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CHERENKOV DIFFRACTION RADIATION AS A TOOL FOR BEAM DIAGNOSTICS

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Abstract

Over the past 3 years, the emission of Cherenkov Diffraction Radiation (ChDR), appearing when a relativistic charged particle moves in the vicinity of a dielectric medium, has been investigated as a possible tool for non-invasive beam diagnostics. ChDR has very interesting properties, among which is the emission of a large number of photons in a narrow and well-defined solid angle which provides excellent conditions for signal detection with very little background. This contribution will present a collection of recent beam measurement results performed at several facilities such as the Cornell Electron Storage Ring (CESR), the Advanced Test Facility 2 (ATF2) at KEK and the CLEAR test facility at CERN. These results, complemented by simulations, are showing that both the incoherent and coherent emission of Cherenkov Diffraction radiation could open the path for a new kind of beam diagnostic technique for relativistic charged particle beams.

INTRODUCTION

The emission of Cherenkov radiation by charged particles travelling through matter was discovered in 1934 [1, 2] and, due to its fascinating properties (i.e. the emission of a large number of photons in a narrow and well-defined solid angle), has found numerous applications in many fields including astrophysics [3], and particle detection and identification [4, 5]. Recently, a first experiment was performed to investigate the possibility of non-invasive beam diagnostic techniques based on the detection of incoherent Cherenkov diffraction radiation (ChDR) [6]. The latter refers to the emission of Cherenkov radiation by charged particles travelling not inside, but in the vicinity of, a dielectric material. This combines the already well-known advantages of Cherenkov radiation with non-invasive photon generation, making it an ideal technique for beam instrumentation. In this paper we present a summary of the work performed by our team in developing both incoherent and coherent ChDR techniques over the past 3 years. This includes the development of a theoretical model to predict the characteristics of the emitted radiation for a given geometry and 3D electromagnetic simulations that can be used to simulate coherent radiation emitted at mm wavelength for any geometry. We also present an overview of the experimental results to date from several different beam facilities.

PHYSIC MODEL AND SIMULATIONS

Cherenkov diffraction radiation can be considered as Polarization Radiation (PR) resulting from polarization currents in the volume of a dielectric induced by the electromagnetic field of a passing particles. The model developed in [7, 8] predicts that the photons radiated by a relativistic particle in a simple geometry such as the one presented on Fig. 1 are emitted at the Cherenkov angle all along the dielectric before being refracted out at the end of the radiator. An example of the calculated angular spectral density for such a case is given in Fig. 2, which shows the horizontal and vertical polarization content of the radiation emitted by a 5.3 GeV positron propagating at a distance of 0.8 mm from the surface of a 2 cm long dielectric made out of fused silica.

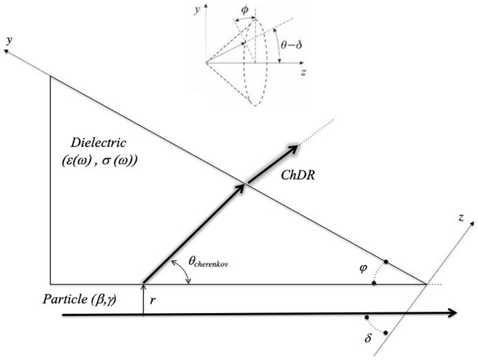

Figure 1: Emission of Cherenkov diffraction radiation by a charged particle propagating at a distance ρ from the surface of a dielectric material.

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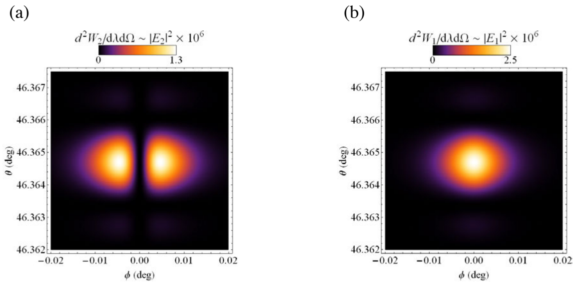

Figure 2: Angular distribution of the horizontal (a) and vertical (b) ChDR polarization field produced by a 5.3 GeV positron propagating at a distance of 0.8 mm from the surface of a 2 cm long dielectric made out of fused silica.

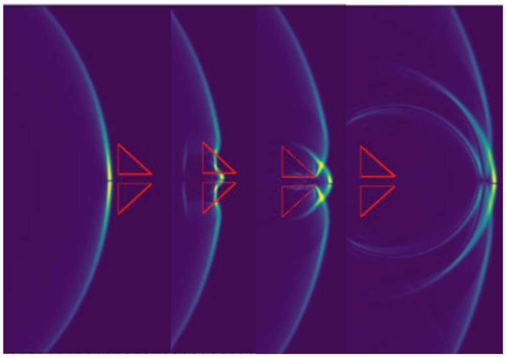

Figure 3: Field maps of a short bunch traversing a hollow, conical, dielectric structure.

