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The coherent Vavilov-Cherenkov radiation for a bunch length diagnostic

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Summary. — Coherent Vavilov-Cherenkov radiation generated by a 6.1 MeV bunched electron beam traveling in the vicinity of a solid dielectric target (PTFE and Paraffin) has been investigated experimentally. In addition, we have also demonstrated the simple scheme of the Cerenkov interferometer for non-invasive longitudinal electron bunch length diagnostics.

PACS `41.60.Bq` – Cherenkov radiation.

1. – Introduction

The efficiency of some modern accelerator complexes such as colliders or free-electron lasers, is determined not only by the transverse sizes of a bunch but also by the longitudinal size of a bunch. The optimization and detailed control of the longitudinal electron distribution in the bunch is an important feature in order to maximize the luminosity in the future complexes. Crucial requirement of beam diagnostic tools is the possibility to measure parameters of a single electron bunch without noticeable beam deformation. We propose to use coherent Cherenkov radiation (ChR) for noninvasive beam diagnostics.

ChR that is emitted while a charged particle moves in a medium with velocity exceeding the speed of light in this medium, is developed theoretically and experimentally and is a widely used tool for detecting particles [1, 2]. The radiation cone in the transparent medium id defined by the following condition:

$$\cos\theta = \frac{1}{n \cdot \beta}, \tag{1}$$

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where θ is the radiation angle, β is the electron velocity in the speed of light units, n is the refraction index of the medium.

ChR may also appear while a charged particle travels in the vacuum nearby the medium due to the fact that this radiation is caused by the charged particle's electromagnetic field that has the transverse dimensions of about $\gamma\lambda$ (γ is the particle Lorentz factor, λ is the radiation wavelength). This fact becomes clear if we remember that ChR is one of the kinds of the so-called polarization radiation [3]. Our geometry of radiation differs from the conventional one as diffraction radiation differs from the transition one. The theoretical possibility of simultaneous appearance of Cerenkov radiation and diffraction one was shown by Karlovets and Potylitsyn [4].

When the bunch travels near the target, the longitudinal form-factor drastically changes the intensity of polarization radiation. The simple estimation proves the fact that the coherency of any kind of polarization radiation strongly depends on the longitudinal bunch [5]. The total spectral-angular density of polarization radiation (both coherent and incoherent) from the bunch of N_e electrons may be written as (we neglect transverse bunch size effects):

$$\frac{\partial^2 W_{\text{coh}}}{\partial\omega\partial\Omega} = \frac{\partial^2 W_{\text{incoh}}}{\partial\omega\partial\Omega} N_e(1 + (N_e - 1)|f_z(\sigma_z)|^2), \tag{2}$$

$\frac{\partial^2 W_{\text{incoh}}}{\partial\omega\partial\Omega}$ is the spectral-angular density of radiation from one electron, N_e is the number of electrons in the bunch, $|f_z(\sigma_z)|^2$ is the longitudinal form factor of the electron bunch. For the Gaussian bunch with rms σ_z the form-factor looks like the following:

$$|f_z(\sigma_z)|^2 = \exp\left[-\frac{\omega^2\sigma_z^2}{\beta^2 c^2}\right]. \tag{3}$$

Most of existing bunch length measurement methods using a coherent radiation are based on the measurement of the radiation spectral density distribution with the subsequent bunch length calculation using spectral density features. Usually to obtain a spectral density distribution a radiation beam is to be splattered into two beams and the autocorrelation function (interferogram) is measured using some types of interferometer [6, 7].

On the other hand, if one has a target material with frequency dispersion [8], a different radiation wavelength is generated under different angles. In this case one may change the complicated spectra measurements for convenient angular measurements in order to find coherent threshold and determine the bunch length [9].

In the first part of the paper we show our experimental results devoted to characteristics of coherent ChR from two prisms with different refractive indexes in millimeter wavelength region. In the second part of the paper we discuss the possibility of the measurement of the bunch length.

2. – Experiment

We have carried out our experimental research on the extracted beam of Tomsk Polytechnic University microtron with parameters listed in table I.

