13th Int. Particle Acc. Conf. IPAC2022, Bangkok, Thailand JACoW Publishing
ISBN: 978-3-95450-227-1 ISSN: 2673-5490 doi:10.18429/JACoW-IPAC2022-MOPOPT033

STUDY OF CHRENKOV DIFFRACTION RADIATION FOR BEAM DIAGOSTICS*

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Abstract

Vavilov-Cherenkov diffraction radiation (ChDR) has been paid attention to non-beam-destructive diagnostics [1,2,3]. The physical understanding of ChDR is, however, not well satisfied yet because precise experimental measurement is not much easier than one expects. Although we do not deny the Cherenkov radiation and ChDR are fully explained by the classical electromagnetism, we encounter a couple of difficulties in actual applications. For instance, the theory is usually established for the far-field observation, in spite of that the radiation is often observed near-field in the realistic beam diagnostic tools employing photon measurements. In addition, the theory, as a matter of course, includes some assumptions which is sometimes not valid for the specific experiments. We have carried out test experiments for observation of coherent ChDR in a THz frequency region emitted from ultra-short electron bunches supplied by the t-ACTS accelerator at Tohoku University [4]. In this manuscript, a concept of ChDR as a probe of the beam diagnostics is discussed and some experimental results are shown.

INTRODUCTION

Diffraction radiation (DR), which is emitted from charged particles passing through in the close vicinity of a metallic or dielectric medium, is a beam diagnostic probe without beam interception [5,6]. Considering the beam is passing through the centre of a circular aperture in a screen perpendicular to the beam trajectory, radiation cones appear in both backward and forward directions with an opening angle of ~1/γ with the relativistic factor γ of charged particle. The backward DR is a reflected electromagnetic field of the beam itself, it can be teared off from the beam line by tilting the screen. The backward DR is often used as beam diagnostic tools. However, the opening angle is still very small. According to the theoretically deduced DR intensity [7], the well-known Ginzburg-Frank formula for transition radiation (TR) is attenuated in accordance with an aperture radius function K [8,9],

$$\boldsymbol{K} = \exp\left(-2\xi\right) \text{ with } \xi \equiv \frac{\boldsymbol{h\omega}}{\boldsymbol{\beta\gamma c}}, \tag{1}$$

where ω, β and c are the angular frequency of the radiation, the relative velocity of the charged particle and the velocity of light. The aperture radius, h, is therefore an impact parameter that is a distance between the charged particle and the boundary of medium. The function $K(\xi)$ is usually called the coupling factor, and it should be noted that the Eq. (1) is valid for $\xi \gg 1$, and in case of $\xi \ll 1$, K~1.

Here we consider a cylindrical hollow dielectric for a ChDR radiator as shown in Fig. 1. Cherenkov angle, the opening angle of Cherenkov radiation (CR), is given by

$$\cos\theta_C = \frac{1}{n\beta}. \tag{2}$$

The refractive index n of dielectric medium is usually larger than 1, so that the larger opening angle can be obtained. Since the manner of the coupling factor K is essentially identical for the ChDR, the radiation intensity may depend on the azimuthal angle because the distance between the beam and the inner wall surface of dielectric dominates K, so that it would be expected an azimuthal angle dependence of ChDR contains information of the beam position inside of the aperture.

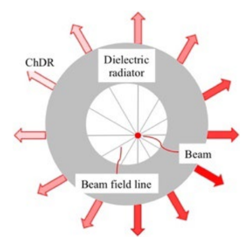

Figure 1: Cross section view of cylindrical hollow radiator and ChDR.

THEORETICAL BACKGROUND

Intensity of CR

The speed of light in the dielectric medium is varied as $c_n = c/n$ and the relative velocity of the particle becomes $\beta_n = n\beta$. Evaluating the Lienard-Wiechert potential with some math, the intensity of CR per unit frequency and per unit solid angle is written as,

$$\frac{d^2W}{d\omega d\Omega} = \frac{\mu_0}{4\pi}\frac{e^2\omega^2}{4\pi^2 c_n}\sin^2\theta\left(\frac{\sin\alpha}{\alpha}\right)^2(\Delta z)^2, \tag{3}$$

with

$$\alpha = \frac{1}{2}\left(1-\beta_n\cos\theta\right)\omega\Delta t \tag{4}$$

where μ_0, e, Δz and Δt are magnetic permeability in the vacuum, elementary charge, trajectory length of the particle in the dielectric and its duration, respectively. Eq. (3) is consistent with Tamm's formula [10]. One can find the CR intensity is roughly proportional to the square of the particle trajectory length, which is preferable for beam diagnostics because the intensity can be enhanced by using a long dielectric radiator. Although one can simply

