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EXPERIMENTAL OBSERVATION OF SUBMILLIMETER COHERENT CHERENKOV RADIATION AT CLARA FACILITY

K. Fedorov*[1], P. Karataev, A. Oleinik[3]
John Adams Institute at Royal Holloway, University of London, Egham, United Kingdom
T. Pacey[2], Y. Saveliev[2]
ASTeC, STFC Daresbury Laboratory, Warrington, United Kingdom
A. Potylitsyn
Tomsk Polytechnic University, Tomsk, Russia
[1]also at Tomsk Polytechnic University, Tomsk, Russia
[2]also at Cockroft Institute, Warrington, United Kingdom
[3]also at Laboratory of Radiation Physics, Belgorod National Research University, Belgorod, Russia

Abstract

In current work we present the experimental results on Coherent Cherenkov Difraction Radiation generation, observation and it further spectral analysis. All experimental work was performed at CLARA (Beam Area 1) facility (35 MeV beam energy at up to 10 Hz pulse repetition rate and sub-ps bunch length). For spectral analysis we used Martin-Pupplet interferometer as it provides higher signal to noise ratio and allows us to perform charge normalisation. Furthermore we demonstrate the procedure of longitudinal beam profile reconstruction for a bunch with 0.6 ps Full Width at Half Maximum duration.

INTRODUCTION

Production and maintenance of short bunches in modern particle accelerators are forefront issues. Examples of accelerators that require short bunches are high quality particle physics facilities and linac-based fourth generation light sources. In practice, in order to verify the design and optimize the operation of such accelerators, it is necessary to obtain information on the bunch duration at various points along the accelerator beam line. Nowadays, the state of the art in non-invasive bunch length diagnostics is based on electro-optic technique. However, it is a cumbersome and an expensive device requiring a team of people to operate. The method of longitudinal beam profile diagnostic based on coherent radiation techniques is considered as one of the most perspective [1], because it could be embodied in a form of simple in use, robust and relatively inexpensive devices. Also, it has been theoretically demonstrated that coherent radiation techniques does not have any fundamental limitations for a bunch length diagnostics.

Nowadays, most studied coherent radiation technique is diagnostic with Transition Radiation (TR) [2], but its invasive nature excludes its use in modern and future facilities where the beam losses are limited. During past years reports about short bunches diagnostic based on Coherent Diffraction Radiation [3] mechanism have been also published. However, this methods suffers from coherent radiation background (wakefields, synchrotron radiation, etc.) co-propagating alone the beam and reflecting from the target. In this paper we report on another perspective method based on Coherent Cherenkov Diffraction Radiation (CChDR), which is induced by a charged particle traveling in the vicinity of a dielectric medium with the speed of particle higher than the speed of light inside this medium. First of all, this method promises relatively high intensity of coherent radiation, since according to the paper published by Tamm and Frank [4], the light intensity scales proportionally to the length of the radiator, which could be used to produce large photon flux by increasing the radiator size. Secondly, as it was shown later in 1955 by Linhart [5], Cherenkov Diffraction radiation could be induced by the interaction of electromagnetic field of the moving charged particle and atomic electrons on the surface of the dielectric, which is opens the way for noninvasive diagnostic. Thirdly, CChDR is emitted at an angle θ, defined as $\theta = \cos\theta = 1/\beta n$, where n is the refractive index of radiator, and so could be separated from background radiation. In this work we report on successful implementation of diagnostics of 600 fs electron bunch via CChDR effect at CLARA machine at Daresbury laboratory. We will present the solution divided into three parts as follows:

- Theoretical calculation of ChDR single electron spectrum for the real experimental parameters;
- Experimental measurement of coherent ChDR spectrum at CLARA facility using Martin-Puplett interferometer as a most effective instrument for THz spectroscopy;
- Reconstruction of longitudinal beam profile using Fourier Transform and Kramers-Kronig phase analysis.

