DIFFRACTION CHERENKOV RADIATION FROM LONG DIELECTRIC MATERIAL: AN INTENSE SOURCE OF PHOTONS IN THE NIR-THZ RANGE

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Abstract

This paper presents the design on the Cornell Electron Storage Ring (CESR) of an experimental set-up to measure incoherent Diffraction Cherenkov Radiation (DChR) produced in a 2 cm long SiO_2 radiator by a 2.1 GeV electron beam. The electron beam is circulating at a distance of few mm from the edge of the radiator and the DChR photon output power is expected to be significantly higher than the diffraction radiation power emitted from a metallic slit of similar aperture. The radiator design and the detection set-up are presented in detail together with simulations describing the expected properties of the emitted DChR in terms of light intensity and spectral bandwidth. Finally, potential applications of DChR are discussed.

INTRODUCTION

Diffraction Radiation (DR) [1] is produced as charged particles pass in the close vicinity of a dielectric or metallic medium. DR from slits and holes has been investigated over the last 15 years for as non-interceptive beam diagnostics for beam size [2,3,4] and position [5] monitors. An experimental set-up has been installed since 2010 on the Cornell storage ring [6] to test such radiation processes using 2.1 GeV electrons. With a 1 mm aperture slit, the radiated power emitted in the visible range becomes high enough for beam diagnostic purposes [7] but the beam lifetime in the ring is strongly affected by this aperture restriction, making operational use of such a technique impractical.

For a high energy beam, the DR photon flux emitted by a dielectric sitting at a distance h from the particle, also known as impact parameter, becomes significant for a wavelength $\lambda = 2\pi h/\gamma$, with γ the beam relativistic factor. Working with target apertures of several mm would shift the photon spectrum towards the Near Infrared (NIR) but would also reduce the photon flux as it scales with $ln(1/\lambda)$ [1]. At such an impact parameter, and corresponding NIR wavelength, instead of DR from slits, Diffraction Cherenkov Radiation (DChR) from longer dielectric material can be used. For DChR the flux of photons is directly proportional to the length of the radiator. In this paper, we present the design of an experimental set-up using a 2 cm long fused silica radiator emitting DChR photons in the NIR. The target design and the detection set-up are presented in detail with calculations describing the expected properties of the emitted radiation in terms of light intensity and spectral bandwidth. Finally, potential applications of DChR are discussed.

GENERAL PROPERTIES OF DIFFRACTION CHERENKOV RADIATION

According to Tamm's theory [8], the number of Cherenkov photons per unit wavelength ($d\lambda$) and per unit solid angle ($d\Omega$) emitted by an electron from a dielectric material, characterised by its length L and its index of refraction n, is given by

$$\frac{d^2N_{cph}}{d\Omega d\lambda} = \frac{\alpha n}{\lambda}\left(\frac{L}{\lambda}\right)^2 \left(\frac{\sin\big(X(\lambda,\theta)\big)}{X(\lambda,\theta)}\right)^2 \sin^2\theta$$

$$\text{with } X(\lambda,\theta) = \frac{\pi L}{\beta\lambda}(1-\beta n\cos\theta) \quad (1)$$

where α is the fine structure constant, β the ratio of the velocity of the particle to the speed of light and θ the angle between the particle trajectory and the direction of observation. The spectrum of Cherenkov light depends on the properties of the dielectric and its transparency at different wavelengths. It typically peaks for shorter wavelength and then decays as $1/\lambda$.

When the particle is not passing through the dielectric itself, but at a distance h from its surface, the atoms of the dielectric experience a polarising field reduced by a factor K, which depends on particle energy and the wavelength as follows [9]

$$K = e^{\left(-2\pi\frac{h}{\gamma\beta\lambda}\right)} \quad (2)$$

The resulting number of diffraction Cherenkov photons emitted per unit wavelength and per unit solid angle from an electron travelling in the centre of a hollow dielectric of radius, h, would then be

$$\frac{d^2N_{Dcph}}{d\Omega d\lambda} = \frac{d^2(K\cdot N_{cph})}{d\Omega d\lambda} \quad (3)$$