Unlike incoherent radiation in the visible range, the generation of coherent Cherenkov diffraction radiation from a short bunch at mm wavelengths can be simulated using 3D electromagnetic codes. We present in Fig. 3 a simulation performed using the VSim particle-in-cell solver [9] of a 2 ps electron bunch propagating through a hollow, conical structure. The radiator, made out Teflon (PTFE), has an internal radius of 5 mm. The figure is a compilation of 4 images taken at different times as the bunch traverses the dielectric structure. The direct bunch field is visible in front, followed by the Cherenkov radiation generated inside the cone.

MEASUREMENTS USING CHERENKOV DIFFRACTION RADIATION

Since 2017, our team has been experimentally studying the properties of ChDR on three different accelerators. The initial investigations started on the CESR ring at Cornell (USA) using highly relativistic electrons and positrons. These studies were then pursued following two different investigative paths. The first aimed at measuring the beam size resolution limit using the small transverse beam sizes available on the ATF2 extraction line at KEK (Japan) [10]. The second focused on investigating the sensitivity limit of such a detector using longer dielectric radiators at the CLEAR beam facility [11] at CERN. In parallel, coherent ChDR was also tested at CLEAR for bunch length and beam position monitoring.

Experiments Performed at CESR

The emission of Cherenkov diffraction radiation by an electron in CESR is shown in Fig. 4. The equation for the PR spectral-angular distribution for a prismatic radiator is presented by Eq. (18) in [8]. Using this formula, and the beam parameters of CESR, the photon spectrum emitted by a single particle have been calculated for two different energies and for different distances from the radiator (impact parameter). The results are presented in Fig. 5 . Two independent tests were performed to confirm this prediction in April and October 2017 with particle beam energies of 2.1 and 5.3 GeV respectively. When considering an identical impact parameter, the photon intensity increases for higher beam energies while the photon spectrum also reaches shorter wavelengths. For 2.1 GeV the radiation power spectrum peaks in the near infrared, while for 5.3 GeV it peaks in the visible.

The experimental set-up used a vacuum tank initially built and installed in 2010 for non-invasive beam size measurements using Diffraction Radiation from dielectric slits [12]. The ChDR radiator is mounted onto a mechanism with two degrees of freedom: translation to insert the radiator once the

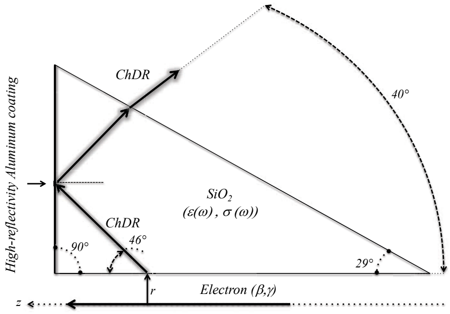

Figure 4: Emission of Cherenkov diffraction radiation by an electron in CESR.

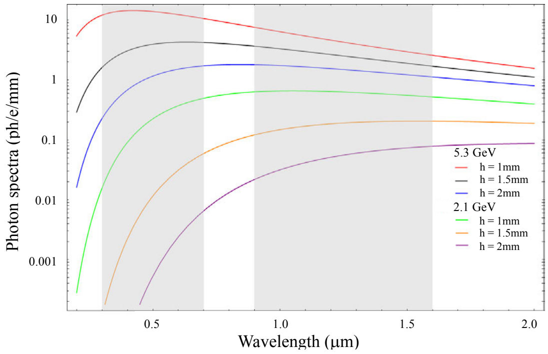

Figure 5: Photon spectral density of ChDR calculated for 2.1 and 5.3 GeV electrons or positrons for different impact parameters.

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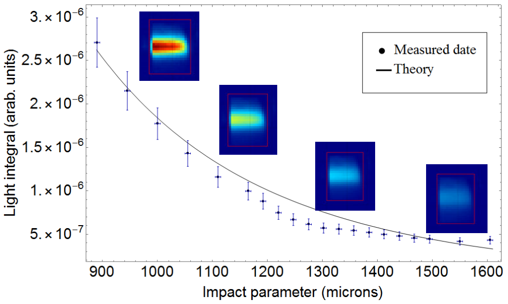

Figure 6: Evolution of the light intensity emitted by 2.1 GeV electrons and measured in the near infrared as a function of impact parameter.