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presume the intensity of ChDR would be deduced by multiplying Eq. (3) and Eq. (1) together, it is perhaps not correct because the complete far-field approximation Eq. (3) is evaluated in a dielectric continuum space.

Coherent ChDR

Regardless of any radiation from very short electron bunches, the intensity is coherently enhanced by a form-factor $f(\omega)$ when the radiation wavelength is shorter than the bunch length as

$$\left.\frac{d^2W}{d\omega d\Omega}\right|_{\text{coherent}} = \left[n_e\{1-f(\omega)\}+n_e^2 f(\omega)\right] \times \left.\frac{d^2W}{d\omega d\Omega}\right|_{\text{single-particle}}, \tag{5}$$

where n_e denotes number of electrons in a bunch.
The form-factor for Gaussian charge distribution in a bunch is written as

$$f(\omega) = \left|\exp\left(-\frac{\omega^2\sigma_B^2}{2}\right)\right|^2 \tag{6}$$

where σ_B is the bunch length along a longitudinal axis. The bunch length of 100 fs (30 μm) bring a form-factor of ~ 0.7 for the 1 THz (= $\omega/2\pi$), so the radiation intensity is dominated by the coherent part.

EXPERIMENTAL

t-ACTS Accelerator

A test facility, t-ACTS (test accelerator as coherent THz source) has been developed at Tohoku University for production of ultra-short electron bunch [11]. We have employed a thermionic RF gun consist of two independent cells to manipulate the longitudinal beam phase space [12], and velocity bunching scheme in the traveling wave accelerating structure is applied to the beam [13]. Main parameters of t-ACTS are listed in Table 1.

Table 1: t-ACTS Parameters

Beam energy	22 MeV (γ = 43)
Normalized horizontal emittance	~ 3 mm.mrad
Normalized vertical emittance	~30 mm.mrad
Micro-bunch charge	6 pC
Bunch length	~ 80 fs
Macropulse duration	2 μs
RF Frequency	2856 MHz

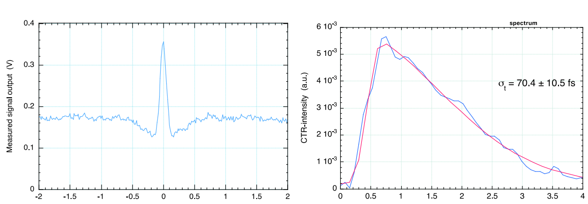

Figure 2: An interferogram of TR measured by a Michelson interferometer (left), and frequency spectrum (right).

Since the thermionic RF gun is very stable, the bunch length arround 80 fs is usually available. The bunch length is monitored by the frequency spectrum of coherent TR emitted from a Al mirror at the beginning and end of experiments. The intensity of TR is not dependent on the frequency basically so that the slope of TR spectrum is very much sensitive to the bunch length as shown in Fig. 2.

ChDR Radiator

A cylindrical hollow radiator was mode of HDPE (high density polyethylene), which is well transparent at a frequency range below 2 THz. Employing a THz-TDS system (Advantest TAS7500TS-000), the refractive index of radiator was measured to be 1.536 ± 0.003 and is almost constant below 4 THz), so that the Cherenkov angle θ_C is 49.4º. In Fig. 3 show the shape of HDPE radiator and its assembly.

Detection System

As shown in Fig. 3, to detect ChDR after passing through a z-cut quartz window, a pyroelectric detector (Sensor und Lasertechnik GmbH, THz10) is used [14]. The detector is operated inside of a nitrogen atmosphere to suppress absorption in the water vapor. Distance from the center of radiation to the detector is ~ 100 mm, and the detector position can be moved to measure angular distributions of ChDR intensity. The Michelson interferometer is able to be equipped at the position of the Cherenkov angle.

