NON-INVASIVE BEAM DIAGNOSTICS WITH CHERENKOV DIFFRACTION RADIATION

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Abstract

Based on recent measurements of incoherent Cherenkov Diffraction Radiation (ChDR) performed on the Cornell Electron Storage Ring, we present here a concept for the centering of charged particle beams when passing close to dielectric material. This would find applications as beam instrumentation in dielectric capillary tubes, typically used in novel accelerating technologies, as well as in collimators using bent crystals for high-energy, high-intensity hadron beams, such as the Large Hadron Collider or Future Circular Collider. As a charged particle beam travels at a distance of a few mm or less from the surface of a dielectric material, incoherent ChDR is produced inside the dielectric. The photons are emitted at a large and well-defined angle that allows their detection with a limited contribution of background light. A set of ChDR detectors distributed around a dielectric would enable both the beam position and tilt angle to be measured with a good resolution.

INTRODUCTION

Beam instrumentation is of prime importance for any accelerator. In the framework of novel accelerating technologies, plasma and dielectric accelerators rely on challenging beam parameters that put high constraints on the performance of the required beam diagnostics [1-4]. Dielectric capillary tubes are commonly used in novel technologies for laser-based [5] and beam-based [6] plasma acceleration, dielectric acceleration [7] and plasma lenses [8]. The control of the beam travelling through the capillary is a crucial aspect of the tuning of such accelerators, as transverse wakefields would induce large beam kicks that would lead to emittance dilution [9].

For high energy hadron machines, bent crystals have been used since the early 90s [10-13] to produce large deflection angles for tail particles that channel through the crystal plane. This technique is now considered as an upgrade of the collimation system for the Large Hadron Collider [14] and in the framework of Future Circular Collider studies [15].

In recent years, incoherent Diffraction Radiation (DR) [16] has been developed for non-invasive beam size monitoring [17]. DR has also proven its capability to be used for the centering of electron bunches in small aperture slits with high resolution [18, 19]. More recently the measurement of incoherent Cherenkov Diffraction Radiation (ChDR) emitted in a 2 cm long fused silica material has been demonstrated using a 5.3 GeV positron bunch circulating in the Cornell electron storage ring [20]. Those results show the great potential of ChDR for non-invasive beam diagnostics. Compared to DR, which is emitted at the interface between two dielectric media, the flux of ChDR photons is directly proportional to the length of the dielectric used and could therefore provide larger photon fluxes. Moreover, as the photons are emitted at a large angle, the light can be extracted efficiently with very small contribution from background light (typically coming from synchrotron radiation).

In this paper, we present the concept of a beam position monitoring system embedded in a dielectric material and based on Cherenkov diffraction radiation. A detector design is presented along with calculations describing the expected properties of the emitted radiation in terms of light intensity, spectral properties and beam position sensitivity.

EMISSION OF CHERENKOV DIFFRACTION RADIATION IN DIELECTRIC

A sketch of the principle of emission and detection of Cherenkov Diffraction Radiation in a dielectric is presented in Figure 1.

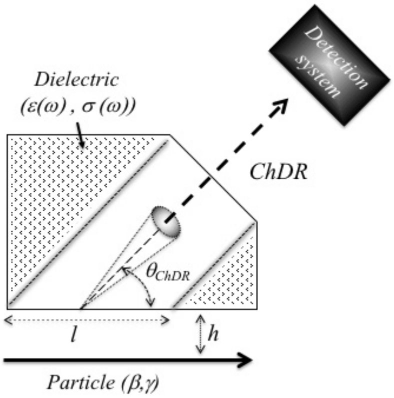

Figure 1: Emission of Cherenkov Diffraction radiation in a dielectric.

We consider a charged particle, defined by its velocity βc and its relativistic factor γ, travelling at a distance h (known as the impact parameter) from the surface of a dielectric. As the particle travels along the material, its electromagnetic field polarises the atoms sitting at the surface of the dielectric, which in turn emit Cherenkov radiation. The photons are emitted inside the dielectric at the characteristic Cherenkov angle θ_{ChDR}, defined as $\cos\theta_{ChDR} = 1/\beta n$, with n being the index of refraction of the material. As presented in Fig. 1, the outer surface of the dielectric should be designed with an appropriate angle in order to refract the photons out of the material so that they can be detected. Table 1 summarises the typical angle of emission of Cherenkov light

Table 1: Emission angle of Cherenkov radiation, θ_{ChDR}, in different dielectric material transparent to visible and near-infrared light, at 500nm. One should note that Silicon is only transparent for infrared radiation and the corresponding Cherenkov angle is calculated for 2µm wavelength.

