

COHERENT CHERENKOV RADIATION FROM A SHORT BUNCH PASSING NEAR A TARGET AND POSSIBILITY OF A BUNCH LENGTH DIAGNOSTICS*

A. P. Potylitsyn[†], S. Yu. Gogolev, D. V. Karlovets, G. A. Naumenko, Yu. A. Popov, M. V. Shevelev, L. G. Sukhikh, Tomsk Polytechnic University, Tomsk, Russia

Abstract

A noninvasive technique to determine a sub-mm length of electron bunches (rms < 100 um) based on a measurement of the coherent Cherenkov radiation spectrum in THz range is proposed. The radiation is generated while electron bunch moves in a vacuum near dielectric target. If the optical properties and geometry of a target are chosen in order to achieve a low absorption with a dispersion allowing expanding the Cherenkov cone, such target may be considered as the natural Cherenkov prism. We demonstrate a feasibility of using of CsI prism for measurement of a bunch length in the range 50-200 um for Lorentz factor $\gamma = 100$. We also measured coherent Cherenkov radiation power from Teflon target generated by the 6.1 MeV bunched electron beam with bunch rms length 1.2 mm. CChR seems to be a promising radiation mechanism for a new beam diagnostics technique.

INTRODUCTION

Noninvasive methods of beam longitudinal diagnostics are widely developed now especially for femtosecond bunches of compressed linac beams. The typical bunch length is about 100 fs. In this case one may use the coherent radiation as a tool to estimate bunch length. In the practice the coherency of radiation (squared dependence of radiated power from the bunch population) is explicitly defined by longitudinal size of the bunch and measuring spectrum of coherent radiation one may calculate bunch length. Such method is known for 15 years and is widely used with transition and diffraction radiation [1, 2]. The spectral measurements are rather complicated in the THz region where 100 fs bunches radiate coherently and that is why it was proposed to use coherent Smith-Purcell radiation [3]. There is convenient dispersion relation connecting radiated wavelength and radiation angle. That means that one may simply measure angular distribution and estimate the bunch length. We propose to use coherent Cherenkov radiation for noninvasive beam diagnostics which possesses some dispersion too.

Cherenkov radiation (ChR) that appears while a charged particle travels in a media with a velocity that exceeds the speed of light in this media is investigated both theoretically and experimentally and is widely used in particle detectors for nuclear physics. The radiation cone in

transparent medium is defined by the following condition:

$$\cos \theta = \frac{1}{\beta n} \quad (1)$$

where θ is the radiation angle, β is the electron velocity in the speed of light units, $n = \sqrt{\epsilon}$ is the refractive index.

CR may also appear while a charged particle moves in the vacuum in a vicinity of the medium due to the fact that this interaction is caused by the charged particle's electromagnetic field that have the transverse dimensions of about $\gamma\lambda$ (γ is the particle Lorentz-factor, λ is the radiation wavelength). If the medium have frequency dispersion the different wavelengths would be radiated under different angles. Making a cone or a prism from such material one may have wide angular distribution of different wavelengths that may be measured with good accuracy.

In the first part of the paper we have measured the coherent ChR from two prisms with different refractive indexes in millimeter wavelengths. In the second part of the paper we discuss the possibility of the measurement of femtosecond bunch lengths.

EXPERIMENT

We have carried out experimental investigations in Tomsk Polytechnic University at Nuclear Physics Institute microtron. The experimental scheme is shown in Fig. 1. The electron beam extracted into air through 50 μm Be foil was used. The train of bunches with electron energy 6.1 MeV ($\gamma \approx 12$), consisting of $n_b \simeq 10500$ bunches (the maximal bunch population is about $N_e = 10^8$ electrons) with $\tau = 4 \mu\text{s}$ duration travels near the teflon target. The average beam current was about 30 mA. The transverse sizes of electron beam in the extraction point are about $\sigma_x \times \sigma_y = 4 \times 4 \text{ mm}^2$. The longitudinal distribution of electrons in the bunch is believed to be a Gaussian with rms $\sigma_z = 1.2 \text{ mm}$.