THEORETICAL BACKGROUND

Coherent radiation appears when the radiation wavelength is comparable to or longer than the charged particle bunch length. In this case the radiation photon yield is proportional to the number of electrons squared in contrast to the incoherent part of the spectrum, which is linear as a function

* fedorovkval@gmail.com

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of the beam charge. By measuring the radiation spectrum in the wavelength range where the incoherent radiation is transformed into the coherent one, we can deduce information about longitudinal bunch form factor and, subsequently, reconstruct the longitudinal beam profile. We know, that coherent spectral energy density produced by a bunch of N electrons is the product of the spectral energy density from by a single electron, the number of electron squared and modulus of the form factor [6]:

$$\left[\frac{d^2W}{d\omega d\Omega}\right]_{\text{coh}} = N^2 \left[\frac{d^2W}{d\omega d\Omega}\right]_{\text{single}} |F(\omega)| \qquad (1)$$

where:

- $\left[\frac{d^2W}{d\omega d\Omega}\right]_{\text{coh}}$ is the experimentally measured spectrum;
- $\left[\frac{d^2W}{d\omega d\Omega}\right]_{\text{single}}$ is the theoretically calculated single electron spectrum;
- $F(\omega) = \left|\int_{-\infty}^{\infty} \rho(z) \exp\left(i\omega c^{-1} z\right) dz\right|^2$ is the longitudinal bunch form-factor.

Thus, we can say that longitudinal charge distribution is:

$$\rho(z) = \frac{1}{\pi c}\int_0^{\infty} \sqrt{\frac{\left[\frac{d^2W}{d\omega d\Omega}\right]_{\text{coh}}}{N^2\left[\frac{d^2W}{d\omega d\Omega}\right]_{\text{single}}}} \times \times \cos\left(\psi(w) - z\frac{w}{c}\right) d\omega \qquad (2)$$

where $\psi(w)$ is the minimal phase which can be deriving using the Kramers-Kronig [7] approach that takes into account the phase characteristics of the measured spectrum. Thus, the reconstruction of longitudinal charge distribution consist of 3 steps: calculation of single electron spectrum for particular experimental parameters, experimental observation of coherent spectrum, and further longitudinal distribution reconstruction.

Cherenkov Diffraction Radiation as a particular case of polarization radiation (PR) could be described by polarization current approach (PCA) [8–10]. According to PCA, the PR field, emitted by the medium's atoms polarized by the external field E^0 of a passing particle with the energy $\gamma = E/mc^2 = 1/\sqrt{(1-\beta^2)}$, moving rectilinearly and with constant velocity $v = \beta c$ in a substance (or in its vicinity), can be presented as a solution of the "vacuum" set of macroscopic Maxwell's equations. More detailed information about PCA can be found in the paper [10]. In this paper we present calculation results for the prismatic teflon radiator, which was used for the experiment at CLARA and considered as the most efficient geometry for CChDR generation (Fig. 1).

The model in [10] takes into account the following parameters: Lorentz-factor γ, target length a, distance between target and detector A, detector aperture V, distance between beam and target (impact parameter) h, radiator refractive index n, angle between radiator surface and beam direction α. Experimental and simulation parameters are listed below in Table 1. The angular distributions for different radiation frequencies are shown in Fig. 2. The angular distributions (Fig. 2) were integrated over azimuthal angle and impact parameter.

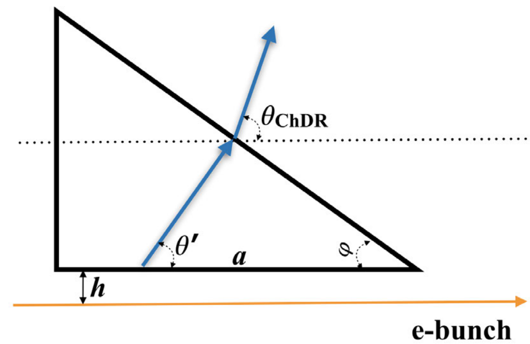

Figure 1: The schematic view of the radiation geometry for a charged particle moving parallel to the surface of the triangular dielectric radiator. Here, θ' is the angle of Cherenkov Radiation appearing inside of dielectric medium, θ_{ChDR} is the angle of Cherenkov Diffraction Radiation. h is the distance between target and dielectric surface, a is the radiator length, φ is the vertex angle of the prism.