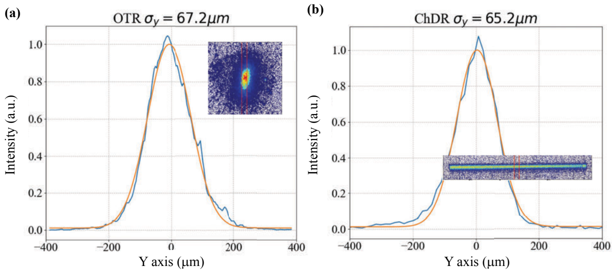

Figure 7: Vertical beam sizes measured with OTR (a) or ChDR (b).

beam is circulating and rotation to allow precise steering of the emitted photons through the optical detection line. The imaging system was composed of a set of mirrors, lenses, band-pass filters and polarisers. The main investigations performed using positrons at 5.3 GeV were reported in [6]. These confirmed the spectral-angular distributions of the radiation in the visible range. We present here complementary measurements using 2.1 GeV electrons, detecting photons in the near infrared (0.9 - 1.6 µm).

A typical beam impact parameter scan is presented in Fig. 6 showing the light intensity decreasing as the beam moves away from the surface of the dielectric. Images acquired at several impact parameters are also displayed, together with a comparison with theoretical prediction, showing a good agreement.

It was shown in [6] that direct imaging of the radiator was, in addition, providing reliable horizontal beam profile measurements in good agreement with the measured beam emittance in the machine. However, with a transverse beam size of several mm at CESR, it was not possible to investigate the resolution limit of ChDR beam size imaging using this set-up.

Experiments Performed at ATF2/KEK

In 2018, a new experimental campaign was started on the ATF2 extraction line, where studies of classical diffraction radiation had already been performed for several years. The experimental apparatus is described in detail in [13]. The beam line delivers a 1.25 GeV electron beam with low beam emittances. The same radiator as the one used on CESR was installed in ATF2 together with an Optical Transition Radiation (OTR) screen [14] that could be used for precise cross-calibration. Vertical beam profiles of 65.2 µm have already been measured using ChDR and found to be in good agreement with OTR measurement. An example of such a measurement is shown in Fig. 7. The study is now aiming at using very small vertical beam sizes down to 1 µm to measure the resolution limit of ChDR.

Experiments Performed at CLEAR

In parallel to the study performed on ATF2, additional studies were performed at the CLEAR facility at CERN using 200 MeV electrons, an energy considerably lower than at CESR or ATF2, resulting in a much lower light yield. To compensate for this loss, longer dielectrics were used, as the photon flux is directly proportional to the length of the radiator. A sketch of the experimental set-up is shown in Fig. 8. It is composed of a 2 mm thick, 2 cm wide and 20 cm long radiator made out of fused silica. The photons are emitted at a Cherenkov angle of 46.4° with a large fraction reflected internally from the outer face of the dielectric. These photons then propagate to the end of the dielectric through multiple internal reflections, travelling together with the new photons generated along the length of the dielectric surface as the electron bunch travels from one side to the other. All the photons emitted along the radiator are finally extracted at the end of the radiator by shaping the dielectric with an angle of 21.8° and coating this surface with aluminium. The emerging light is imaged using an Ethernet camera (Basler acA 1920 40gm) and a Fujinon camera lens with a focal length of 25 mm. The whole set-up is installed in air and mounted on movable translation tables that allows the precise positioning of the radiator with respect to the beam trajectory.

An impact parameter scan, measured with a bunch of 500 pC, is presented in Fig. 9. A beam size with a σ of 130 µm was measured just upstream of the radiator using a scintillating screen. The exponential decay of the radiation intensity with impact parameter is observed as expected, but the signal is still visible even at distances larger than 7 mm.

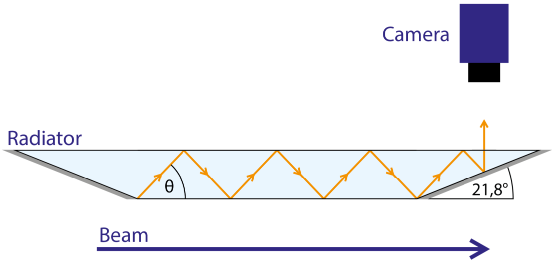

Figure 8: Sketch of ChDR emission in long dielectrics at CLEAR.

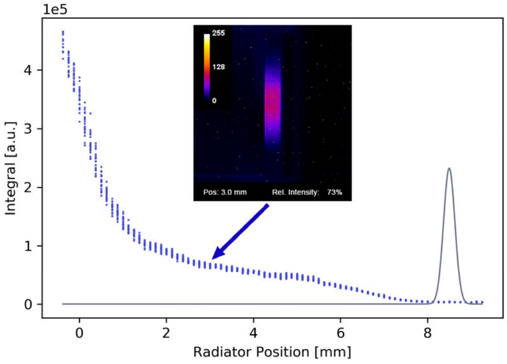

Figure 9: Impact parameter scan obtained with a 500 pC bunch and using a 600 ± 10 nm optical band-pass filter.

