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EXPERIMENTAL VERIFICATION OF SEVERAL THEORETICAL MODELS FOR ChDR DESCRIPTION

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Abstract

In recent years the potential of using Cherenkov Diffraction Radiation (ChDR) as a tool for non-invasive beam diagnostics has been thoroughly investigated. Although several theoretical models of ChDR have been developed, differences in their assumptions result in inconsistent predictions. The experimental verification is therefore needed in order to fully understand ranges of validity of available models. In this contribution we present a detailed theoretical study of the radiation yield as a function of the beam-radiator distance. Following identification of beam parameters and frequency range for which differences between the model predictions are most prominent, we compare theoretical estimates with the results of a dedicated experiment.

INTRODUCTION

Beam diagnostics based on Cherenkov diffraction radiation (ChDR) [1] were intensively investigated over last few years, and require a good knowledge of the expected characteristics of the emitted radiation. Since the exact solutions of the electromagnetic problems are often not known, and detailed computer simulations require extensive time and resources, the properties of the radiation are often derived from simplified models, that assume specific assumptions on the radiator shape.

The first group of models can be labelled as *Stationary Models*. The name comes from the assumption that the radiator is infinitely long and uniform. As examples of the stationary models one can refer to the results obtained by Ulrich [2] for an infinitely wide and thick flat radiator, and the formulae provided by Olsen [3], which describe the ChDR emitted by a particle travelling through an infinite cylindrical tunnel excavated in an unbounded medium. Although such models will be clearly not suitable in cases when wavelength of the studied radiation is comparable to the radiator size, for most of the real case applications they would provide a good approximation for radiation emitted in the visible, ultraviolet and X-ray range. It is also worth mentioning a series of studies [4–8] that uses predictions of such models for the initial radiation yield, which is then modified based on the specific geometry of the radiator following the optical principles.

Alternatively, one might introduce some limitations on the longitudinal size of the radiator when calculating of the initial radiation yield. This approach distincts another group of models, namely *Non-Stationary Models* with a notable example, known as the Polarisation Current Approach (PCA) [9]. PCA describes ChDR emitted in various geometries of radiators, but, in this paper, we will focus on a result given for a flat, infinitely thick and transversely wide rectangular target [10], which is a geometry comparable to one described in the Ulrich model to allow a direct comparison between Stationnry and non-Stationary models. The latter include additional edge effects, such as diffraction radiation and transition radiation. In the case of short radiators these effects dominate the total radiation yield, but surprisingly PCA predictions differ from the stationary results even for arbitrarily long radiators.

Differences between the models can be illustrated by comparing spectral distributions of the energy radiated by a single electron as predicted by stationary and non-stationary models. Relevant spectra are presented in Fig. 1 assuming an electron beam energy of 200 MeV and a $\epsilon = 2.1$ radiator located 1 cm away from the beam. In the low frequency limit, where radiation wavelength λ is higher than the impact parameter h, all the models are compatible and their predictions follow the same dependence as Cherenkov radiation described by Frank-Tamm (F-T) formula [11]. Then, in the $\lambda < h < \gamma\lambda$ regime, stationary and non-stationary models diverge. While stationary results predict a decay proportional to freq^{-2}, according to PCA radiated energy stays at a constant level. Finally, at higher frequencies the intensity of radiation falls exponentially according to both models.

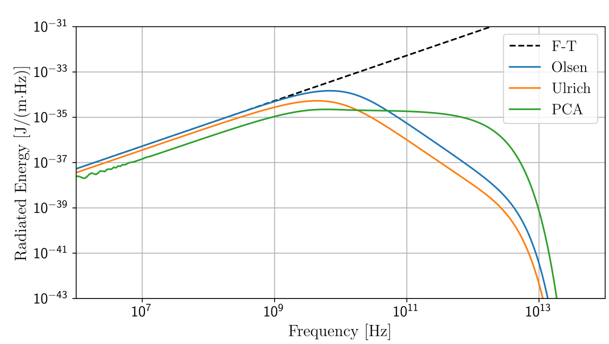

Figure 1: Spectral distribution of ChDR as predicted by different models.

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Answering the question, which of the two models better describes reality, is of prime importance in the context of the beam diagnostics. Recent investigations determined the observation of incoherent high-frequency ChDR as a promising candidate for a diagnostic tool in the next generation of high-energy particle colliders, such as the Future Circular electron-positron Collider (FCC-ee) [12]. In this case, Ulrich and PCA predictions of the ChDR yield in the visible range differ by over six orders of magnitude.

VERIFICATION PRINCIPLES

Recently an experiment was carried out at the CERN's CLEAR facility [13]. It relied on the observation that the intensity of ChDR of a given wavelength λ scales differently with the change of the impact parameter according to each model. For impact parameters in the range $\lambda < h < \gamma\lambda$ Ulrich model predicts a h^{-3} dependence, while according to PCA the intensity is proportional to h^{-1}. Performing an impact parameter scan over a broad range within the $\lambda < h < \gamma\lambda$ limit, makes it possible to compare the shape of the experimentally obtained dependence to the theoretical predictions.