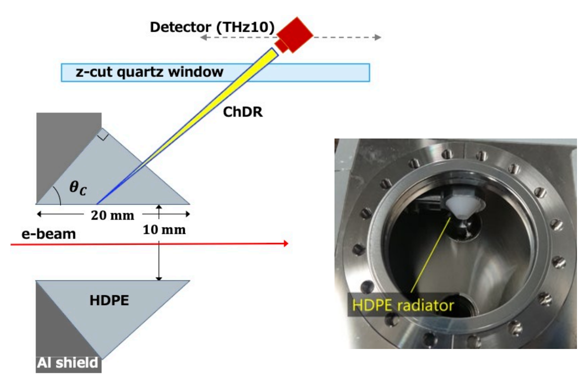

Figure 3: HDPE radiator shape and detection apparatus for ChDR (upper), and a view of assembly on the beam line in the vacuum chamber (lower).

RESULTS OF TEST EXPERIMENT

The beam profile can be observed by putting the Al mirror into just upstream of the radiator, so that the impact parameter is controllable and the beam size as well. In the test experiments, the beam size in both planes was focused to be 100 μm. The measurements were done along the beam longitudinal axis as shown in Fig. 3, therefore the azimuthal angle is 0 degree (see Fig. 1).

Impact parameter dependence of the ChDR angular distribution was measured by varying the vertical position of

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the beam as shown in Fig. 4. The beam passes through the center of aperture when an impact parameter is $h = 5$ mm. At larger impact parameters than 3 mm, coherent ChDR was not observed. As the beam gets close to the inner surface of radiator, ChDR rapidly grows and the peak appears around the Cherenkov angle. An FWHM of ChDR angular spread is ~ 5° (87 mrad). It should be noted that the angular distributions observed in a near-field.

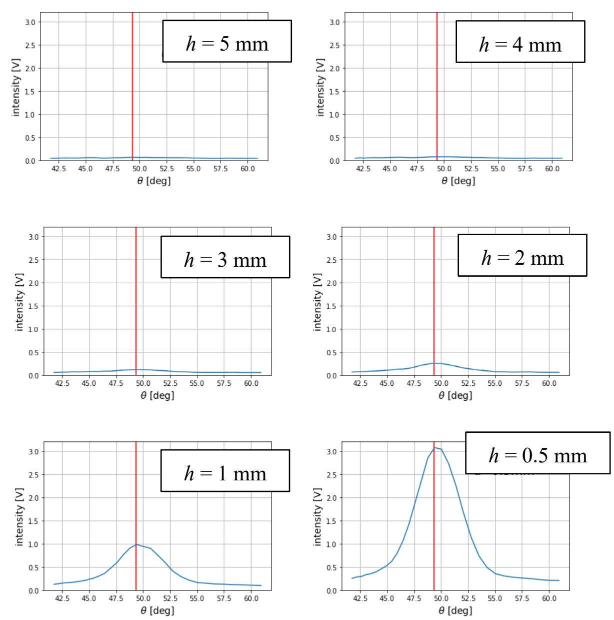

Figure 4: Angular distribution for various impact parameters from 5mm to 0.5 mm. Refraction due to the quartz window and solid angle variation are corrected. Red lines denote the Cherenkov angle.

Looking at Eq. (3), the CR peak position would depend on the radiation frequency, so that spectrometry at the Cherenkov angle was carried out. Figure 5 shows measured frequency spectra at the impact parameters of 0.5 mm, 0.75 mm and 1.0 mm, respectively.

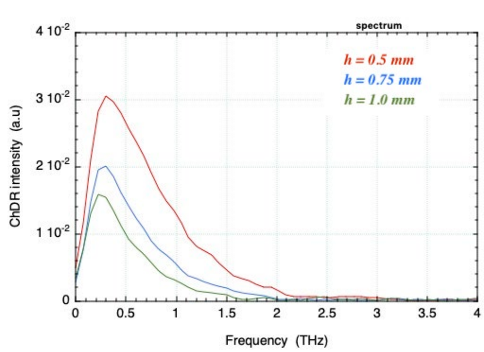

Figure 5: Frequency spectra of coherent ChDR measured at the Cherenkov angle.

