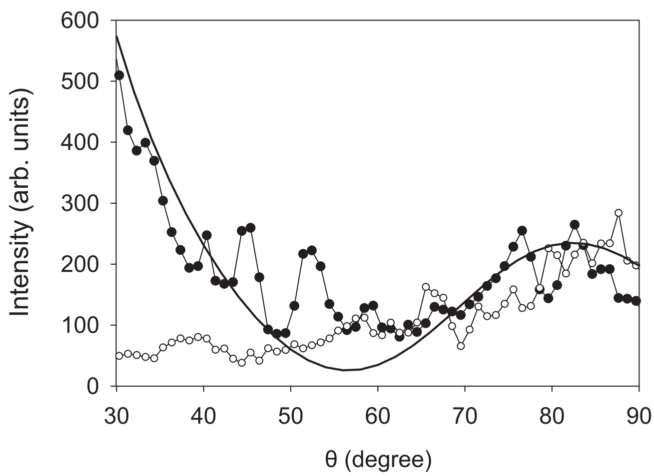

Fig. 5. The radiation angular distribution from the Teflon target for the angle $\psi = 20^\circ$.

the target far exceed longitudinal dimensions *b*. In this case the emitted radiation from target face *b* is not considered. For this reason the target face *b* was screened by the absorber *A*-I during the all steps of experiment thus the radiation from target face *b* is not detected.

The experiment was carried out in two steps:

1. The first step consists of measuring the radiation intensity depending on the rotation angle θ of parabolic telescope, for the different target positions ($\psi = 0^\circ$ and $\psi = 20^\circ$). In this case, we can detect both types of radiation: DR and ChR.
2. The second step is based only on measurements of the ChR angular distribution. In order to exclude contribution of the DR in the angular distribution, the screen *A*-II was installed.

3. Results and discussion

In the present experimental setup two types of radiation are considered, namely ChR and DR. Figs. 4 and 5 are shown the measurement results of intensity radiation angular distribution for different values of the screen rotation angle ψ. The dependence of the intensity radiation angular distribution on angle θ is represented by the solid circle curve. The curve denoted by open circles is the angular distribution with installed screen *A*-II (second step). The solid curve is shown the theoretical dependence of the emitted radiation intensity on the polar angle θ obtained by the method of polarization currents [1–4] for our experimental conditions.

It should be mentioned that the ChR intensity for experimental geometry without screen *A*-II was suppressed in several times due to the destructive interference of DR and ChR fields (see Fig. 4). The destructive interference between DR and ChR occurs as a result of the bunch Coulomb field effect on DR. A part of bunch Coulomb field is taking by the parabolic mirror and detected in combination with the radiation field. That is why we used the absorption screen *A*-II to neutralize the interference effect and measured "pure" ChR. However, the effect of destructive interference was suppressed due to the change of the propagation direction of DR and ChR at the angle $\psi = 20^\circ$.

According to the well-know Cherenkov condition (1) the maximum of the peak intensity inside the target is about $\Theta_{Ch} = 45^\circ$. For the find the maximum of the peak intensity outside the target (in vacuum), as required the determining the Cherenkov condition via the vacuum angle θ_{Ch}. For this reason we used the expression obtained in the paper [3]:

$$\left|\cos\psi - \beta\sqrt{\varepsilon - \sin^2\theta_{Ch}} + i\gamma^{-1}\sin\psi\right| \to 0. \quad (2)$$

Hence, due to refraction radiation on the boundary between the medium and vacuum, the maximum of ChR intensity was detected on the angle $\theta_{Ch} = 60^\circ$ for $\psi = 0^\circ$ and $\theta_{Ch} = 80^\circ$ for $\psi = 20^\circ$. As it appears from Figs. 4 and 5 these theoretical predictions are in a good agreement with the observed data.

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