Coherent Diffraction and Cherenkov Radiation in Fibers

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Abstract. The ability to use radiation of relativistic electrons in optical fibers in beam diagnostics was proposed by X. Artu at symposium RREPS-11. In this work the properties of different types of radiation induced in fibers by electromagnetic field of relativistic electron were considered. In this report we present the results of experimental investigation of this phenomenon in millimeter wavelength region for conditions of complete coherence. The nature and properties of radiation in fibers were analyzed experimentally for different geometry of fiber position with respect to the electron beam.

1. Introduction.

Dielectric fibers are widely used in technic for light transport. In this paper we consider more complicated electromagnetic processes in fibers, namely, generation and propagation of electromagnetic waves in fibers excited by Coulomb field of relativistic electrons. If a relativistic electron crosses a dielectric fiber or moves in vicinity of it, the different types of radiation, such as transition radiation (TR), diffraction radiation (DR) and Cherenkov radiation (ChR) might be generated. Optical fibers are already used as particle detectors, using scintillation or Cherenkov light [1, 2]. Here we present the experimental analysis of the nature of radiation generated by relativistic electron field in fibers in millimetre wavelength region. The geometry, when electrons move in vicinity of fiber, may be applied in a noninvasive diagnostics of relativistic electron beams.

For intuitive understanding of these processes we will use the pseudo-photon description of the interaction of Coulomb field of electron with matter, which was proposed by E. Fermi [3] and developed by E.J. Williams [4]. According to this viewpoint TR and DR is the Coulomb field, refracted at a boundary of fiber, but in case of DR the electros do not cross the fiber. ChR is the result of interference of radiation, induced in fiber by the Coulomb field of electron from each point of electron trajectory. According to the traditional viewpoint ChR is generated if electrons cross a target, but in [5, 6] it was shown that ChR may be generated even when the electrons move in vicinity to the target and don't cross the target material.

The theoretical analysis of radiation of relativistic electrons in fibers was done by X. Artru in [7]. However, experimental results of this phenomenon are absent.

2. Experimental setup

In experiment the radiation intensity, generated and propagated in fibers for different positions of fiber (the angle θ between the fiber and electron beam, and distance h between electron beam and fiber, i.e. impact-parameter) was investigated. Thus two geometries of fiber position are possible:

a) The electron beam and fiber are coplanar. In this case the impact-parameter h is the distance between the electron beam and the end of fiber (see figure 1*a*).

b) The fiber is situated under the electron beam at a distance *h* (figure 1*b*). The end of fiber is at a distance $l > \gamma\lambda$ from the electron beam (γ is the Lorenz-factor of electrons, λ is the wavelength for investigation).

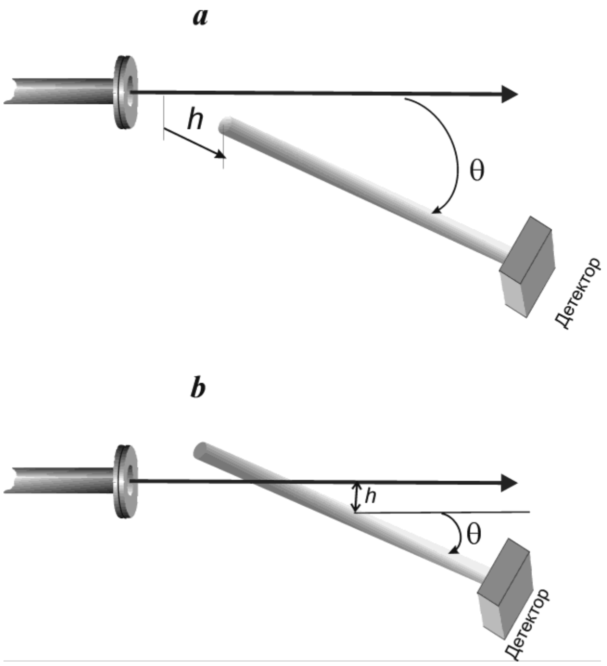

Figure 1. Two geometries of fiber position.