The experimental scheme is shown in fig. 1. The electron beam extracted into air through the 40 μm Be foil was used. The train of bunches travels near a target. The detecting system consisted of the parabolic telescope, which represented a paraboloidal

TABLE I. – *Electron beam parameters.*

Electron energy	6.1 MeV($\gamma = 12$)	Bunch spacing	380 ps
Train duration	$\tau \approx 4\,\mu$s	Bunch population	$N_e = 6 \cdot 10^8$
Bunches in a train	$n_b \approx 1.6 \cdot 10^4$	Bunch length	$\sigma_z \approx 2$ mm

mirror (diameter 170 mm, focal distance 145 mm) in the focus of which the detector was set up. This tool provides the possibility to measure the angular radiation characteristics in the far-field zone [10]. The radiation from each train has been detected using DP-21M detector. The last 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 region 11–17 mm is approximately equal to 0.3 V/mW [11]. The wavelength region was limited by coherent threshold in the smaller wavelengths and by the beyond-cutoff waveguide (diameter 15 mm) that passes wavelengths lower than 25 mm and is used to decrease accelerator RF background. Incoherent radiation cannot be measured by the detector. The measured region yield was averaged over 20 trains. The statistic error was less than 10% during the experiments. The Faraday cup signal allowed measuring a zero point of impact-parameter using the electron beam intensity suppression when the wire scanner crossed the electron beam. The impact-parameter was equal to $h = 25$ mm. ChR in diffraction geometry should be polarized only in the horizontal plane, *i.e.* the plane of electron velocity vector and radiation wave-vector. During the experiment a grid polarizer was used.

In our experiment we used two various solid dielectric targets with different refractive indexes. Teflon (Polytetrafluoroethylene -PTFE) target with the length equal to 247 mm and the height equal to 74 mm was used during the experiment. The target was a prism based on a right-angled isosceles triangle in order to decrease ChR refraction losses. Paraffin target with length equal to 253 mm and height equal to 80 mm was also used. The target was a prism with 40 deg. The refractive indexes of Teflon and paraffin for the millimeter wave region were measured to be equal to 1.41 and 1.49 for $\lambda > 10$ mm, respectively.

At first, we have measured the ChR peak positions while scanning over θ angle for both targets. Figure 2 shows the result of θ scan. The measured distribution of the radiation

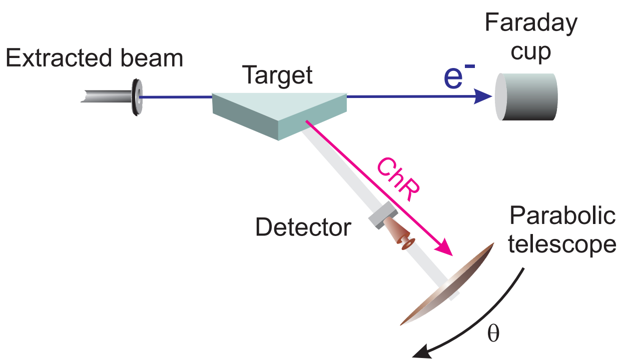

Fig. 1. – Experimental scheme.

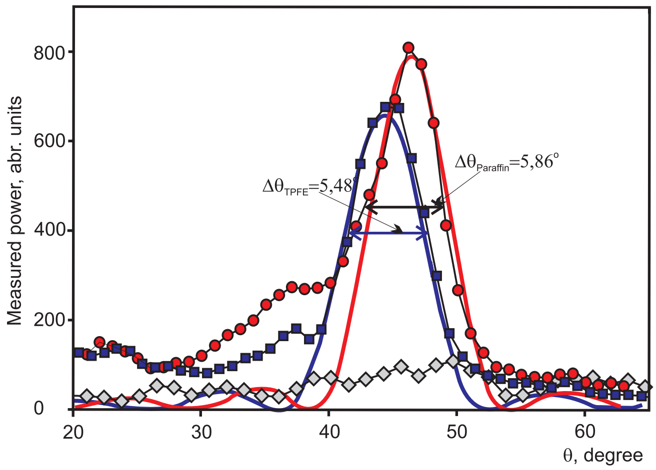

Fig. 2. – The angular dependence of ChR: the circle—horizontal polarization component of radiation from the Paraffin target, the squares—horizontal polarization component of radiation from the PTFE target, the inclined squares—vertical polarization component of radiation from the PTFE target, the solid lines—theoretical calculations.

from the Teflon target is shown in fig. 2. by the squares and from the paraffin target by the circles. The corresponding curves in this figure show the theoretical calculation of ChR [4]. It should be noted the angular width of ChR cone θ is defined by a dispersion law and target sizes but not by the Lorentz factor. From fig. 2 one may clearly see that the vertical polarization component is suppressed as expected (inclined squares).