The detecting system consisted of so-called "telescope", which represented a parabolic mirror (diameter 170 mm, focal distance 151 mm) in focus of which the detector was set up. Such telescope allows to measure the angular radiation characteristics equal to wave-zone ones [4]. 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 diode and preamplifier. The average sensitivity of the detector in the radiation wavelength region $11 \div 17 \text{ mm}$ is approximately equal to 0.3 Volt/mWatt [5]. The measured region was limited by coherent threshold in the smaller wavelengths and by

* This work was partly supported by Federal Agency for Education of Russian Federation within the program "Scientific and educational specialists of innovation Russia", Grant No. III1143.

[†] pap@interact.phtd.tpu.ru

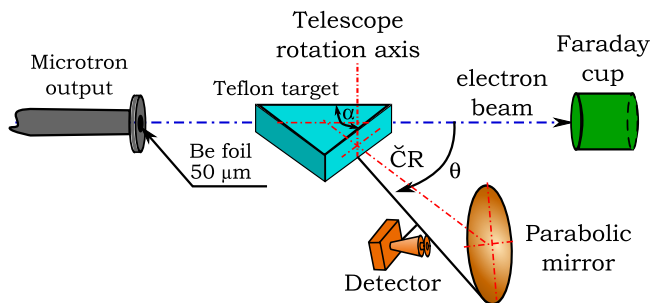


Figure 1: Experimental scheme and some definitions.

the beyond-cutoff waveguide (diameter 15 mm) that passes wavelengths lower 25 mm used to decrease accelerator RF background. Incoherent radiation can not be measured by the detector. The measured radiation yield was averaged over 20 trains. The statistic error was less than 10% during the experiments. The wire scanner was used to find the electron beam axis which was used as a starting point to determine the impact-parameter that was equal to $h = 25$ mm. ČR in diffraction geometry should be polarized only in horizontal plane, i.e. the plane of electron velocity vector and radiation wave-vector. During the experiment a grid polarizer was used. The Faraday cup was used to measure beam current.

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 right-angled isosceles triangle in order to decrease ČR refraction losses. Teflon refractive index in abovementioned wavelength region is equal to $n_t = 1.45$ [6] and $n_t = 1.439$ in region less than 5 mm according to [7]. Paraffin target with length equal to 253 mm and height equal to 80 mm was also used. The target was a prism with $\alpha = 40$ deg. The refractive index was equal to 1.49.

As the first step we have measured the coherency of radiation. In order to find whether the radiation is coherent or not the beam current dependence was measured. The latter is shown in Fig. 2. Measured radiation is shown by the red circles and the solid line shows the fit by the function $y = a + bx + cx^2$. One may see from Fig. 2 that the fit function agrees very well with measured data and, therefore, radiation is coherent.

As the second step we have found the ČCR peak positions while scanning over θ angle for both targets. Fig. 3 shows the result of θ scan. The measured distribution of the radiation from the teflon target is shown in Fig. 3 by the red circles and from the paraffin target by the blue squares. The theoretical peak positions obtained using Eq. (1) for $n_t = 1.45$ and $n_p = 1.49$ are shown by the solid lines. It should be noted the angular width of ČR cone $\Delta\theta_{t,p}$ is defined by a dispersion law and target sizes but not by the Lorentz-factor.

06 Beam Instrumentation and Feedback

T03 Beam Diagnostics and Instrumentation

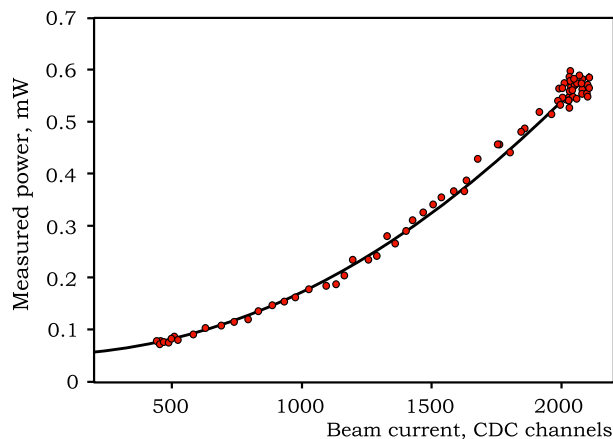
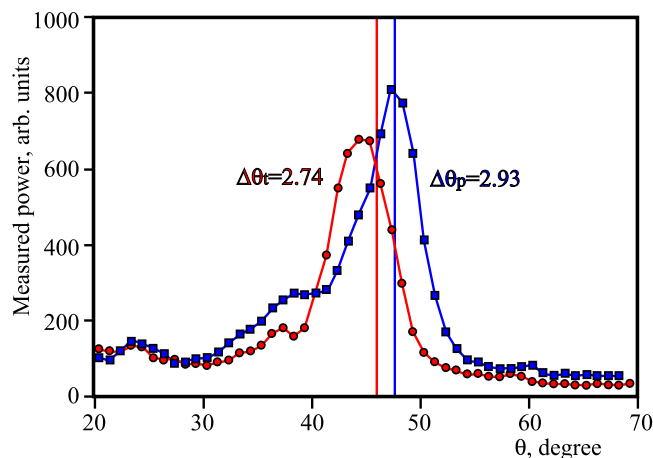