Both these geometries were investigated. In these geometries all types of radiation (ChR, DR and TR) may be generated. ChR satisfies to the condition $\cos\eta = \frac{1}{n\beta\cdot}$, where η is the radiation angle with respect to the electron beam direction, β is electron velocity in light velocity units and *n* is the target refractive index. DR and TR in fibers satisfy the refraction law for transit from vacuum into the fiber. Main condition for evolution of radiation inside the fiber is the requirement $\psi > \psi_{FIR}$, where ψ is the incidence angle of radiation propagation to the normal vector to the fiber internal surface, ψ_{FIR} is the angle of total internal reflection. For ChR, if θ=0, η corresponds to ψ_{FIR}, so for finite electron beam divergence approximately half part of ChR leaves the fiber. DR and TR at the front end of the fiber mainly propagate along the fiber, but DR and TR at the wall of the fiber already leave it.

The experiment was carried out in the extracted electron beam of the Institute of Physics and Technology of Tomsk Polytechnic University microtron with parameters presented in Table 1.

Table 1. Electron beam parameters

Electron energy	6.1 MeV ($\gamma = 12$)	Bunch period	380 psec
Train duration	$\tau \approx 4\mu$sec	Bunch population	$N_e = 6\cdot10^8$
Bunches in a train	$n_b \approx 1.6\cdot10^4$	Bunch length	$\sigma \approx$1.9~2.4 mm

For the radiation measurements the room temperature detector DP20M was used, with parameters described in [8]. The detector efficiency in the wavelength region of λ = 3~16 mm is estimated to be constant to *a* ±15 % accuracy. The detector sensitivity is 0.3 V/mW. The high frequency limit (λ_{min} = 9 mm) of the wavelength interval is defined by the bunch form-factor. The coherent radiation intensity for λ > 9 mm is by 8 orders of magnitude larger than the incoherent one. The cylindrical Teflon fibers with diameter of 10 mm, length of 500 mm and refractive index *n* = 1.41 were used. The range of variation of impact-parameter is defined by effective transversal size of electron field which is $\approx \lambda\gamma$. For experimental conditions $\gamma = 12$, $\lambda = 17$ mm (maximal wavelength for our fibers).

3. Experimental results

3.1. Measurements for the geometry a of the scheme of experiment shown in figure 1a

In this experiment the radiation intensity as a function of fiber angle θ was measured for different values of impact-parameters *h* (figure 2*a*).

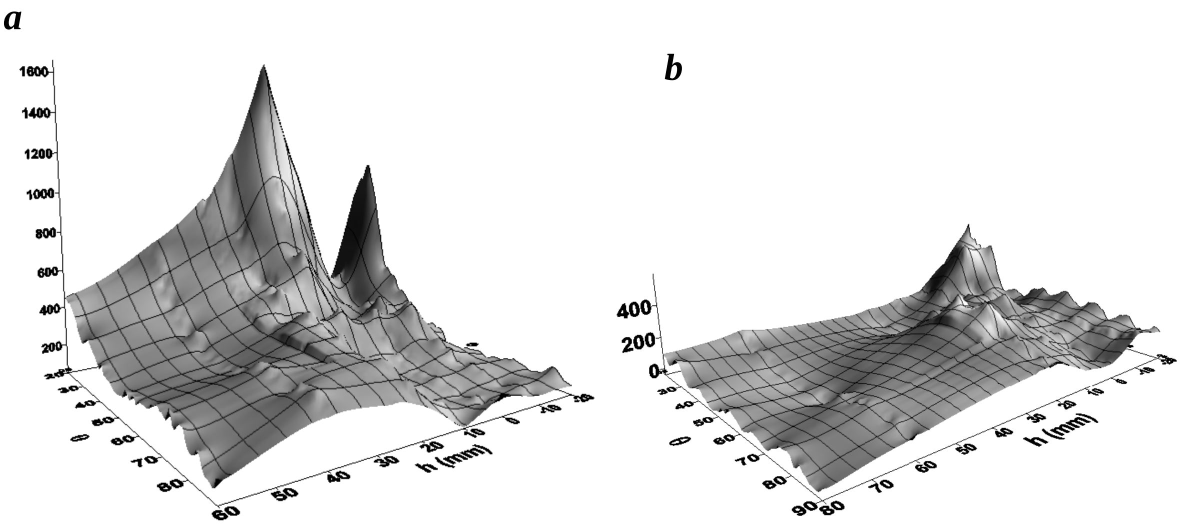

Figure 2. Radiation intensity as a function of fiber angle θ for different values of impact-parameters h. a – the end of fiber is opened; b – the end of fiber is screened by conductive screen

To clarify the nature of the radiation we had measured the same dependence when the edge of fiber was screened by a conductive screen (figure 2*b*).

