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Cherenkov Radiation in Targets with Broken Azimuthal Symmetry

M. V. Bulgakova[a, b], **V. S. Malyshevsky**[a, *], **and G. V. Fomin**[a]

[a] *Southern Federal University, Rostov-on-Don, 344006 Russia*

[b] *Belgorod State National Research University, Belgorod, 308015 Russia*

**e-mail: vsmalyshevsky@sfedu.ru*

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Abstract—It is shown that the breaking of azimuthal symmetry during the oblique entry of relativistic particles into a thin target leads to oscillations of the spectral-angular density of polarized Cherenkov radiation along the azimuthal angle. The effect of modulation of the angular distribution of Cherenkov radiation can be observed in quartz glass on individual spectral lines in the optical and near ultraviolet ranges. The interference maxima have a small angular width not exceeding 10^{-2} rad. The effect can be used in the diagnostics of the angular characteristics of beams of accelerated relativistic particles.

Keywords: Cherenkov radiation, transition radiation, relativistic particles, emittance, quartz glass

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INTRODUCTION

For the efficient operation of accelerators and colliders, information about the beam parameters is required: its position, size, and angular divergence [1, 2]. Beam emittance is an important parameter of accelerators, which determines the efficiency of their use. Traditional methods for diagnosing the parameters of charged-particle beams are based on recording optical radiation arising when particles fly through phosphorescent screens and thin metal targets or near them, i.e., optical transition and diffraction radiation [3–6]. These methods have their limitations, and their use becomes problematic for small sizes and a low angular divergence of accelerated-particle beams. The work analyzes some features of polarized Cherenkov radiation during the oblique entry of particles into a target, which can be useful for the diagnostics of accelerated-particle beams.

AZIMUTHAL OSCILLATIONS OF THE SPECTRAL-ANGULAR RADIATION DENSITY

At normal incidence on the surface of a target of finite thickness, the angular distribution of Cherenkov radiation has the form of concentric rings [7–10]. These oscillations along the polar angle are explained by the interference of waves propagating in the direction of particle motion and reflected from the boundaries of the target. The thicker the target, the more frequent the oscillations. The angular width of the rings is inversely proportional to the thickness of the target L. In addition, in the case of the normal incidence of relativistic particles on a target, the output of Cherenkov radiation may become impossible due to total internal reflection from the second boundary of the target. To record radiation in the direction of particle motion in this case, the particle must fly to the target at a certain angle ψ between the direction of its movement and the normal to the surface. Then, at a rather large ψ angle, part of the radiation will experience total internal reflection at the boundary of a target of thickness L, and part will propagate in the direction of particle motion [11, 12].

When particles enter the target obliquely, the angular distribution becomes asymmetrical, which was previously established in a number of works (for example, [13–15]). Moreover, when flying to a target at a certain angle, its effective thickness increases, which reduces the angular width of the Cherenkov rings. In contrast to normal incidence, the effective thickness for different directions of radiation in the Cherenkov cone begins to depend on the azimuthal angle. The latter circumstance leads to the fact that the phases of the waves reflected from the boundaries of the target are now not constant, and also begin to depend on the azimuthal angle. Thus, it should be expected that the breaking of azimuthal symmetry will lead to additional interference oscillations along the azimuthal angle. In this case, the angular distribution will take on a rather complex form and will manifest itself most clearly in thin targets. Such redistribution of the spectral-angular density of radiation, as will be shown below, significantly increases its output in some narrow angular intervals and can have important practical applications, in particular, for controlling the angular divergence of beams of accelerated particles.

It is well known that in the case of the normal incidence of a fast charged particle at an interface, the resulting electromagnetic radiation is polarized in the so-called radiation plane containing the wave vector of the radiation **k** and the normal to the surface. When particles are incident at an angle to the interface between two media, additional polarization of the radiation occurs in the plane orthogonal to the radiation plane. However, the intensity of this component is much lower (for example, [16, 17]) and is not considered here.

If the target thickness is so small that particle-energy losses and multiple scattering can be neglected, then to solve the problem of electromagnetic radiation in an absorbing target of finite thickness, we will use the known results of solving Maxwell's equations, based on the method of matching normal and tangential field components at interfaces [18]. This method allows us to obtain the most complete information about the spectral-angular distribution of the resulting electromagnetic radiation.

