COHERENT DIFFRACTION AND CHERENKOV RADIATION FROM SHORT ELECTRON BUNCHES IN FIBERS*

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Abstract

The ability to use a radiation of relativistic electrons in optical fibers in beam diagnostics was considered by X. Artu and C.Ray [1,2]. In this report the properties of different types of radiation, such as diffraction and Cherenkov radiation, induced by an electromagnetic field of a relativistic electron in fibers were considered. We present the results of experimental investigations of this phenomenon in millimetre wavelength region. The nature and properties of radiation was analysed experimentally for different geometries of the fiber and the electron beam disposition. The spectral characteristics and radiation yield depending on the orientation of fibers relative to the electron beam for straight and bent fibers were investigated.

INTRODUCTION

Dielectric fibers are widely used in particle and accelerator physics. In the work [3] authors used optical fibers placed aside an accelerator beam trajectory in order to measure beam losses detecting Cherenkov radiation (CR) from particles leaking the main beam. Recently authors of the work [4] proposed to use a fiber-mesh array to determine a transverse beam profile. CR is generated when a beam crosses a few fibers and light from each one depends on a part of the beam which intersects such a fiber.

X.Artru and C.Ray considered the case when a charged particle passing near an optical fiber produces CR due to polarization of fiber atoms by a field of the particle and proposed to use such CR light for a noninvasive beam diagnostics.

A transverse component of the relativistic charged particle with Lorenz-factor γ can excite such a polarization radiation with wavelength λ in a target if the distance between the particle trajectory and a target (so-called impact parameter) less (or comparable) than $\gamma\lambda$. The typical manifestation of polarization radiation is CR which can be effectively generated by a beam passing in vacuum near a dielectric target (see, for instance, experiments [5,6]).

Authors of the work [2] underlined the important role of the light "channeling" in a fiber introducing term "particle – induced guided light (PIGL)". They considered two types of the PIGL: type 1 for a particle passing near a straight part of the fiber and type 2 for a particle passing near an end of the fiber. Generally speaking it is more evidently to classify PIGL-1 as Cherenkov radiation and PIGL-2 as Diffraction radiation (DR). In the latter case the main part of radiation is generated via DR mechanism at a flat entrance surface of the fiber.

THEORETICAL BACGROUND

The detailed theoretical analysis of radiation propagation in strait fibers was done in [2]. Here we focus attention on the features of radiation propagation in bent fibers. The flexible metallic waveguides was considered theoretically in [7]. For dielectric flexible fibers we can use the approach used in [8]. Main feature of a bent fiber in comparison with a straight one is the dependence of radiation attenuation along the fiber on the bending angle. According to [8] the attenuation factor α' may be presented for our conditions as:

$$\alpha'(u,w)=\frac{1}{2\omega}\sqrt{\frac{\pi}{\frac{2R}{d}w^3}}\cdot\exp\left(\frac{2w^3 2R/d}{\left(\frac{3}{2}\omega d\right)^2}\right)\cdot\frac{u^2}{d\cdot\left(v\cdot K_1(w)\right)^2} \quad (1)$$

where d is the fiber diameter, R is bending radius, ω is the radiation frequency, $v=\omega d/2\sqrt{\varepsilon-1}$, u,w are the usual dimensionless kinematical variables, ε is the dielectric permittivity and K_1 is the Bessel function.

After integration of (1) on the kinematical variables u,w over the experimental spectral region $\{u_1,u_2\},\{w_1,w_2\}$

$$\alpha=\int_{w_1}^{w_2}\int_{u_1}^{u_2}\alpha'(u,w)du\,dw$$

the radiation intensity may be presented as:

$$I=I_0\cdot e^{-2\alpha\cdot\omega\cdot\Phi} \quad (2)$$

where Φ is the bending angle in radians. This expression may be used for the comparison with experimental results after averaging over the experimental spectral region.

EXPERIMENTAL SETUP

The experiment was carried out at the TPU microtron with the next parameters: the energy of electrons is 6.1 MeV; the macro-pulse duration is 3–5 μs; the macro-pulse frequency is 1–8 Hz; the length of the electron bunch is $\sigma_b \approx 2$ mm; the number of electrons in the electron bunch is $N_e \approx 10^8$; the number of bunches in the macro-pulse is $\approx 10^4$; the beam size at the output of the

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microtron is 4×2 mm; and the angular divergence of the output beam is $\sigma = 0.08$ rad. For the wavelength region $\lambda > \pi \cdot \sigma_b \approx 8mm$ a bunch emits polarization radiation in coherent regime, i.e. radiation intensity enhanced incoherent level more than 8 orders of magnitude. Geometry of our experiment is shown in Fig.1.