Table 1: Simulation and Experimental Parameters

Parameters	**Value**
Lorentz - factor γ	70
Target length a	5 cm
Vertex angle of the prism φ	45°
Angle between radiator surface and beam direction α	0°
Radiation frequency f	[0-1.5] THz
Index of refraction $n(f)$	1.4 (Teflon)
Impact parameter h	[1.5-2.5] mm
Azimuthal angle ϕ	[10-30]°
Polar angle θ	[40-60]°

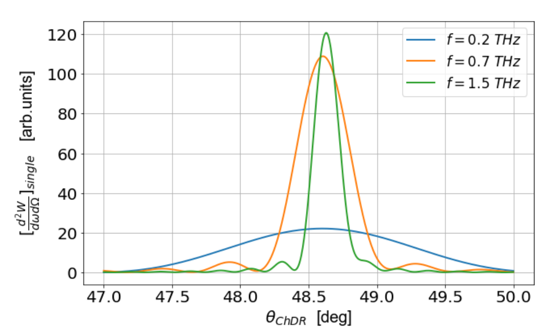

Figure 2: Spectral-angular distribution of CChDR calculated for the experiment conducted at CLARA facility.

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Table 2: CLARA Machine Parameters

Parameters	**Value**
Electron energy E	35 MeV
Longitudinal beam compression ρ	[2-0.3] ps
Bunch repetition rate PRR	10 Hz
Charge C	[70-100] pC
Transverse beam size σ	200 µm

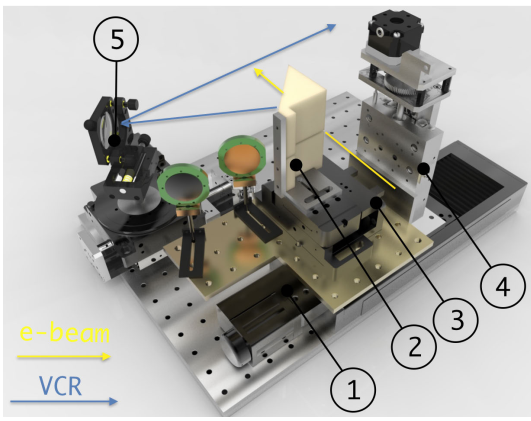

Figure 3: Setup inside vacuum chamber: 1 - horizontal positioning stage, 2 - teflon (ChDR) target, 3 - tip-tilt stage, 4 - vertical positioning stage, 5 - concave mirror.

EXPERIMENTAL SETUP

Experimental work for this studies was conducted at CLARA/VELA facility in Daresbury Labaratory, STFC [11]. All experimental setup was located in Beam Area 1 (BA1), which is equipped with all necessary manipulation, diagnostic and data acquisition systems. Machine parameters are shown in Table 2.

The main idea of the first experiment was to observe CChDR and reconstruct the longtudinal profile. For this purpose CChDR radiator was installed on a movable platform inside the vacuum chamber, as it shown in Fig. 3. For CChDR scanning, movable platform was set to the position where the beam passed along the target base at 1 mm impact parameter to ensure noninvasive production. Radiation generated by the target was reflected by a concave mirror, which also served as a collimator (this mirror was installed at 101.6 mm from The ChDR target which is its focal length). Then radiation was extracted through a quartz window. Further, CChDR was delivered into a Martin – Puplett interferometer using a system of motorized mirrors.