Material	***Index of refraction***	***θ_{ChDR} (degrees)***
Fused silica	1.46	46.8°
Sapphire	1.76	55.4°
Diamond	2.37	65.0°
Silicon	3.45	73.2°

A theoretical model based on the so called 'polarisation current approach' [21- 24] has been developed in order to calculate the characteristics of polarisation radiation emitted by a charged particle propagating in the close vicinity of a dielectric surface. This model accounts for the emission of both DR and ChDR in the dielectric. The photon spectra emitted in a 1mm long fused silica for particles with different beam energies are shown on Figure 2. In this example an impact parameter of 1 mm has been considered.

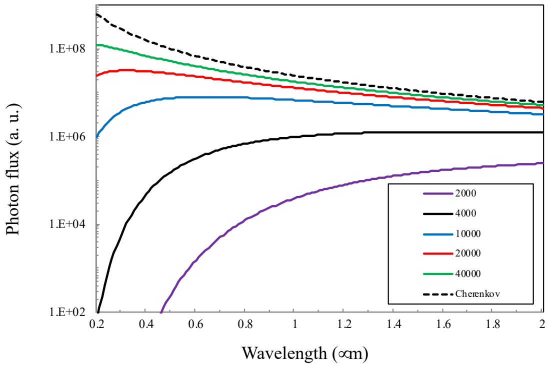

Figure 2: ChDR photon spectra emitted in fused silica by a particle travelling at an impact parameter of 1 mm with different beam energies (γ = *2000, 4000, 10000, 20000 40000*). For comparison, the dashed black curve corresponds to the Cherenkov radiation spectra that would be emitted when a particle (γ = *40000*) would directly travel through the dielectric.

With increasing beam energies, the photon spectrum shifts towards shorter wavelength. For a wavelength of 200 nm, there are more than 6 orders of magnitude difference in the photon intensity emitted by particles with relativistic factors of 2000 and 20000, i.e. electrons of 1 and 10 GeV, respectively. The number of photons emitted through ChDR at a given wavelength λ becomes significant (i.e. comparable to direct Cherenkov radiation) for beam energies satisfying the condition $\gamma \geq 2\pi h/\lambda$. As an example, the number of photons emitted in fused silica has been calculated both in the visible (i.e. [400, 600] nm) and in the near-infrared (i.e. [800, 1500] nm) range. These two wavelength ranges have been chosen as they correspond to the spectral sensitivity of standard photodiodes based either on Silicon (visible) or Indium-Gallium-Arsenide (NIR) sensors. The results are presented in Table 2. There are always more photons emitted in the near-infrared than in the visible range. However, the difference becomes negligible for the highest beam energies.

Table 2: Number of photons emitted per charged particle per mm of fused silica in the visible and near-infrared range. The impact parameter considered for the calculation presented in this table is 1 mm. The number of photons was calculated assuming a 25 mrad detection cone angle similar to that used at Cornell [20]

Relativistic factor γ	**Wavelength [400, 600] nm**	**Wavelength [800, 1500] nm**
2 10^{3}	0.6 10^{-6}	3.8 10^{-4}
4 10^{3}	2.5 10^{-4}	5.6 10^{-3}
1 10^{4}	1.1 10^{-2}	3.1 10^{-2}
2 10^{4}	4.0 10^{-2}	5.7 10^{-2}
4 10^{4}	7.7 10^{-2}	7.7 10^{-2}

One should note that ChDR can be emitted over a wider range of wavelengths depending on the transparency of the dielectric used. Diamond, for example, can emit ChDR from the UV to mm wavelengths.

AN OPTICAL BEAM POSITION MONITOR EMBEDDED IN A CAPILLARY TUBE

Proposed Geometry

We consider the emission of ChDR in a dielectric material. A sketch of the proposed geometry is depicted in Figure 3. It shows a charged particle, propagating in the centre of a dielectric, with two ChDR detectors located upstream. Denoted as 'top' and 'bottom' detectors, they will measure the number of photons emitted as a function of the beam position. The tilt angle of the beam with respect to the dielectric surface could also be measured by adding two additional detectors downstream.

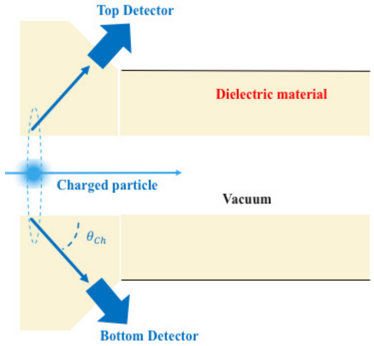

Figure 3: Proposed geometry for the centring of charged particle beams near dielectric material.

Let us consider as an example a charged particle with γ *of 2000* propagating parallel to the surface of a fused silica radiator. The ChDR photon spectra emitted for impact parameters ranging from 0.5 to 2 mm are presented in Fig. 4. Similarly to what was shown in Fig. 2, the photon spectrum shifts towards shorter wavelength as the particle travels closer to the surface. The light intensity measured by the top and the bottom detectors would then strongly depend on the wavelength used for the detection system.

