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CHARACTERISATION OF CHERENKOV DIFFRACTION RADIATION USING ELECTRO-OPTICAL METHODS

A. Schlögelhofer[1,*], T. Lefèvre, S. Mazzoni, E. Senes, CERN, Geneva, Switzerland
L. Duvillaret, KAPTEOS, Saint-Helene-du-Lac, France
[1] also at TU Wien, Vienna, Austria

Abstract

The properties of Cherenkov diffraction radiation (ChDR) have been studied extensively during the recent years to be exploited for non-invasive beam diagnostic devices for short bunches. The dependence of charge and the influence of the bunch form factor on the coherent part of the radiated spectrum have been demonstrated and studied in the past. However, the actual field strength of coherent ChDR as well as its study in time domain need further investigation. In this contribution we are using electro-optical techniques to investigate and quantify these parameters. The electro-optical read-out brings the advantage of high bandwidth acquisition and insensitivity to electromagnetic interference, whereas at the same time a large fraction of the acquisition setup can be installed and operated outside of the radiation controlled areas. We will present experimental results from the CLEAR facility at CERN as well as simulations of the peak field of the temporal profile of beam-generated ChDR pulses.

INTRODUCTION

Cherenkov diffraction radiation (ChDR) describes the radiation produced at the surface of a dielectric by the electric field of a relativistic charged particle passing by in the vicinity of the dielectric. This mechanism is illustrated in Fig. 1, where the ChDR is emitted at the well-defined Cherenkov angle $cos(\theta_{Ch}) = 1/(n_1 \beta)$ with n_1 denoting the refractive index of the dielectric medium and $\beta = v/c$ the normalized velocity of the charged particle. The produced ChDR can be analysed to measure critical properties of a beam of charged particles, e.g. its length or position [1]. While previous work focused on studying the qualitative behaviour of ChDR and measuring the frequency spectrum to reconstruct beam properties [2–4], this contribution shows the measurement of the electric field strength generated by coherent ChDR in terms of absolute numbers by sampling its temporal profile.

METHODOLOGY

An electro-optical probe (eo-probe) [5] was used to obtain a real-time high bandwidth measurement insensitive to electromagnetic interference.

Working Principle of the Eo-Probe

The eo-probe is fully dielectric and, amongst other optical elements, contains a sensing crystal made out of BSO ($Bi_{12}SiO_{20}$). It utilizes the Pockels effect, which describes

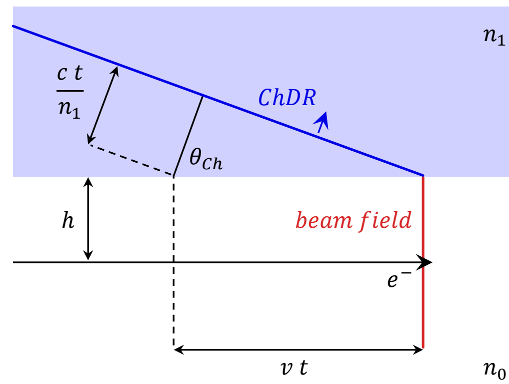

Figure 1: Schematic of the ChDR principle in a dielectric medium ($n_1 \approx 3$). The Cherenkov condition $n_1 \cdot v/c > 1$ must be satisfied to produce ChDR.

the linear change of the refractive index of a medium exposed to an external electric field. This induced refractive index change introduces a birefringence in the BSO crystal. A continuous-wave sensing laser of known polarization is sent through the crystal. During exposure to an external electric field, the BSO crystal alters the polarization state of the sensing laser. The modulated laser light passes through polarizers, and its changed polarization state is then analyzed with fast photodiodes. Using this principle, the eo-probe measures the electric field vector up to field strengths of MV/m.

The eo-probe (with a bandwidth ≤ 10 GHz) was placed in the accelerator hall. All the other parts of the detection system were placed outside the radiation-controlled area. The sensing laser was transported to the probe via 20-metre-long optical fibres. The signal was measured with a high-bandwidth oscilloscope (10 GHz, 256 GSa/s, 10-bit) and then corrected for the change of insertion loss during the measurement as well as converted according to the antenna factor of the probe to obtain an absolute electric field measurement. As the electric field strength scales linearly with the bunch charge, the bunch charge was also independently recorded. All the data presented in this contribution are normalized to a bunch charge of 300 pC.

CALIBRATION

To calibrate the system's response, a first measurement campaign was performed on the direct beam field of an electron bunch propagating in air.