As a second step, we have checked the coherency of radiation. In order to find whether the radiation was coherent or not the beam current dependence has been measured. This dependence is presented in fig. 3. Measured radiation is shown by dots and the solid line shows the fit by the function $y = a + bx + cx^2$. One may see from fig. 3

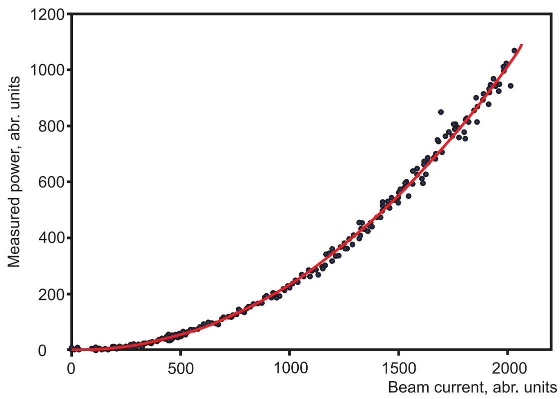

Fig. 3. – The current dependence of CCR: the dots—experimental data, the solid line—quadratic fit function.

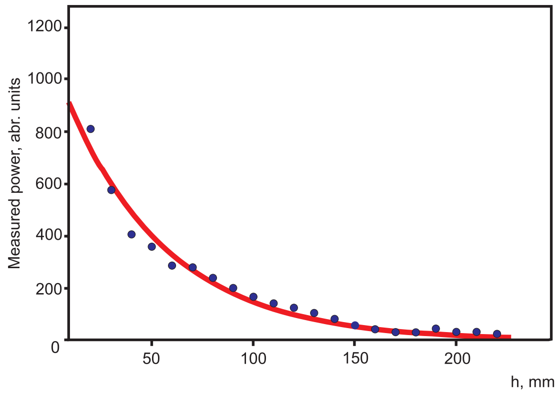

Fig. 4. – The dependence on the impact parameter: the dots—experimental data, the solid line—fit function.

that the fit function agrees very well with measured data and, therefore, radiation is coherent.

The measured coherent Cherenkov radiation (CChR) intensity as a function of impact-parameter is presented in fig. 4. The solid line in fig. 4 is the fit for CChR intensity with a function $y = 1085.5 \cdot \exp[-0.02 \cdot h]$.

Figure 5 shows by the histogram bars the spectrum of CChR measured at the angle of radiation maximum. For the spectral measurements the low-pass filters, described in [12] were used. The filters were set up at (before) the detector horn. The solid line presents the radiation form-factor from eq. (3) for $\sigma_z = 2\,\text{mm}$.

3. – Longitudinal beam diagnostics

As a rule, in order to measure the spectrum of coherent radiation and reconstruct the bunch length one should use an interferometer. We propose to use a compound CChR

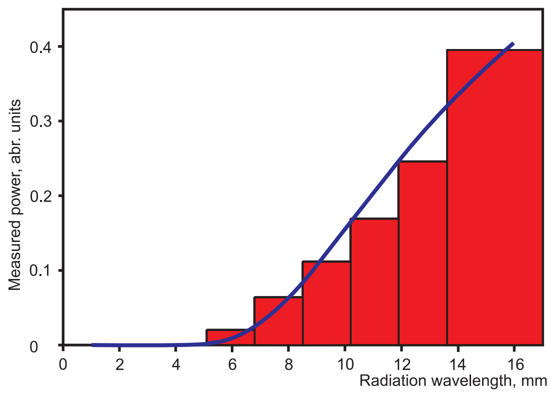

Fig. 5. – The spectrum of CCR measured at radiation peak angle $\theta = 44.5°$. The histogram bar—experimental data, the solid line—form factor from eq. (3).

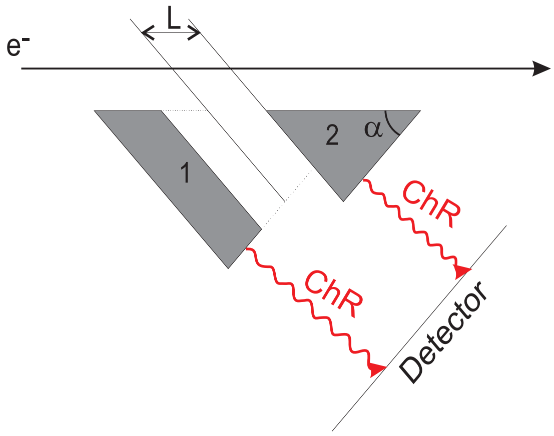

Fig. 6. – The scheme of Cherenkov interferometer.

target as an interferometer. The scheme of a compound CChR target is shown in fig. 6. As can be seen in fig. 6, the target consists of two parts, and the parts volumes are equal. When the beam moves near the CChR target, the CChR is generated by each part of the target. If the detector is installed at the angle of radiation maximum, one may measure CChR yield moving the second part of the target. In this case one may obtain a detuning curve (interferogram).