For coherent radiation spectrometry we used Martin-Puplett interferometer (MPI) as one of the most efficient instruments in the millimeter and sub-millimeter wavelength range (MPI is schematically illustrated in Fig. 4). Compared to a Michelson, the Martin-Puplett interferometer deals with polarization characteristics of radiation and has an advantage of higher signal-to-noise ratio and two radiation output ports. The ratio of the difference and the sum of the two

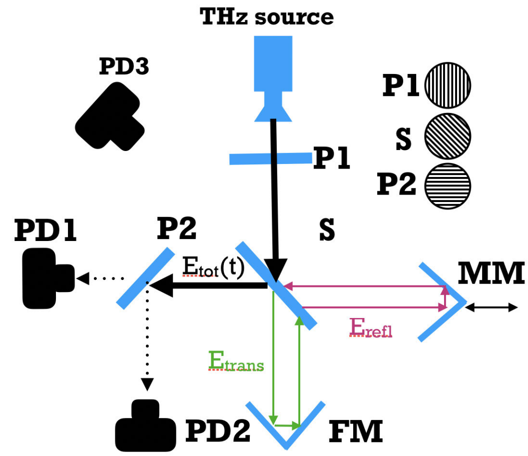

Figure 4: Schematic view on Martin-Pupplet interferometer. The interferometer consists of three wire grids (P, S, P2), two roof mirrors (FM and MM) and two pyroelectric detectors (PD1 and PD2, Gentec-51). Additional pyroelectric detector (PD3) were used to collect all noise from the environment (vibrations, acoustic noise, light fluctuation, etc.).

detector signals returns a normalized interference pattern $\delta(x)$ (see, for instance, Fig. 5 bottom) which is less sensitive to beam intensity fluctuations than the individual detector signals [12]:

$$\delta(x) = \frac{I_{\text{PD1}} - I_{\text{PD2}}}{I_{\text{PD1}} + I_{\text{PD2}}} \quad (3)$$

Figure 5 (top) shows the signals from pyroelectric detectors measured simulteneously. The anti-correlated response of the two detectors is caused by observing either the transmitted or the reflected polalrization component behind the analyzing grid. The sum of both signals is proportional to the total radiation power. A scaling correction was applied because of different sensitivity of two detectors. Multi-shot averaging (50 successive shots per movable mirror step) was used to reduce the statistical uncertainty. Normalized interferogram is shown in Fig. 5 (bottom).

RECONSTRUCTION RESULTS AND DISCUSSION

The CChDR spectra in Fig. 6 (green line) were calculated using Fourier transform of $\delta(x)$ interferogram with using triangular appodization window as the only post-processing technique. Theoretical single-electron spectrum was calculated using parameters from Table 1. Both curves show that intensity decreases at lower frequencies, when the radiated wavelengths comparable with radiator dimensions. At higher frequencies some parts of the spectrum were effected by the humid air absorption lines, which were taken into account during further analysis.

The extracted longitudinal bunch form-factor is presented in Fig. 7, which was derived using Eq. (1). The extrapolation procedure enables us to eliminate low frequency supression and also reduce the influence of low signal to noise

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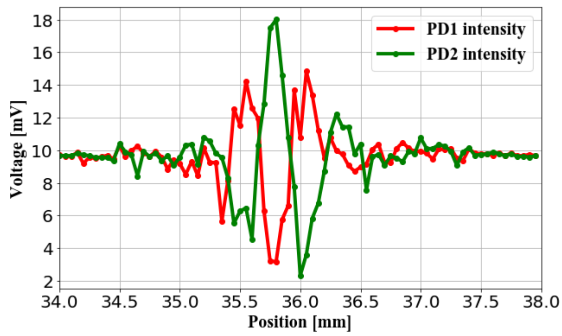
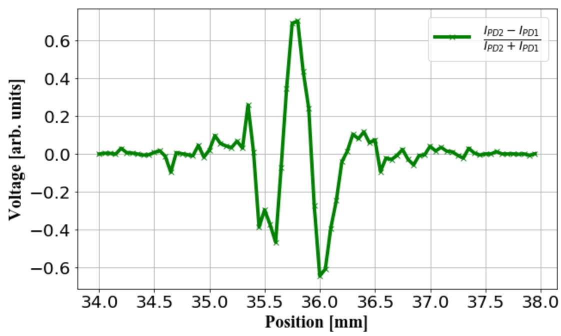


(a)



(b)

Figure 5: Top - interferograms measured with two detectors; bottom - normalized interferogram.