The bandwidth of the data acquisition system is limited to 10 GHz. Therefore, as electron bunches at the CLEAR

* andreas.schloegelhofer@cern.ch

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facility [6] typically are only a few ps long, the bandwidth is insufficient to measure the entire power spectrum of the electron bunches. The direct beam field of an electron bunch was measured to calibrate the data acquisition system for short bunches. The calibration setup is illustrated in Fig. 2. This measurement was compared to the analytical formula describing the peak electric field strength obtained from the direct beam field of a particle bunch [7]:

$$E_{analytic} = \frac{e}{2\sqrt{2}\pi^{3/2}c\epsilon_0}\frac{N}{\sigma}\frac{1}{r} \qquad (1)$$

where e denotes the elementary charge, c is the speed of light in vacuum, and ϵ_0 is the vacuum permittivity (it is assumed $\epsilon_0 = \epsilon_{air}$ in this frequency range). The transverse distance from the beam is denoted r (cf. Fig. 2). The number of particles in the bunch N and the bunch length σ must be adapted to the experimental conditions. For a charge of 300 pC and a bunch length of 5 ps (1 σ), Eq. (1) yields $E_{analytic}$ = 1435.2 / r [V/m] for the peak electric field.

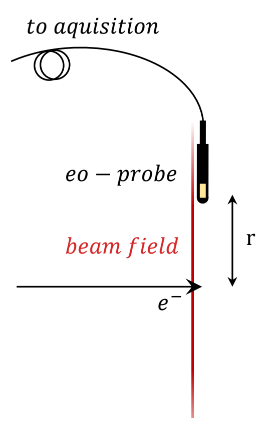

Figure 2: Schematic of the measurement of the direct beam field using an eo-probe. For the calibration measurement, the distance r between the beam and eo-probe was varied over a distance of ≈ 100 mm.

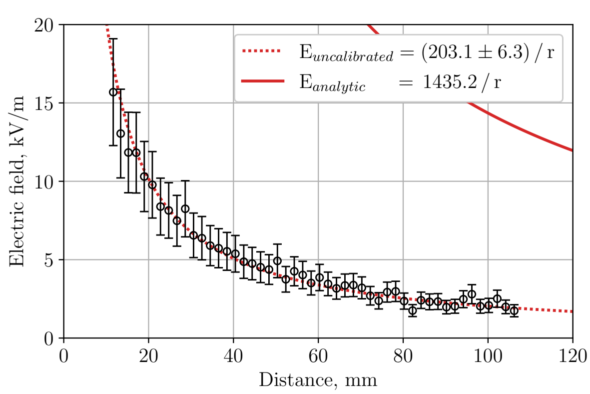

Figure 3: Uncalibrated peak electric field strength of the beam field as a function of the distance (dashed line) to be compared to the analytical expectation (solid line).

Figure 3 shows the measured peak electric field strength as a function of the distance from the beam. The measured value of 203.1 ± 6.3 V is smaller by a factor 7.1 ± 0.2 than the analytical value of 1435.2 V. This discrepancy is expected due to the bandwidth limitation of the acquisition system itself as well as the timing jitter between the trigger signal and the electron beam. Both these effects lead to a lower signal amplitude being measured and the resulting discrepancy is discussed in detail below.

Bandwidth Limitation

The bandwidth of the acquisition system was limited to an upper frequency of 10 GHz for all the presented measurements. As the electron bunches are only a few ps long, a significant part of the high-frequency spectrum is not measured accordingly. This behaviour is shown in Fig. 4 and accounts for a factor ≈ 4.0 for a bunch length of 5 ps (1 σ) and an upper-frequency limitation of 10 GHz.

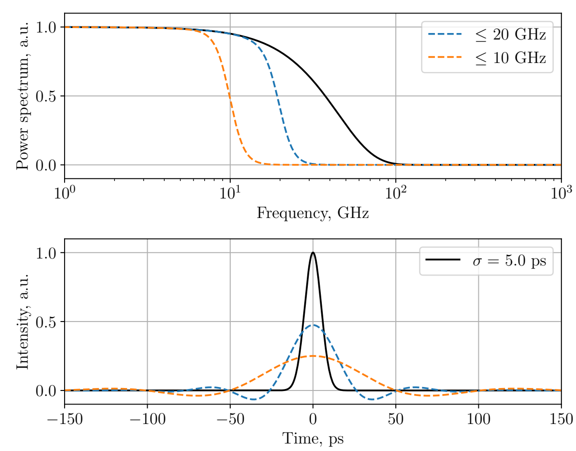

Figure 4: Power spectrum and time profile of bandwidth limited acquisition (dashed lines) compared to full bandwidth (solid line).

Timing Jitter

Single shot traces were analyzed to get a rough estimate of the reduction of the peak signal due to the timing jitter present. For the data point closest to the beam (r = 11.7 mm), 600 single-shot traces were acquired. The average of the maximum of each single trace divided by the maximum of the averaged traces yields a factor 2.1, which is also illustrated in Fig. 5.

Together with the bandwidth limitation, this rough estimation yields a total scaling factor of 8.4, which needs to be compared to the obtained factor of 7.1 from the calibration measurement. Using this simple approach, we would overestimate the results by ≈ 18%. However, it shows that the obtained factor of 7.1 from the calibration is justified.