DISCUSSION AND PROSPECT

As shown in Fig. 2, the spectrum of coherent TR reaches ~ 4 THz, while the highest frequency of coherent ChDR spectra is ~ 2 THz. The bunch form factor is considered to be identical, and according to Eq. (3) the intensity of CR is proportional to ω^2, hence the difference may be caused by the coupling factor $K(\xi)$. For this experimental condition, ξ is around 1 which means K is neither 1 nor Eq. (1). In addition, it is still unclear whether Eq. (3) is valid for ChDR.

To understand characteristics of ChDR and to investigate possibility for a beam diagnostic probe, further study is highly required. The experimental chamber is planned to be modified so as to measure dependences of the azimuthal angle. Furthermore, a curious FDTD code for large simulation space has been developed, which will be published elsewhere.

ACKNOWLEDGEMENTS

Part of this work was carried out for Mr. D. Yamamoto's master thesis [15]. We appreciate much Beam Physics group at Research Center of Electron Photon Science, Tohoku University for their cooperation in these experiments.

REFERENCES

[1] J. Zheng *et al.*, "Cherenkov radiation generated by a beam of electrons revisited", *Phys. Plasmas*, vol. 12, p. 093105, Sep. 2005.

[2] A. P. Potylitsyn *et al.*, "Investigation of coherent Cherenkov radiation generated by 6.1 MeV electron beam passing near the dielectric target", *J. of Physics: Conf. Series*, vol. 236, p. 012025, 2010. doi:10.1088/1742-6596/236/1/012025

[3] R. Kieffer *et al.*, "Direct observation of incoherent Cherenkov Diffraction radiation in the visible range", *Phys Rev. Lett.*, vol. 121, p. 054802, Aug. 2018. doi:10.1103/PhysRevLett.121.054802

[4] S. Ninomiya *et al.*, "Measurement of Cherenkov Diffraction Radiation from a Short Electron Bunches at t-ACTS", *in Proc. IPAC'19*, Melbourne, Australia, May 2019, pp. 2536-2538. doi:10.18429/JACoW-IPAC2019-WEPGW031

[5] A. H. Lumpkin *et al.*, "Near-infrared imaging of optical diffraction radiation generated by a 7-GeV electron beam", *Phys. Rev. ST Accel. Beams*, vol 10, p.022802-022809, Feb. 2007. doi:10.1103/PhysRevSTAB.10.022802

[6] R. Kieffer *et al.*, "Optical diffraction radiation for positron monitoring of charged particle beams", *Nucl. Instr. and Meth. B*, vol. 402, pp. 88-91, Jul. 2017. doi:10.1016/j.nimb.2017.03.089Get

[7] D. V. Karlovets and A. P. Ptylitsyn, "On the theory of diffraction radiation", *J. of Exp. and Theor. Phys.*, vol. 107, num. 5, pp. 755-768, Dec. 2008. doi:10.1134/S1063776108110058

[8] R. Ulrich, "Zur Cerenkov-Strahlung von elektronen dicht über einem dielektrikum", *Z. Phys.*, vol. 194, p. 180, 1966.

[9] J. D. Jackson, *Classical Electrodynamics, 2nd ed.*, Wiley, New York (1975).

[10] I. E. Tamm, "Radiation emitted by uniformly moving particles", J. Physic, Moscow 1, 1939.

ISBN: 978-3-95450-227-1 ISSN: 2673-5490 doi:10.18429/JACoW-IPAC2022-MOPOPT033

[11] S. Kashiwagi et al., "Proof-of-principle experiment of velocity bunching for ultra-short electron pulse production", Energy Procedia, vol. 89, pp. 346-352, Jun. 2016. doi:10.1016/j.egypro.2016.05.045

[12] F. Hinode et al., "Development of a thermionic RF gun for coherent THz source at Tohoku University", in Proc. IPAC'10, Kyoto, Japan, May 2010, paper TUPEC010, pp. 1731-1733.

[13] L. Serafini and M. Ferrario, "Velocity bunching in photo-injectors", *AIP Conf. Proc.*, vol. 581, p. 87, Sep. 2001. doi:10.1063/1.1401564

[14] THz series standard, https://www.pyrosensor.de/Standard-924644.html

[15] D. Yamamoto, "Basic study of beam diagnostics employing coherent Cherenkov diffraction radiation", master thesis, Tohoku University, Japan, 2022.