The intensity of Diffraction Cherenkov photons becomes significant for a distance $h \le \gamma\lambda/2\pi$. The number of photons per unit wavelength is obtained by integrating equation (3) over all solid angles. This is shown in Fig. 1 for electrons of 2.1GeV travelling in the centre of a hollow SiO_2 ($n = 1.46$, $L = 2$ cm) tube, for various tube radii. For large radii, i.e. above 1 mm, the photon spectrum shows exponential reduction in the UV-Visible range due to the strong reduction of the particle field in the dielectric at such wavelengths. At 200 nm, there is more than 10 orders of magnitude difference in photon production between inner radii of 2 and 0.5 mm. For an inner radius of 0.5 mm, the photon spectrum emitted spans across the whole of the visible and NIR range. It peaks at a wavelength of 800 nm and then decays as ln(1/λ) for longer wavelength as for standard Cherenkov radiation.

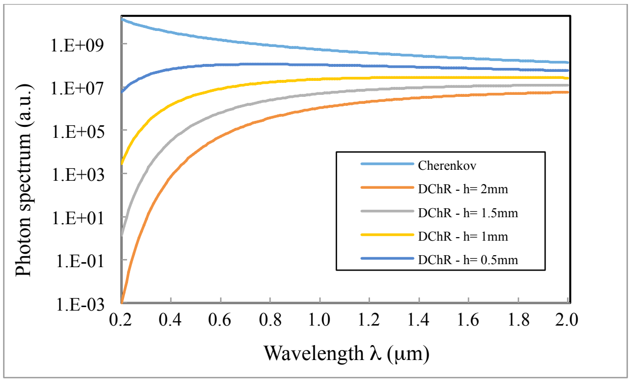

Figure 1: Diffraction Cherenkov photon spectrum emitted as an electron travels in a hollow SiO2 tube of differing inner radius. The Cherenkov spectrum that would be emitted if the electron traverses the bulk of the same radiator is also plotted for comparison.

EXPERIMENTAL SET-UP

CESR Machine Layout and Parameters

Cornell Electron Storage Ring (CESR), as depicted in Fig. 1, is nowadays mainly used as a synchrotron radiation light source. The tests of diffraction Cherenkov radiation use a set-up initially built and installed in 2010 for diffraction radiation studies in the L3 straight section [7].

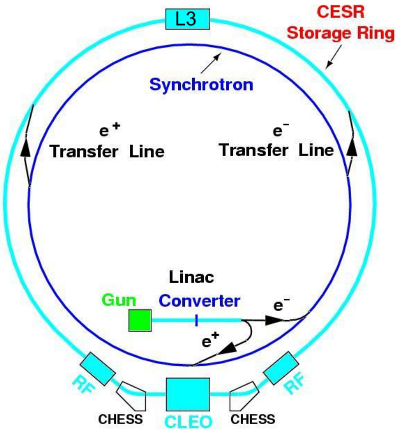

Figure 2: Layout of the CESR.

The main parameters of the ring are summarised in Table 1. One should note that CESR also has the possibility to run with positrons.

Table 1: Main Ring and Beam Characteristics

Ring circumference	768m
Beam Energy	2.1 GeV
Particles per bunch	$1.6\ 10^{10}$
Number of bunch	1-10

Diffraction Cherenkov Radiator

An overview of the vacuum tank is shown in Fig. 3. Similarly to what was done for diffraction radiation studies, the DChR target is mounted onto a mechanism with two degrees of freedom: translation to insert and retract the target once the beam circulating in the ring and a rotation around this axis to allow a precise steering of the photons through the optical line for detection. A replacement chamber is also mounted on an in/out mechanism to avoid local heating when CESR is running with high beam intensities for SR production.

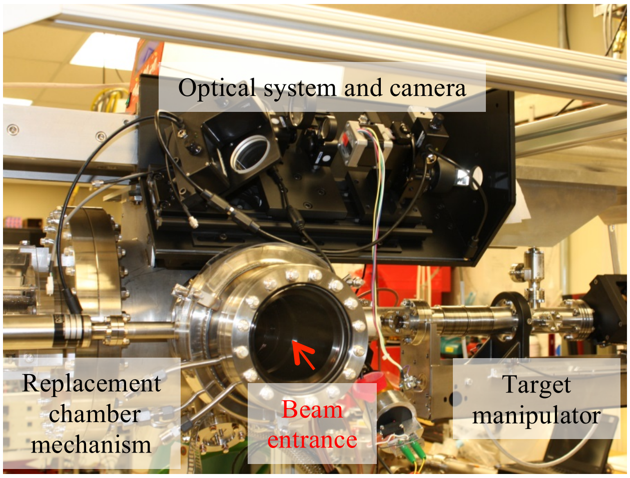

Figure 3: View of the DChR tank. The target is inserted from right to left.