Let us denote the charge of a particle flying into the medium by Ze and let us assume that the magnetic permeability of the medium $\mu = 1$. Then the corresponding analytical expressions for the spectral-angular density of radiation polarized in the radiation plane are $dI(\mathbf{k},\omega) = I(\mathbf{k},\omega)\,d\omega d\Omega$ in the frequency range $\omega, \omega + d\omega$ at the solid angle $d\Omega$ in the direction of particle motion in a medium with a complex dielectric constant $\varepsilon = \varepsilon' + i\varepsilon''$ will look as follows:

$$I(\mathbf{k},\omega) = \frac{Z^2e^2}{\pi^2 c}\frac{\beta_z^2\cos^2\theta_z}{\sin^2\theta_z} \times \frac{|\varepsilon - 1|^2}{\left|\left[A^2 - \beta_z^2x^2\right]\left[A^2 - \beta_z^2\cos^2\theta_z\right]\right|^2} \times \frac{|B(\omega,\mathbf{k},\mathbf{v})|^2}{\left|(x+y)^2\exp\left(-i\frac{\omega L}{c}x\right) - (x-y)^2\exp\left(i\frac{\omega L}{c}x\right)\right|^2}, \quad (1)$$

$$\begin{aligned} B(\omega,\mathbf{k},\mathbf{v}) &= (x+y)(A+\beta_z x) \\ &\times \left[\left(A - \beta_z^2 - \beta_z x\right)\sin^2\theta_z + \beta_x\beta_z x\cos\theta_x\right]\exp\left(-i\frac{\omega L}{c}x\right) \\ &+ (x-y)(A-\beta_z x)\left[\left(A - \beta_z^2 + \beta_z x\right)\sin^2\theta_z - \beta_x\beta_z x\cos\theta_x\right]\exp\left(i\frac{\omega L}{c}x\right) \\ &- 2x\left[(A+\beta_z y)\left(A-\beta_z^2\right)\sin^2\theta_z + \beta_z\left(\beta_x\cos\theta_x - \sin^2\theta_z\right)\left(\beta_z x^2 + Ay\right)\right]\exp\left(-i\frac{\omega L}{v_z}A\right), \end{aligned} \quad (2)$$

where $x = \sqrt{\varepsilon - \sin^2\theta_z}$, $y = \varepsilon\cos\theta_z$, $A = 1 - \beta_x\cos\theta_x$. The direction of the electron velocity is, with the axis z, angle ψ, so $\beta_x = \beta\sin\psi$, $\beta_z = \beta\cos\psi$, $\beta = v/c$; the direction of radiation is determined by the direction cosines relative to the axes x, y, and z: $\cos\theta_x = \sin\theta\cos\varphi$, $\cos\theta_y = \sin\theta\sin\varphi$, $\cos\theta_z = \cos\theta$, where θ and φ are the polar and azimuthal angles, respectively.

Among the materials considered for the generation of monochromatic Cherenkov radiation in various frequency ranges, the most studied is quartz glass, which has a very wide transmission spectrum, and a low absorption and resistance to ionizing radiation. All these properties can be useful for the use of quartz glass as a target for generating Cherenkov radiation in various spectral ranges. The dispersion properties of this material have been studied in sufficient detail in a wide range of wavelengths from the X-ray region to terahertz [19, 20].

The results of some calculations of the angular distribution of polarized radiation ($\lambda = 0.16\ \mu$m) of Cherenkov charged particles near the threshold in a thin fused quartz plate are shown in Fig. 1. We note that due to the refraction of radiation emerging from the target, the center of the Cherenkov cone is displaced relative to the direction of particle motion. As follows from the calculation results, the angular width of the interference maxima does not exceed 10^{-2} rad. The magnitude of the radiation output (1), expressed in dimensionless units Z^2e^2/π^2c, reaches values of 10^5–10^6 at the interference maxima. This makes it possible to estimate the number of photons emitted from a unit length of the target at the interference maximum, in the frequency range from ω_1 to ω_2 and at solid angle $\Delta\Omega$:

$$N \approx \frac{1}{L}\int_{\Delta\Omega} d\Omega \int_{\omega_1}^{\omega_2} d\omega\, I(\mathbf{k},\omega)/\hbar\omega. \quad (3)$$

In the visible range, a simple estimate gives the quantity $N \approx 10^2\ \mathrm{cm}^{-1}$, which is sufficient for confident recording of the effect.