The radiation detection system from a previous study on ChDR beam position monitoring [14] was used. In this setup, the radiation is detected by means of a zero-bias RF diode detector, sensitive to radiation in the Ka-Band (26.5-40 GHz, i.e. wavelengths between 7 and 11.32 mm).

In the case of the CLEAR facility, the range of impact parameters that can be scanned for such radiation wavelength spans between approximately 1 - 100 mm. The lower limit is directly linked to the transverse size of the beam, as at small impact parameters the tails of the bunch may penetrate the radiator emitting large amounts of the standard Cherenkov radiation. The upper bound was determined experimentally, as for larger distances the measured Ka-band ChDR intensity decreases below background level. For Ka-wavelengths and a nominal CLEAR energy corresponding to $\gamma \approx 392$, the intersection of the 1 - 100 mm range with $\lambda < h < \gamma\lambda$ spans between approximately 1 and 10 cm.

Verification based on relative rather than absolute measurements is advantageous for several reasons. The calibration of RF diodes to short radiation pulses is not yet well studied such that it is difficult to measure the emitted radiation power accurately. In addition, at frequencies of interest, the radiation at CLEAR is not fully coherent, so that the absolute level of the radiation intensity strongly depends on the bunch profile. Finally, relative measurements allow one to disregard all the attenuation effects and losses, as long as one can ensure that these are not position dependent.

EXPERIMENTAL SETUP

The radiator used in the experiment was a PTFE rod with a 10 cm diameter and 10 cm length, cut at 45 degrees. The size of the radiator was chosen considering that compared models assumed an infinite transverse radiator size. As in a real case this assumption cannot be fulfilled, one needs to ensure that only a negligible part of the total ChDR yield was supposed to transfer through the non-existing part of the radiator. The energy flow map can be created using the IW2D framework [15]. It was verified that, according to IW2D, for impact parameters below 5 cm, a dominant part of the radiated energy is confined within the central 10 cm of the radiator and the rod can approximate infinitely high radiator.

An aluminium shielding leaves only one face of the radiator exposed to the beam (see Fig. 2). The purpose of this shielding is to repel the background radiation from the radiator walls and the acquisition system. In addition, the internal walls of the shielding were covered with RF-absorbing foam. The setup was placed in the last section of the CLEAR accelerator beamline. The particles exit the beamline window and travel in air for approximately 1 meter, until they hit the beam dump. The shielding containing the radiator was placed on a movable horizontal motor, which allows changing the distance between the front face of the radiator and the beam in the 0.7 - 11 cm range.

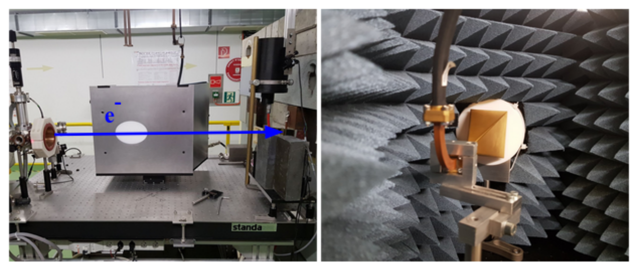

Figure 2: Front and back view of the experimental setup.

The radiation produced by the beam is coupled to the detection system through a horn antenna located behind the back face of the radiator. The captured signal is filtered using a waveguide band-pass filter. The filtered radiation is transmitted to a technical gallery through a network of W28 waveguides, that includes a flexible section to accommodate the setup movement when changing the impact parameter. The variation in the transmission loss of the waveguide network due to the setup movement was verified to be negligible for the purpose of this experiment. In order to ensure a constant diode sensitivity, the input power to the diode is maintained constant by means of a motorised attenuator, that is set to a known factor for each measurement setup. Finally, the signal was amplified and digitised using an oscilloscope.

DATA COLLECTION AND RESULTS

Impact parameter scans were obtained in two separate time periods in September and November 2021. During the first session, the measurements were taken at a single beam energy of 220 MeV, but two different band-pass filters were used to probe signals at two distinct frequencies: 30 GHz filter with 300 MHz bandwidth and 26 GHz filter with 1 GHz bandwidth. The aim of the second session was to study the impact of energy on the impact parameter curves and to repeat the experiment under more controlled conditions.

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During the September test, the ChDR power per single electron was estimated at each impact parameter based on a statistics of 200 beam shots. The beam energy was equal to 220 MeV. The radiation intensity and the beam charge were recorded. Only results from 2-5 cm impact parameter range were included in the analysis. Impact parameters above 5 cm were excluded due to the previously discussed constraints put by the radiator size. Values below 2 cm were not taken into consideration to limit possible background from the in-air Cherenkov radiation. The results are presented in Figs. 3 and 4. As a reference, the theoretical h^{-1} and h^{-3} curves are plotted with a scaling factor determined with the least squares fit to the data. As it can be noted, at both frequencies the measurement deviates significantly from these predictions. On the other hand, the measurement fits well with the exponential curve ae^{-bh}, which is not predicted by any of the examined models. The fitted values of the b parameter obtained with the least squares methods are

$$b_{30\,\mathrm{GHz}} = 58.58\ \mathrm{m}^{-1}, \quad b_{36\,\mathrm{GHz}} = 72.52\ \mathrm{m}^{-1},$$

which suggests that the value of the parameter b is proportional to the frequency.