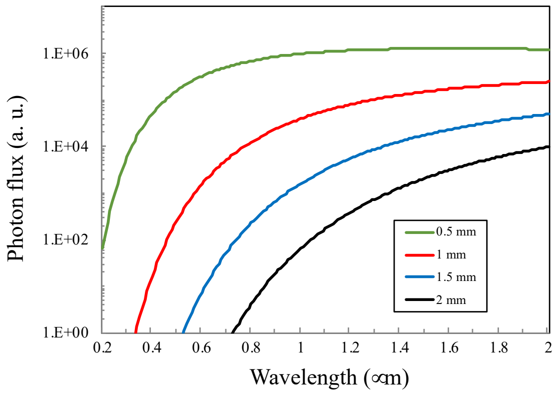

Figure 4: ChDR photon spectra emitted in fused silica by a charged particle with $\gamma = 2000$ travelling at impact parameters of 0.5, 1, 1.5 and 2 mm.

If we assume a dielectric capillary tube with an internal radius of 1 mm. The expected signals measured by the top and bottom detectors can be calculated, with the results presented in Fig. 5 as a function of the beam position. When the beam is centred, both detectors receive an equal number of photons, with the amplitude of the signal a hundred times larger when detecting photons at a wavelength of 1500 nm compared to 500 nm, as expected from Fig. 4.

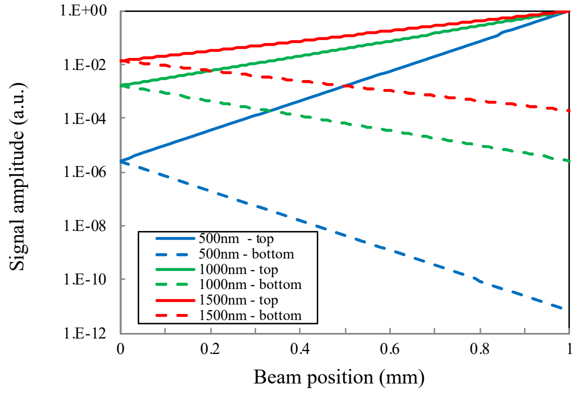

Figure 5: Number of photons detected by the top and bottom detectors as a function of the beam position. Calculations are performed considering a capillary with a 1 mm radius and a charged particle with $\gamma = 2000$.

Contrary to the near linear response of classical electrostatic or electromagnetic beam position monitors [18], the position response (difference between top and bottom detectors) of a ChDR monitor is exponential [14]. Moreover, this exponential difference scales with the inverse of the detection wavelength, implying that the sensitivity of the detector is always higher for the shortest possible wavelength. In order to quantify this behaviour, one can calculate a normalised beam position as follows

$$Normalised\ Beam\ position = \frac{N_{top} - N_{bottom}}{N_{top} + N_{bottom}}$$

with N_{top} and N_{bottom} the number of photons measured by the top and bottom ChDR detectors. The corresponding beam position sensitivities are then presented in Fig. 6 for three different wavelengths, with the best sensitivity obtained when using the shortest wavelength. This is nevertheless at the expense of the range of beam positions over which the system is sensitive. It is also at the expense of photon flux, requiring the measurement of smaller light intensities. This limitation can be mitigated, at least to a certain extent, by the use of longer dielectric detectors.

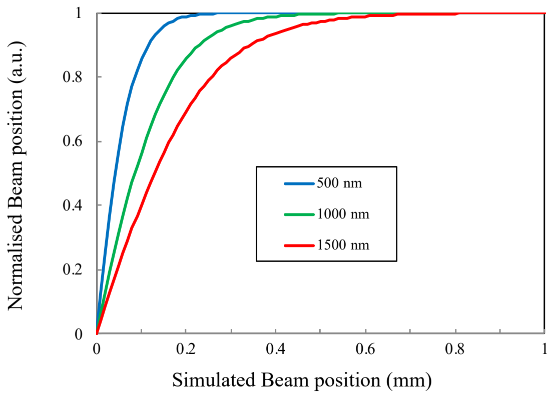

Figure 6: Expected beam position sensitivity for 500 nm, 1000 nm and 1500 nm wavelengths and a charged particle with $\gamma = 2000$.

CONCLUSION AND PERSPECTIVES

Collimator with embedded electrostatic beam position monitors have already been developed for the Large Hadron Collider and have been shown to be extremely useful for the rapid set-up and monitoring of very small collimator gaps with great accuracy [25]. We propose in this paper a conceptual design for a beam position monitoring system based on the detection of incoherent Cherenkov Diffraction Radiation in the visible or near-infrared range in dielectric material that could be embedded in dielectric capillary tubes or bent crystal collimators.

The expected number of photons produced is sufficiently high to allow the use of a simple detection system, and the sensitivity to beam position looks promising. One should note that when using extremely short bunches the ChDR emission would become coherent in the visible range, degrading the sensitivity to beam position.

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