The tank was initially equipped with only one viewport, at an angle of 40 degrees to measure the backward emitted DR photons. An additional flange was included in the tank to look at the target in the forward direction at a downward angle of 40 degrees. Cherenkov radiation is emitted at an angle *($\cos(\theta) = 1/\beta n$),* which differs significantly from the specular reflection angle of backward DR. The shape of the DChR target was therefore designed to use both of these flanges as observation ports. The radiator is made from two distinct blocks of high purity fused silica (Corning HPFS SiO_2 7980) as depicted in Fig. 4.

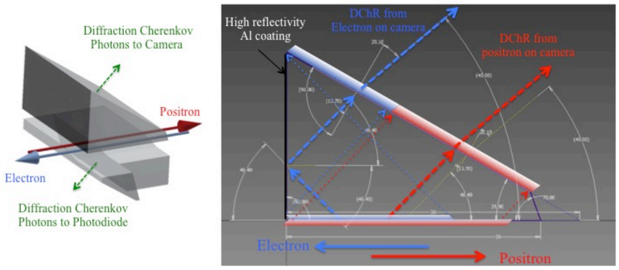

Figure 4: CESR Diffraction Cherenkov radiator.

Cherenkov radiation is emitted at an angle of *46°* inside the target. Both upper and lower radiators have a triangular shape with an angle of 30 degrees so that the Cherenkov photons are refracted out of the radiator at 40 degrees towards the upper and lower viewports respectively.

However, as the upper viewport is facing the front of the radiator, the back face of the radiator has a metallic coating in order to reflect the Cherenkov photons backwards in the direction of the viewport. This upper radiator is also shaped in such a way as to make it compatible with the detection of DChR photons produced by positrons, which would come from the opposite direction on CESR.

Detection System in NIR

The physical aperture between the lower and upper sides of the radiator has been chosen to range from 3 to 4 mm in such a way that the beam lifetime in the ring remains unaffected as the beam travels between the radiators. According to Eq. 3, the expected photon spectrum ranges from a wavelength of 800nm to 2μm.

Two detection systems have been designed to measure at the same time the photons emitted by the upper and the lower radiators. A cooled 640x512 pixels InGaAs camera [10] with 14bit ADC and an integration time from 1 μs to 40 ms is installed on the upper viewport. The lower viewport is equipped with a thermally cooled and amplified InGaAs photodiode [11], which is capable of bunch-by-bunch and turn-by-turn measurements. Both detection systems include a NIR lens and the possibility to incorporate band-pass filters at 1000, 1300 and 1500 nm. The angular acceptances of the optical lines are 20 and 5 mrad for the upper and lower radiators respectively. The typical spectral response of the InGaAs photodiode is presented in Fig. 5, with a quantum efficiency as high as 80 % for a wavelength of 1.6 μm.

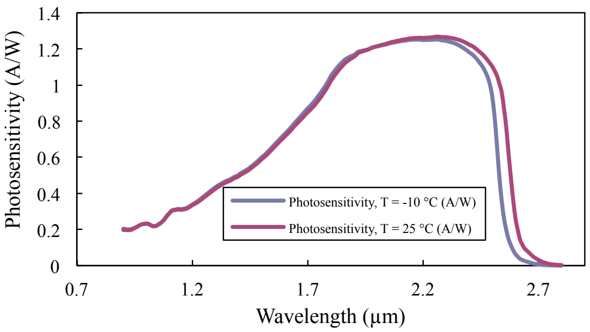

Figure 5: Spectral response of an InGaAs photodiode.