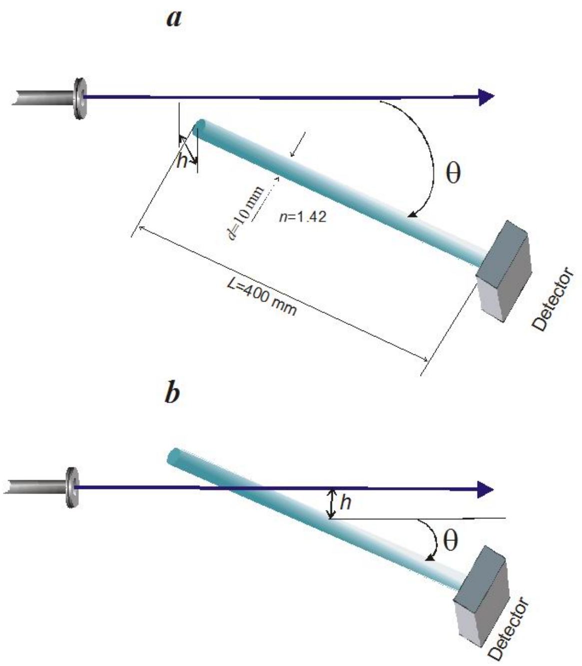

Figure 1: Two geometries of a fiber position.

For Lorenz-factor $\gamma = 12$ and wavelength $\lambda > 8mm$ the impact factor h can be chosen from the condition $h \le \gamma\lambda \approx 100mm$. We investigated dependence of the coherent CR yield from straight and bent dielectric fibers as a function of the fiber orientation angle θ for different impact parameters. For this aim the room temperature detector DP20M was used with sensitivity 0.3 V/mW in the wavelength range λ = 3 – 16 mm [9].The cylindrical Teflon sample with refractive index n=1.42 (L=400 mm, d=10 mm) was used as a straight fiber. For the bent fiber we used flexible polymer with n=1.5 (L=600 mm, d=11 mm) allowing to change a bending radius.

Propagation of radiation along straight and bent fibers we investigated in mm-wavelength range. Both types of excitation (by a field of relativistic electron bunch and by electromagnetic radiation from an emitter based on the Gann diode) were used. Spectral measurements were performed using an interferometer with wave front dividing and two focusing parabolic mirrors (see Fig.2).

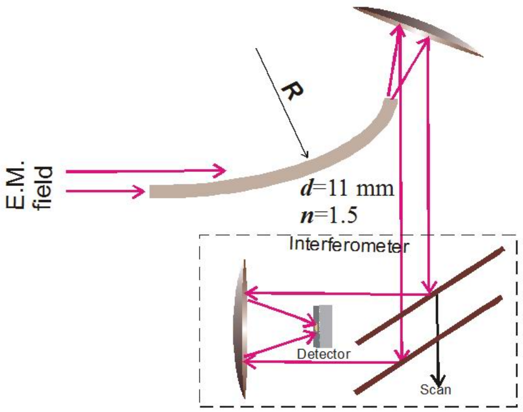

Figure 2: Scheme of spectral measurements.

EXPERIMENTAL RESULTS

The angular dependence of CR yield from the downstream end of the straight fiber is presented in Fig.3 for the geometry shown in Fig.1***a***. In Fig.3***a*** we present results obtained with the "open" upstream fiber end and in Fig.3***b*** results measured with the screened entrance fiber aperture are demonstrated. A conducting screen had the same diameter as the fiber. We observed significant suppression of CR yield for the screened fiber aperture. It means we observed coherent DR mainly (PIGL-2).

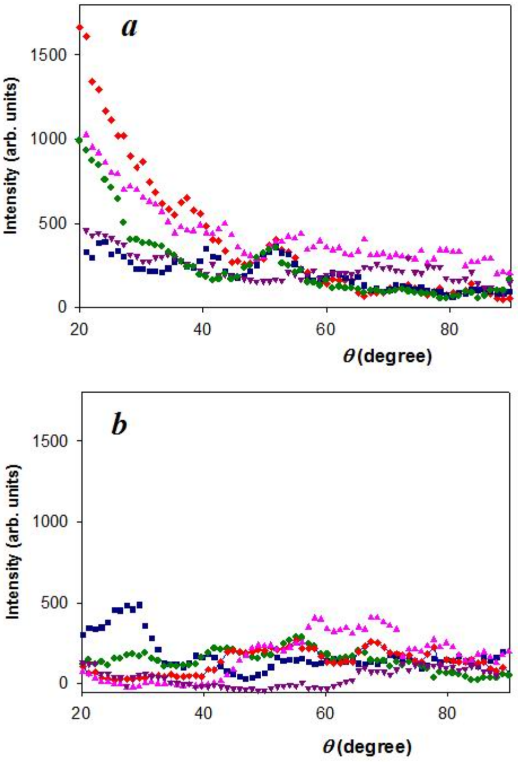

Figure 3: Radiation intensity as a function of fiber orientation angle θ for different impact-parameters h: ■ – h=-10 мм, ● – h=0 mm, ◆ – h=10 mm, ▲ – h=20 mm, ▼ – h=60 mm. ***a*** – open upstream fiber end, ***b*** – the entrance fiber aperture is screened.