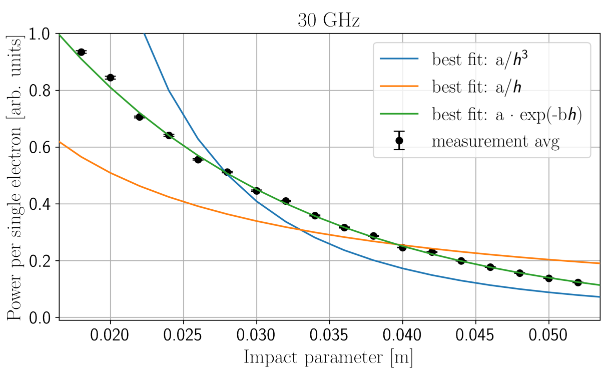

Figure 3: September impact parameter scan, 30 GHz filter.

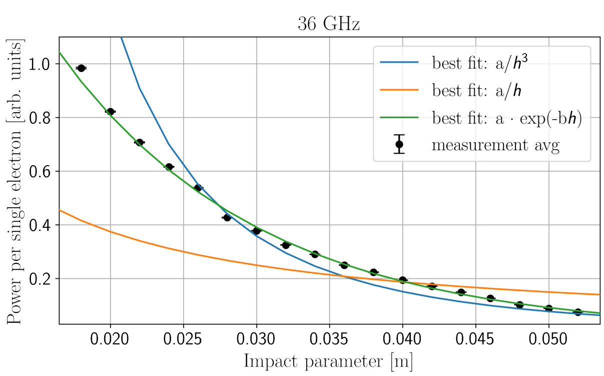

Figure 4: September impact parameter scan, 36 GHz filter.

The same procedure was repeated in November 2021 using electrons at three distinct beam energies: 100 MeV, 150 MeV and 200 MeV. This more detailed analysis took also into account small deviations of beam position and transverse bunch size, increasing the accuracy of the result. Due to time constraints only the 36 GHz filter was used, but the impact parameter scan was performed twice at each beam energy. The results of the impact parameter scans confirmed that the impact parameter curve follows an exponential shape. In addition, the parameter b of the parametrisation of the exponential curve, ae^{-bh}, was within 64.1 – 72.6 m^{-1} for all scans and did not show dependence on the beam energy.

CONCLUSION

The results of the experiment did not support neither predictions of Ulrich model, nor PCA. The measurements, repeated systematically for various beam conditions, showed that the ChDR power in the intermediate $\lambda < h < \gamma\lambda$ impact parameter range is given as an exponential function of the impact parameter. In addition, although impact parameters below 2 and above 5 cm should not be taken into this analysis, during all the scans the exponential shape of the impact parameter curve was preserved over the whole scanned impact parameter range.

The exponential dependence was previously observed in Ref. [14, 16] in a range of impact parameters close to the radiation wavelength. In Ref. [10] it was postulated that the amount of energy radiated in the form of ChDR is proportional to $e^{-4\pi h/\beta\gamma\lambda}$. This dependence was observed during the observation of incoherent ChDR in Ref. [17], but it does not match neither the findings of Ref. [14, 16] nor the results of the experiment described in this section. Assuming, as suggested, that the exponential b parameter is given by $b = 4\pi/\beta\gamma\lambda$, the experimental settings would result in $b_{30\,\mathrm{GHz}} \approx 3.85$ m^{-1}, which is over one order of magnitude smaller than what is determined experimentally. Furthermore, as determined during the November test, the b parameter does not depend on the beam energy. One might then suspect that the $e^{-4\pi h/\beta\gamma\lambda}$ dependence holds in the high frequency limit $\lambda\gamma \leqslant h$ but is not valid for lower frequencies. The exponential shape of the impact parameter curve in the high frequency limit is predicted by Ulrich model and PCA.

At this stage we cannot give a conclusive answer to the question why none of the tested hypotheses matched the experimental results and what is the reason of the exponential shape. A possible explanation might be the impact of the radiator size, verified to be sufficient only based on IW2D simulations, which are using a stationary model. The study performed with such a radiator is however relevant to the actual needs of beam instrumentation. The experimental results presented, although they might not correspond to the idealised geometries of theoretical models, could serve as a reference for future designs of diagnostic devices based on Cherenkov diffraction radiation for long wavelength. A new series of beam tests using electrons and positrons with energies from 10 to 300 GeV are under discussion at the CERN SPS fixed target facility to study the radiation yield of ChDR in the visble range and its dependency to impact paramater and beam energy.

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