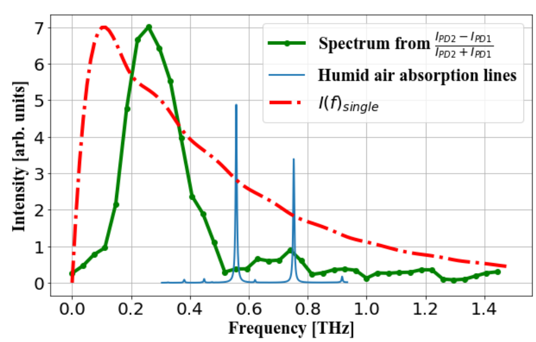


Figure 6: Experimentally obtained Coherent Cherenkov Diffraction Radiation spectrum (green line), single electron Cherenkov Diffraction Radiation spectrum (red line) and humid air absorption lines (blue line).

ratio at higher frequencies. Both high and low frequency extrapolation was performed according to [13].

Any intensity-based interferometry method is subject to the limitation that only the absolute value of the form factor can be measured, and not its complex phase. According to [7] the form-factor amplitude and the phase factor are related by the Kramers-Kronig relation in a way that if the function $F(\omega)$ is measured at all frequencies than the phase factor $\psi(\omega)$ can be obtained as follows:

$$\psi(\omega) = -\frac{2\omega}{\pi}\int_0^\infty \frac{\ln\left(\sqrt{F(x)}/\sqrt{F(w)}\right)}{x^2-\omega^2}dx \qquad (4)$$

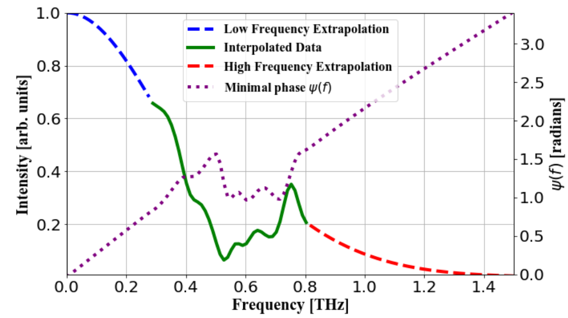


Figure 7: Extrapolated form-factor and Minimal Phase.

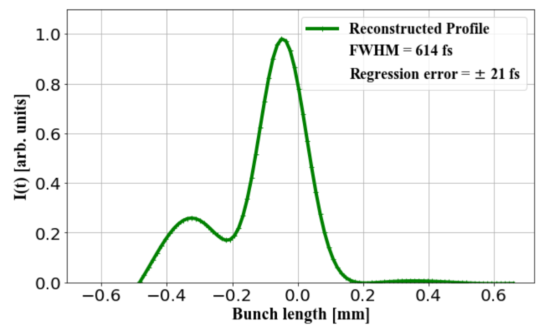


Figure 8: Result of longitudinal profile reconstruction.

where x is integration variable in units of frequency. Minimal phase versus frequency plot is also shown in Fig. 7. Figure 8 shows final result of reconstruction. FWHM (Full Width at Half Maximum) bunch duration is 0.61±0.02 ps consistent with theoretical expectation for this machine. The tail comes from energy tail generated in the machine. This tail can not be measured precisely as it is a result of bunch-by-bunch instabilities. Nevertheless, we assume that the tail exist. To be able to measure it and understand its dynamics we need a single shot spectrometer system.