As one can see from Fig.3 such a kind of radiation is generated for fiber orientation angles $\theta < 45^0$. The calculated value of Cherenkov angle $\theta_{CR} = 1/n\beta$ is equal 45.5^0 for our experimental conditions. We suppose the radiation registered at angles $\theta < \theta_{CR}$ propagates along a fiber due to internal reflections by fiber walls. Flexible fibers are used routinely in the optical range. It seems such fibers for THz- or mm-range radiation can be applied for beam diagnostics. So, we have investigated the yield of coherent CR from bent fibers depending on the bending radius (see Fig.4).

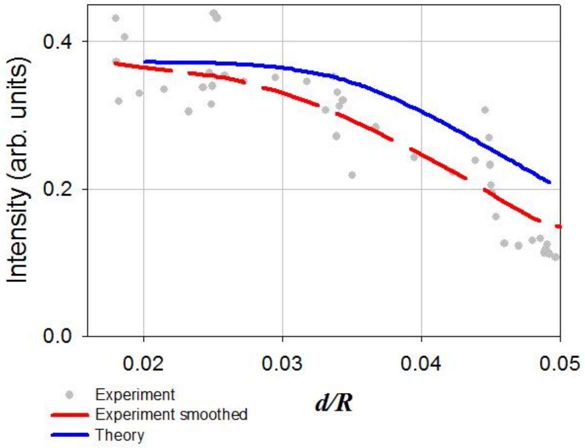

Figure 4: Yield of coherent CR from bent fibers depending on the bending radius R.

As expected CR yield diminishes with decreasing of the bending radius. Calculation using (2) shows a reasonable agreement with experimental results (see blue curve in Fig.4). In our experiment CR is deflected by a bent fiber with radius *R*=*d*/0.05=220 mm for the angle $2\pi \cdot R/L = 132^0$ with detectable intensity.

Figure 5 shows coherent CR spectrum generated and guided by bent fiber with diameter 11 mm and refractive index 1.5 in comparison with spectrum accepted and guided by the straight Teflon fiber with diameter 10 mm and refractive index 1.42.

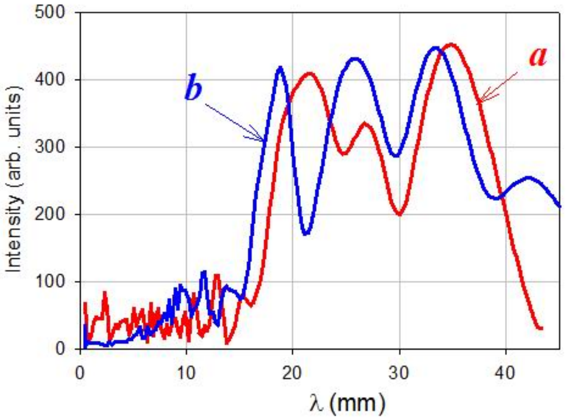

Figure 5: Coherent CR spectra generated and guided by fibers. ***a*** – bent fiber, ***b*** – straight Teflon fiber.

For both cases we have obtained closed spectra. One can estimate the minimal wavelength for both cases $\lambda_{\min} \approx 15\,mm$ but a deflected radiation for the wavelength $\lambda > 40\,mm \gg d$ is suppressed. One of the possible reasons may be connected with a decreasing of efficiency of radiation reflection with wavelength much larger than the fiber diameter.

CONCLUSION

We showed that a short electron bunch passing in vacuum near dielectric fibers (straight or bent) generates coherent Cerenkov radiation, which is guided by fiber walls. Using bent fibers it is possible to deflect CR at angles more than 90^0. Spectrum of the guided CR is determined by the fiber diameter. Two fibers with a vacuum gap between them for a beam can be used for a noninvasive beam position monitoring, for instance. An ultra-relativistic electron bunch (with $\gamma \approx 10^3$) can generate Cherenkov light in ordinary flexible optical fibers with a distance between them $\approx 0.5\,mm$. In this case one can expect to achieve a few micrometers spacing resolution. We would like to emphasize that the resulting light yield from devices [3,4] where particles intersect diagnostical optical fibers will include some additional contribution from particles flying in a vicinity of a fiber and such a contribution should be taken into account.

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