CONCLUSIONS

To observe monochromatic radiation it is necessary, on the one hand, to have a target with sufficient dispersion in the frequency range of interest, and on the other hand, the possibility of collimating radiation to isolate the corresponding region of the spectrum. In the optical range, monochromatic radiation was observed for the first time in targets made of quartz glass [11] and diamond [12]. As follows from the results presented in these works, the angular interval between the lines is quite large, and by choosing the

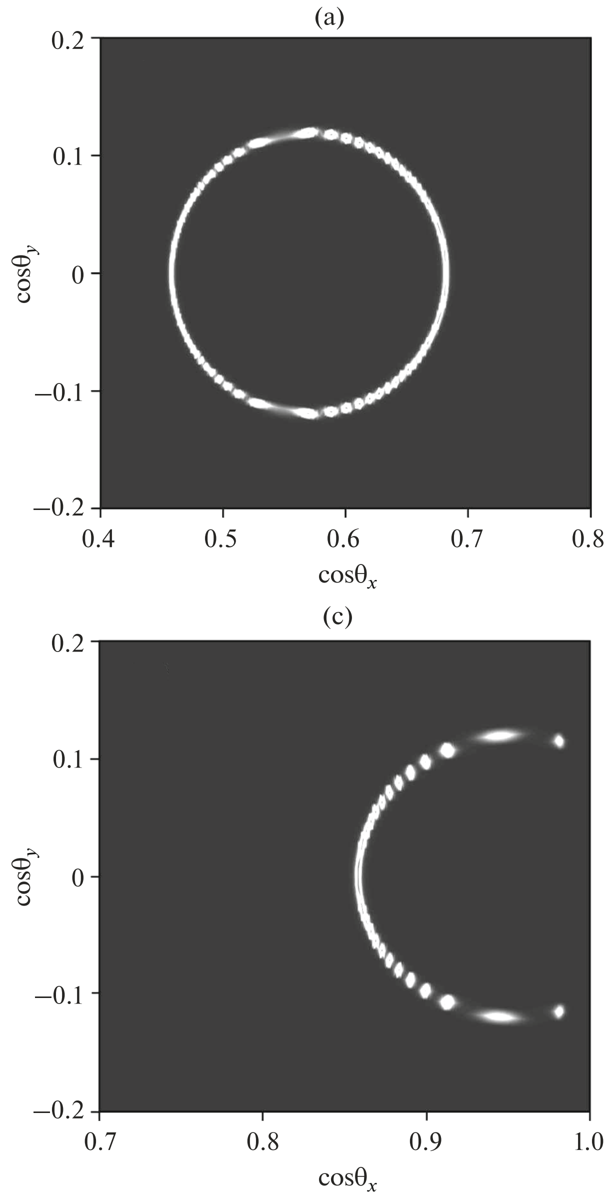

Fig. 1. Calculated angular distribution of polarized Cherenkov radiation of charged particles ($\beta = 0.6$) near the threshold in the near-ultraviolet wavelength range ($\lambda = 0.16\,\mu m$) in a thin fused quartz target of thickness $1.6\,\mu m$. The angle between the direction of particle motion and the normal to the target surface ψ: (a) 20°; (b) 30°; (c) 35°; (d) 40°.

necessary radiation collimation, the recording of individual monochromatic lines is possible. Thus, the effect of modulation of the angular distribution of Cherenkov radiation along the azimuthal angle when azimuthal symmetry is broken in the case when particles enter obliquely into a thin target can be observed on individual spectral lines. The interference maxima have a small angular width and, with sufficient collimation of the radiation, can be separated along monochromatic lines. It is obvious that the angular divergence of the particle beam will affect the width of the interference maxima. Therefore, the effect can be used for diagnostics of the angular characteristics of beams of accelerated relativistic particles.

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CONFLICT OF INTEREST

The authors of this work declare that they have no conflicts of interest.

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