An estimation of the photon flux that should be detected by each of the detection lines has been made by integrating Eq .3 over the angular acceptance of the detection system and over the spectral range of the detectors. The results are presented in Fig. 6, which shows the number of photons per particle and per turn as a function of the impact parameter, h. The top curve shows the total number of photons emitted in both radiators over the spectral transparency range of the radiator [200 nm to 2000 nm]. The number of photons detected by the camera and the photodiode would be 10^3 and 10^4 lower than that respectively, a function of the angular acceptance of the optical lines. The number of photons that would be emitted by diffraction radiation for the same impact parameter is also indicated for comparison and is seen to be 10^4 times less intense than for DChR over the same wavelength range.

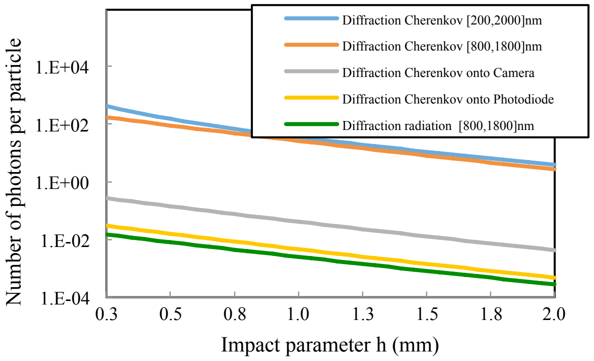

Figure 6: Number of photons per particle and per turn as a function of the impact parameter h.

CONCLUSION AND PERSPECTIVES

An experimental set-up has been designed in order to measure incoherent Diffraction Cherenkov photons produced in a high purity fused silica radiator. The system has been installed on the Cornell Electron Storage Ring, ready for beam tests in spring 2017 using both electrons and positrons at 2.1 GeV.

The main goal of this experiment is to measure the photons flux and photon spectrum emitted by such a process to validate the theory. It is expected that a significantly larger photon flux will be produced compared to Diffraction radiation. This will open up the possibility to use this radiation process for beam diagnostic applications such as beam position monitoring for high-energy electron and hadron beams.

This would also open up the possibility to generate high photons fluxes in the NIR to THz regime using appropriately transparent dielectric like diamond. Using shorter bunches would produce coherent diffraction Cherenkov [13] radiation, with a much higher flux of photons generated. A test at the CLEAR facility at CERN [12] is being prepared to investigate this case.

REFERENCES

[1] A. P. Potylitsyn *et al.*, Diffraction Radiation from Relativistic Particles. Berlin Heidelberg, Germany: Springer 2010.

[2] P. Karataev *et al.*, “Beam-size Measurement with Optical Diffraction Radiation at KEK Accelerator Test Facility”, Phys. Rev. Lett. 93, 244802, 2004.

[3] A. H. Lumpkin *et al.*, “Near-infrared Imaging of Optical Diffraction Radiation generated by a 7-GeV Electron Beam”, Phys. Rev. ST Accel. Beams 10, 022802, 2007.

[4] A. Cianchi *et al.*, “Non Interceptive Electron Beam Size Monitor using Optical Diffraction Radiation Interference”, Phys. Rev. ST Accel. Beams 14, 102803, 2011.

[5] R. Kieffer *et al.*, “Optical Diffraction Radiation for Beam Position Monitoring of Charged Particle Beams”, NIM B, to be published, 2017.

[6] Cornell Electron Storage Ring, LEPP, Cornell University, http://www.lepp.cornell.edu/Research/AP/CESR/

[7] L. Bobb, "Feasibility of Diffraction Radiation for Non-invasive Micron-scale Transverse Beam Size Measurement in Circular Machines", Ph.D. Thesis, Royal Holloway, Univ. of London, 2016.

[8] I.E. Tamm, "Radiation Emitted by Uniformly Moving Particles", J. Physic, Moscow 1, 439, 1939.

[9] R. Ulrich, "Cherenkov Radiation of an Electron Moving Parallel to a Dielectric Boundary", Z Physic, 194, 180, 1966.

[10] InGaAs Camera, model Bobcat from Xenics infrared solution: http://www.xenics.com/en/bobcat-640-gige

[11] InGaAs photodiode model PDA10DT from Thorlabs https://www.thorlabs.com/

[12] CLEAR test facility at CERN: http://clear.web.cern.ch

[13] A.M. Cook *et al.*, "Observation of Narrow-Band Terahertz Coherent Cherenkov Radiation from a Cylindrical Dielectric-lined Waveguide", Phys. Rev. Lett. 103, 095003, 2009.