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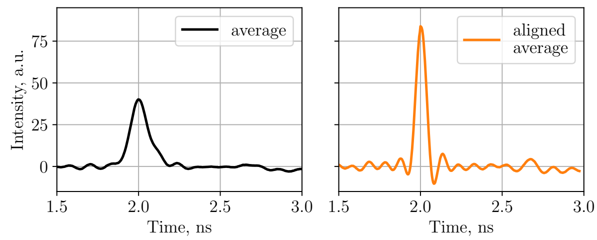

Figure 5: Traces from the closest data point r = 11.7 mm. Left: Average of all traces. Right: Average of traces aligned in time to the maximum of each trace.

MEASUREMENT OF THE COHERENT CHDR FIELD

Using the same eo-probe and acquisition setup as for the calibration measurement, the electric field strength of ChDR emitted from a dielectric radiator was measured. A schematic of the installation is shown in Fig. 6. The experiment was installed in air, therefore $n_0 \approx 1$. The radiator was made out of Alumina (97.6% Al_2O_3) with a relative permittivity of $\epsilon_r \approx 9.0$ (1.0 – 8.5 GHz, 25°C) [8]. The radiator had a cylindrical geometry with a diameter of 36 mm and a central axis length of 47.6 mm. It was inserted into a metal body at its Cherenkov angle $\theta_{Ch} = 70.55°$ and machined to be flush with the chamber aperture (∅ 80 mm). The centre of the chamber aperture was aligned at the corresponding beam position using a reference laser. During the measurements, the whole setup was moved transversely with a motorized linear stage to vary the impact parameter h from 10 - 50 mm. The eo-probe was positioned 10 mm away from the radiator surface on the central axis of the radiator.

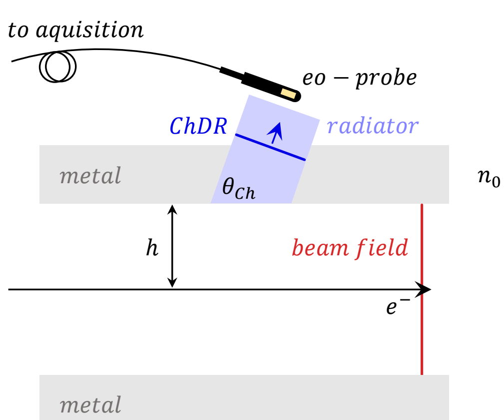

Figure 6: Schematic of the ChDR measurement setup. The impact parameter h was varied during the measurement by moving the setup with respect to the electron beam.

The measurement results are shown in Fig. 7. The peak electric field 10 mm from the exit surface of the radiator is shown as a function of the impact parameter h. The absolute values after calibration are shown in blue. Error bars indicate the standard deviation of each measurement. The experimental data was fitted for a $1/h$ decay. The orange markers stem from a CST simulation [9] considering the experimental setup in a 3D layout. The peak electric field was sampled at 10 mm from the exit surface of the radiator. Table 1 gives an overview of the simulation parameters.

Table 1: CST Simulation Parameters

Solver		Wakefield
Bandwidth		100 GHz
Cells / wavelength		10
Bunch charge		300 pC
Bunch length	σ	5 ps
Lorentz factor	γ	392.4
Impact parameter	h	10-50 mm
Relative permittivity (Al_2O_3)	ϵ_r	9.0

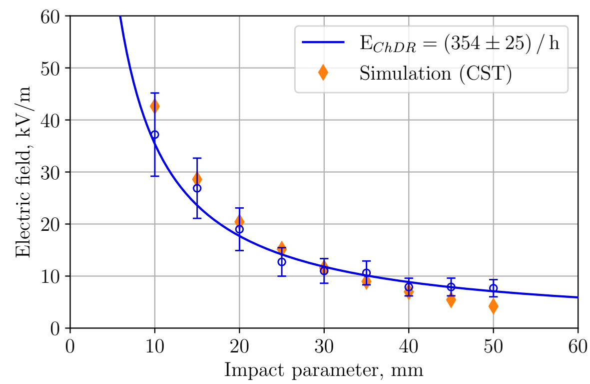

Figure 7: Calibrated peak electric field strength of coherent ChDR as a function of the impact parameter. Absolute values after calibration are shown in blue, error bars indicate the standard deviation of each measurement.

DISCUSSION AND CONCLUSION

The measurement of the absolute electric field strength of ChDR showed that for a short electron bunch (5 ps (1 σ), 300 pC, 200 MeV) the peak electric field is in the order of 10 kV/m for an alumina radiator. It decreases proportionally to the inverse distance between the particle beam and the radiator surface. It also was shown that the numerical simulations performed with CST agree with the experimental findings regarding absolute numbers of the peak electric field. This qualifies numerical simulations to predict coherent ChDR for different beam parameters and radiator geometries. The knowledge of the absolute value of the electric field generated by coherent ChDR enables the targeted development of dielectric diagnostic devices like bunch length monitors and beam position monitors.

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