In our experiment the detector measures radiation yield in some wavelength region that is limited by coherent threshold in the smaller wavelengths and by the beyond-cutoff waveguide that passes wavelengths lower than 25 mm. In this case, the expression for a detuning dependence may be described by the following formula:

$$(4)\qquad P(L,\sigma_z)=\int_0^{\lambda\,\max}\exp\left[-4\pi^2\frac{\sigma_z^2}{\lambda^2}\right]\left(1-\cos\left[2\pi\frac{L}{\lambda}\left(\frac{1}{\beta}-\sin[\alpha]\right)\right]\right)W_{CR}(\lambda)\mathrm{d}\lambda,$$

where $W_{CR}(\lambda)$ is the spectral-angular density of radiation from one target, L is the movement distance.

Calculated detuning dependence for the experimental conditions ($\gamma = 12$, $\lambda_{\max} = 25.5\,\mathrm{mm}$, paraffin target ($\alpha = 40°$), $h = 10\,\mathrm{mm}$, $\sigma_z = 2\,\mathrm{mm}$) is presented by solid (blue) curve in fig. 7. The measured detuning dependence is shown by the (yellow) dots in fig. 8.

In order to obtain information from the detuning curve one may use different ways. Let us empirically introduce the following way to obtain the bunch length. $\tau = \frac{P(0)-P(d_1)}{-P'(d_1)}$, $\varepsilon = \frac{(P'(d_2))^2}{P(d_2)P''(d_2)}$ are some functions, where d_1 is the distance value at the fist derivative minimum for the measured dependence, d_2 is the distance value at the second derivative maximum for the measured dependence. Using these functions one may obtain bunch rms as

$$(5)\qquad \sigma_z(\tau,\varepsilon)=0.65\cdot\tau\cdot\exp\left[\frac{-\varepsilon}{0.785}\right].$$

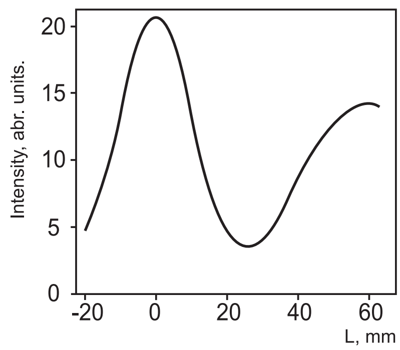

Fig. 7. – (Colour on-line) The calculated dependence of P on L.

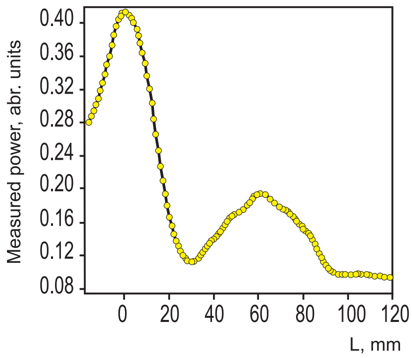

Fig. 8. – (Colour on-line) The measured dependence on L.

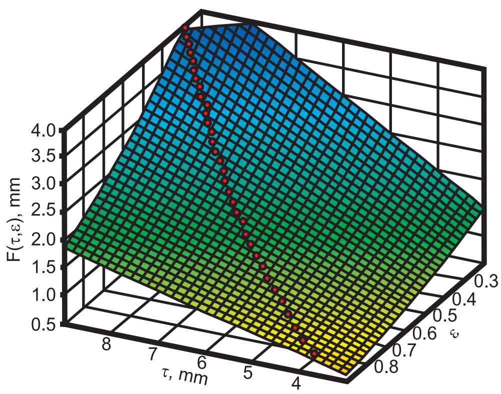

Fig. 9. – The σ_z as a function of τ and ε: the dots—calculated dots, the surface—approximated function $\sigma_z(\tau, \varepsilon) = 0.65 \cdot \tau \cdot \exp\left[\frac{-\varepsilon}{0.785}\right]$.

Figure 9 shows by the dots the calculation of τ and ε functions from the simulated detuning curves (eq. (4)) for different bunch lengths. The surface in fig. 9 shows the proposed function to estimate the bunch length (eq. (5)).

For our experimental interferogram the bunch length is equal to $\sigma_z = 2.45 \pm 0.3\,\mathrm{mm}$ basing on eq. (5).

4. – Conclusion

We would like to point that eq. (1), as expected, is useful for the coherent ChR generated by the relativistic electron bunch passing in the vicinity of the target. We have demonstrated experimentally the square dependence of Cherenkov radiation intensity on the bunch population, which confirms the coherent character of radiation.

We also have demonstrated the possibility to measure the bunch length without a beam distortion. This scheme was tested in the millimeter wavelength region on the 6.1 MeV bunched electron beam of microtron. The measured beam length is in good agreement with the experimental data.

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