Measurement Using Coherent Cherenkov Diffraction Radiation at CLEAR

The emission of coherent ChDR was also tested at CLEAR, where picosecond long bunches emit coherent signals up to frequencies in excess of 100 GHz. A hollow pyramidal radiator made out of PTFE was installed on the in-air test-stand together with 3 diode detectors, two in the horizontal and one in the vertical plane (see Fig. 10). The diodes work in 3 different frequency bands, 60 GHz, 84 GHz and 113.5 GHz, to measure the bunch power spectrum. Measurements [15] were acquired with bunch lengths ranging from 1 to 5 ps, compared to longitudinal profiles measured at CLEAR with an RF deflector ans showed a very good agreement.

Figure 10: Picture of the coherent ChDR set-up tested at CLEAR using a hollow pyramidal radiator made out of PTFE.

This set-up has also been used to test the ability of such a system to measure beam position. By comparing the output of the two horizontal diodes, placed on opposite sides of the radiation, it was possible to extract the beam position during a horizontal alignment scan of the PTFE radiator. The results are shown on Fig. 11, together with simulations performed using Vsim. The data is plotted as a typical 'difference over sum' position signal. As the diodes measured different frequencies, their signal amplitude were adjusted to take into account the difference in power expected for a given bunch length. This is the main cause of the limited resolution observed experimentally. But it does demonstrate the ability of such a set-up to measure position as well as bunch length. More precise beam position measurements could then be obtained with a perfectly identical detection system on both sides on the pick-up.

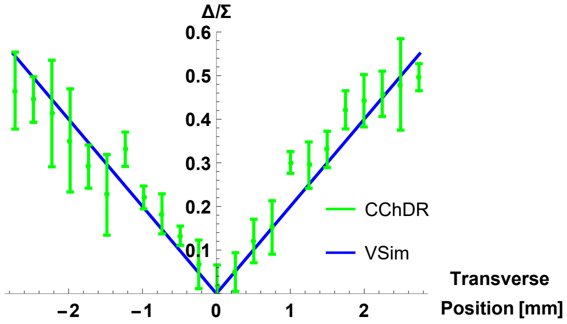

Figure 11: Beam position dependency measured using coherent ChDR in a PTFE radiator.

CONCLUSIONS AND PERSPECTIVES

Over the last 3 years, we have intensively studied the characteristics of Cherenkov Diffraction radiation for beam instrumentation applications. Transverse beam profiles as small as 65 µm have been successfully measured at the ATF2 facility using a simple, compact imaging system. Both theoretical and experimental validations are now aiming to measure the line spread function of ChDR which will give the resolution limit of such monitors. It is already possible to say that, in general, the best imaging condition will be met when the beam size is small with respect to the distance between the beam and the surface of the dielectric.

Long dielectric materials emitting ChDR have also been investigated with some exciting, preliminary results obtained at the CLEAR facility. This should open the path for the development of optical beam position monitors capable of measuring high energy, low intensity beams as well as debunched beams that are not measurable with electromagnetic pick-ups.

The use of coherent ChDR emitted by short bunches has also been tested on CLEAR with encouraging results as a bunch length and beam position monitor. Similar tests are being conducted at the CLARA facility at Daresbury laboratory [16]. A new ChDR BPM with dielectric buttons is currently being constructed and will soon be tested at

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CLEAR. If successful this is then planned for installation on the AWAKE test facility [17] at CERN.

ChDR diagnostics can be applied to a wide range of accelerators, from high energy leptons and hadrons colliders to synchrotron light sources and free electron laser facilities. For example, the magnetic lattice design of the most recent light sources is based on a very compact magnet assembly where typical beam position monitors cannot be installed. Compact optical-based monitors using ChDR could instead be embedded inside those magnetic structures in order to tune and optimise the accelerator performance. A a test-stand at the Diamond Light Source [18] has recently been equipped to study this possibility.

In the framework of novel accelerating technologies, there is a need to develop beam diagnostics adapted to new environments. Dielectric capillary tubes are commonly used in Cherenkov free electrons lasers, laser-based and beam-based plasma accelerators, as well as in dielectric accelerators and plasma lenses. The control of the beam travelling through the capillary is a crucial aspect of tuning such accelerators, as transverse wakefields induce large beam kicks leading to emittance dilution. ChDR provides the opportunity to develop beam instrumentation [19] that can be embedded into such dielectric capillaries or dielectric structures, which would allow a better monitoring and control of the beam in these novel accelerators.

Cherenkov Diffraction radiation should also be emitted by plasmonic waves, waves excited by passing relativistic charged particles in thin metallic films on dielectric substrates [20]. Simulations of such a process has been initiated using a code developed at CERN [21]. The use of such surface plasmon resonances would provide a more monochromatic emission of Cherenkov radiation.

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