CONCLUSION

We have demonstrated a complete cycle for longitudinal non-invasive bunch profile diagnostic using coherent Cherenkov diffraction radiation at CLARA facility. With precise alignment, Cherenkov radiation from teflon prism (base size of 5 cm, width = 4 cm) was easily detectable. In combination with Martin-Puplett interferometer it gives us a quasi-continuous spectrum. Obtained results are in good agreement with estimated ones for CLARA machine. Complete cycle of bunch length measurement (including measurement of interferogram, FFT, single spectrum normalization, and Kramers-Kronig bunch profile reconstruction) could take up to 15 minutes with current experimental procedure and can be reduced down to one minute by applying detectors with higher signal to noise ratio, for example, quazi-optical Schottky detectors, and automatizing analysis.

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REFERENCES

[1] O. Grimm and P. Schmüser, "Principles of Longitudinal Beam Diagnostics with Coherent Radiation", DESY, Hamburg, Germany, Rep. TESLA-FEL 2006-03, 2006.

[2] Bernhard Schmidt *et al*, "Longitudinal Bunch Diagnostics using Coherent Transition Radiation Spectroscopy", DESY, Hamburg, Germany, Rep. DESY 18-027, 2018. doi:10.3204/PUBDB-2018-01372

[3] M. Veronese, R. Appio, P. Craievich, and G. Penco, "Absolute Bunch Length Measurement Using Coherent Diffraction Radiation," Physical Review Letters, vol. 110, p. 074802, 2013.doi:10.1103/physrevlett.110.074802

[4] I. E. Tamm and I. M. Frank, "Coherent radiation of a fast electron in a medium", *Sov. Phys. Dokl. AN SSSR*, vol. 14, p. 107, 1937.

[5] J. G. Linhart, "Čerenkov Radiation of Electrons Moving Parallel to a Dielectric Boundary", *Journal of Applied Physics*, vol. 26, pp. 527–533, 1955. doi:10.1063/1.1722033

[6] J. S. Nodvick and D. S. Saxon, "Suppression of Coherent Radiation by Electrons in a Synchrotron" *Physical Review*, vol. 96, pp. 180–184, 1954. doi:10.1103/physrev.96.180

[7] R. Lai and A. J. Sievers, "Determination of a charged-particle-bunch shape from the coherent far infrared spectrum", *Physical Review E*, vol. 50, pp. R3342–R3344, 1994. doi:10.1103/physreve.50.r3342

[8] D. V. Karlovets and A. P. Potylitsyn, "Diffraction radiation from a finite-conductivity screen", *JETP Letters*, vol. 90, pp. 326–331, 2009. doi:10.1134/s0021364009170032

[9] M. Shevelev and A. Konkov, "Peculiarities of the Generation of Vavilov–Cherenkov Radiation Induced by a Charged Particle Moving Past a Dielectric Target", *Journal of Experimental and Theoretical Physics*, vol. 118, pp. 501– 511, 2014.

[10] M. Shevelev, A. Konkov, and A. Aryshev, "Soft-x-ray Cherenkov radiation generated by a charged particle moving near a finite-size screen", *Physical Review A*, vol. 92, 2015. doi:10.1103/physreva.92.053851

[11] P. A. Mcintosh *et al.*, "he VELA and CLARA Test Facilities at Daresbury Laboratory", in *Proc. LINAC'16*, East Lansing, MI, USA, 2016, pp. 734–739.

[12] D. H. Martin and E. Puplett, "Polarised interferometric spectrometry for the millimetre and submillimetre spectrum", *Infrared Physics*, vol. 10, pp. 105–109, 1970. doi:10.1016/0020-0891(70)90006-0

[13] M. Micheler, R. Ainsworth, G. A. Blair, G. Boorman, R. Corsini, P. Karataev, T. Lefevre, and K. Lekomtsev, "Longitudinal beam profile monitor at CTF3 based on Coherent Diffraction Radiation", *Journal of Physics: Conference Series*, vol. 236, p. 012021, 2010. doi:10.1088/1742-6596/236/1/012021