 Figure 2: The current dependence of ČCR: the red circles – experimental data, the solid line – quadratic fit $y = a + bx + cx^2$.


Figure 3: The angular distribution of coherent ČR: the red circles – the teflon target, the blue squares – the paraffin target. Solid lines shows the positions of ČR peaks according to Eq. (1).

LONGITUDINAL BEAM DIAGNOSTICS

According to presented experimental data one may see that coherent ČR in the diffraction geometry is generated according to Cherenkov condition as it was expected. If one has target material with frequency dispersion, different radiation wavelengths be generated under different angles. In this case one may change the complicated spectral measurements for convenient angular measurements in order to find coherent threshold and to determine the bunch length. As it was mentioned before for femtosecond bunches (for $\sigma_z = 30$ μm a coherent threshold lies near 1 THz) CsI prism may be used as a target. The dispersion relation for the material was measured in paper [8] and Sellmeyer's formula may be written as:

$$\varepsilon(\lambda) = 1 + \frac{1.33 \lambda^2}{\lambda^2 - 26569} + \frac{3.77 \lambda^2}{\lambda^2 - 9522}, \quad (2)$$

where λ is measured in microns.

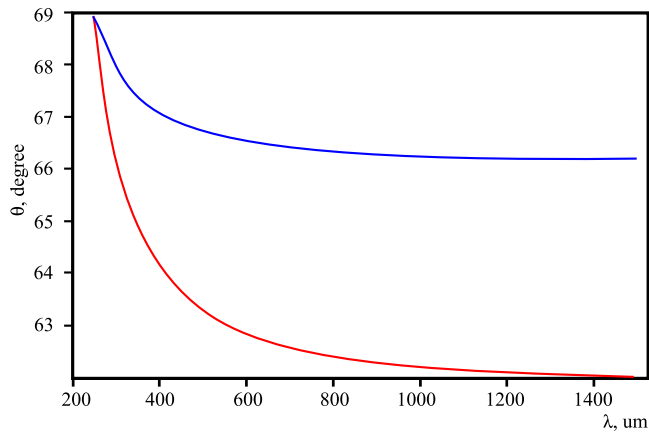


Figure 4: Dispersion relation of coherent ChR from CsI prism. Blue line – without Snell's law, red line – with Snell's law. Prism angle is equal to 69 deg.

For simple estimation one may use Eq. 1 and Eq. 2 taking into account Snell's law for a prism with output surface normal to e.g. 69 deg ($\alpha = 21$ deg). Fig. 4 shows the dispersion curve obtained such way: blue curve obtained without Snell's law and red one taking it into account. One may see that region of interest (wavelengths near 300 μm) occupies rather large angular range, approximately 5 deg. This gives us a hope to measure the coherent threshold with good accuracy.

Following the recent papers [9, 10] in which rather simple and physically clear method for the solution of a problem of polarization radiation including ChR is developed it is possible to carry out more detailed simulation and to deal with intensities change but it would take too much space and will be published elsewhere. We may say that the main result will be almost the same.

CONCLUSION

In conclusion we would like to point that coherent ChR generated by the ultra-relativistic electron bunch passing in a vicinity of target medium with frequency dispersion seems to be a promising mechanism to estimate the length of the bunch without additional spectrometers. In this case the medium would operate as spectrometer and it is enough to measure angular distribution of the radiation. In this sense the Smith-Purcell radiation have the same properties but the intensities are incomparable: the ChR is significantly more powerful. The CsI material is well-known and commercially available and may be convenient for construction of the diagnostic stations for bunches of approximately 100 fs length.

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