In figure 2 we can see, that for the open end of fiber in region of angles θ between 20 and 50 degrees the radiation intensity is large and has a deep minimum at $h = 0$ (when the end of fiber crosses the electron beam). On the other hand, in the region $\theta > 50^0$ and 10 mm < *h* < 60 mm the observed radiation intensity does not depend on the screen presence.

3.2. Measurements fort the geometry b of the scheme of experiment shown in figure 1b

In this experiment the fiber is situated under the electron beam so, that the centre of the fiber is strictly under the beam. In this geometry the radiation intensity as a function of fiber angle θ was measured for different values of impact-parameters *h* (see figure 3).

It should be noted, that in this geometry we see the oscillations in the angular dependence. To check possible contribution of radiation reflection from the end of fiber, the similar measurement was performed when the end of fiber was screened by the absorber. These measurements showed the same results, i.e. the reflection contribution is absent.

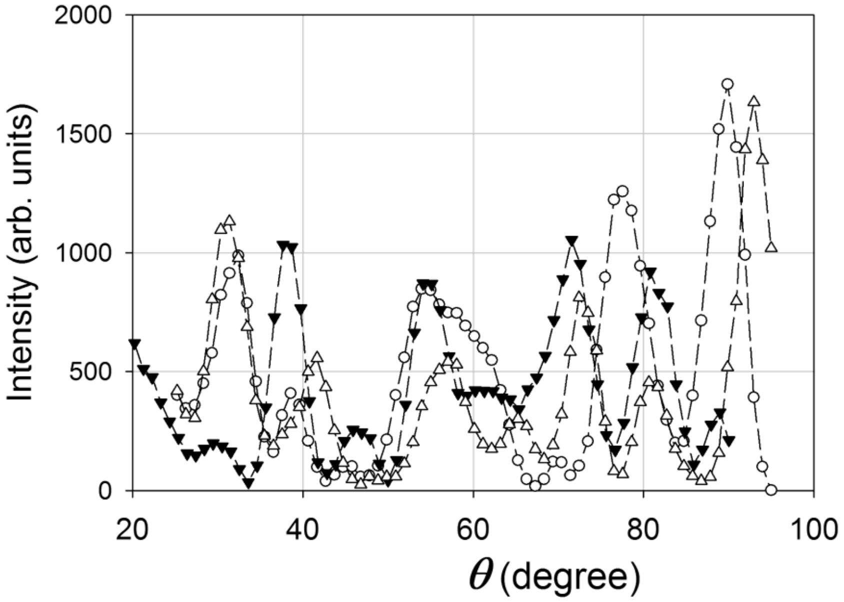

Figure 3. Radiation intensity in geometry *b* as a function of fiber angle θ for different values of impact-parameter *h*: ○ – $h = 0$ mm, △ – $h = 30$ mm, ▼ – $h = 70$ mm.

4. Discussion

In measurements in the figure 1*a* geometry it should be noted, that for a small angle θ pseudo-photons of the electron field are refracted at a small angle to the wall of fiber (less than angle of the total internal reflection, which for Teflon is $\approx 45^0$). This radiation, which may be classified as a DR at the end surface of fiber, propagates along the fiber without losses (see figure 2*a* in region near the point $\theta = 20^0$ and *h* = 20 mm). However, the angle of propagation of ChR is close to the angle of the total internal reflection, therefore due to the electron beam divergence, some part of ChR leaves the fiber. In this case the DR gives the main contribution to the registered radiation. With the increasing of angle θ (see figures 2*a* and 2*b* in region near the point $\theta = 60^0$ and *h* = 30 mm) the situation is reversed, and the ChR gives the main contribution to the registered radiation. Let's note that the DR, which is generated on the wall of fiber, may not propagate along the fiber, because in this case the condition of total internal reflection is not satisfied.

In geometry 2*b* in contrast to geometry 2*a*, we see the oscillations in the angular dependence. As was shown above, this isn't the result of reflection from the end of fiber. To understand the reason of such behaviour let's note that the horizontal (in our geometry) component of the electron field at the left and right side of the electron beam is of the opposite direction. This field generates ChR with opposite phases in the left and right halves of the fiber. The interference of this radiation may cause oscillations in angular dependence.

Of course, these explanations are simplified. Really, the propagation of radiation along a fiber is more complicated. It may be single-modal, multi-modal or prohibited, depending on the relation between wavelength and radius of fiber (see [7]), but simplified explanation may be useful for intuitive understanding of these processes. For the future we plan the experimental investigation of the spectral characteristics of radiation in fibres and dependence of this radiation on the fiber curvature, which is important for applications.

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