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RECENT RESULTS USING INCOHERENT CHERENKOV DIFFRACTION RADIATION FOR NON-INVASIVE BEAM DIAGNOSTICS

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Abstract

When a relativistic charged particle travels at a short distance from the surface of dielectric material Cherenkov Diffraction Radiation (ChDR) is produced inside the dielectric. Recent observation of incoherent ChDR in the visible spectrum has opened the possibility of using this radiation for non-invasive beam size and position measurements. An experimental test to study this technique for highly directional beam position measurement has been initiated on the CLEAR facility at CERN, whilst another experimental investigation is underway at the Accelerator Test Facility 2 (ATF2) at KEK, Japan, to measure the resolution limit of ChDR for beam imaging diagnostics. This contribution presents the latest experimental results from both of these test facilities.

INTRODUCTION

Cherenkov diffraction radiation (ChDR) is the radiation emitted through the Cherenkov effect by particles travelling at a given distance h from the surface of a dielectric. This distance is known as the impact parameter. The use of incoherent Cherenkov radiation for beam instrumentation purposes is interesting due to the high number of photons emitted and its highly directional emission [1]. The non-invasive nature of ChDR makes it an ideal candidate for beam diagnostics in an accelerator because it offers the advantage of probing beam information without inserting an object in the beam path, as in more traditional methods like wire scanners, Optical Transition Radiation (OTR) or scintillation screens. Furthermore the emission of radiation in the dielectric is at the well-defined Cherenkov angle, defined by the relation $\theta_{ChDR} = arccos(1/\beta n)$, where n is the index of refraction of the material and β the ratio between the speed of the particle and the speed of light. This directional emission can allow discrimination of the ChDR signal from sources of background, for example synchrotron radiation that is the limiting background source for other non-invasive beam diagnostic techniques such as diffraction radiation monitors [2]. Incoherent ChDR was initially observed, and used for beam size measurements, at the Cornel Electron Storage Ring (CESR) [1,3,4].

We report here on the status of two more recent experiments aimed specifically to study incoherent Cherenkov Diffraction Radiation (ChDR) as a candidate for non-invasive beam position and profile measurement. The experimental setup and the first measurements results of the study on beam position monitoring at the CLEAR facility at CERN are presented [5], along with the experimental apparatus and preliminary measurements on beam size monitoring at the Accelerator Test Facility (ATF2) [6] at KEK, Japan.

BEAM POSITION MONITORING USING A LONG DIELECTRIC

Long Dielectric Radiator

The idea behind the experimental setup on CLEAR is to make use of the linear dependency of photon flux on the length of the radiator to accumulate enough light for diagnostics on a single beam passage. In order to transport and accumulate photons generated along the whole length of the radiator the concept of total internal reflection is used. A schematic of the radiator shape, photon transport and light extraction to a camera is shown in Fig. 1. The radiator is a 2 *mm* thick, 20 *cm* long fused silica prism with two wedges at both extremities.

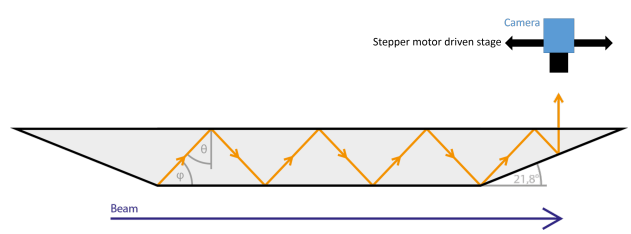

Figure 1: View from the top. The radiation produced all along the surface of the radiator is emitted at the characteristic Cherenkov angle and reflected inside the radiator before extraction to a camera.

The experiment was conducted using the following conditions: electron beam energy $\approx 210\,MeV$, $\beta \approx 1$, refraction index n of the fused silica radiator = 1.45. This results in a Cherenkov angle $\phi \approx 46.4°$. The radiator was installed on the in-air (refraction index $\approx$ 1) test stand present on CLEAR [7]. Thanks to Snell's law it is possible to verify that angle $\theta = 90° - \phi = 43.6°$ is exactly the critical angle $\theta_c = arcsin(n_{SiO_2}/n_{air})$. To extract the radiation at 90° respect to beam propagation direction the radiator has wedge of 21.8° (shown in Fig. 1) coated with aluminum. The emerging light is collected with an ethernet camera (Basler acA 1920 40gm) that images the output surface of the radiator with a Fujinon camera lens of focal length 25 mm. The

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camera was installed on a stepper motor driven stage that allowed it to be moved longitudinally to find the maximum emission point.

Diffraction Cherenkov Emission

Images of the ChDR are recorded after a longitudinal scan in order to optimize the transverse position of the camera within the maximum light emission. Fig. 2 shows two images taken in the optimal transverse position for different beams to dielectric distances. In these pictures, it can be seen that the radiation is confined between two sharp, vertical lines corresponding to the two edges of the wedge.

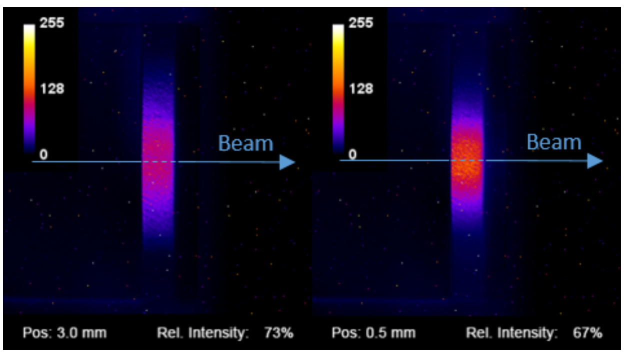

Figure 2: ChDR light recorded on the camera for a beam to dielectric distance of 3 *mm* (left) and 0.5 *mm* (right).

As described in literature [4], the total intensity of the radiation emitted depends on the distance of the beam from the radiator. This is seen in Fig. 2 where the image for a distance of 0.5 *mm* shows a significantly higher intensity than that for a distance of 3 *mm*. A full scan of this distance (the impact parameter) was performed and is presented in Fig. 3.

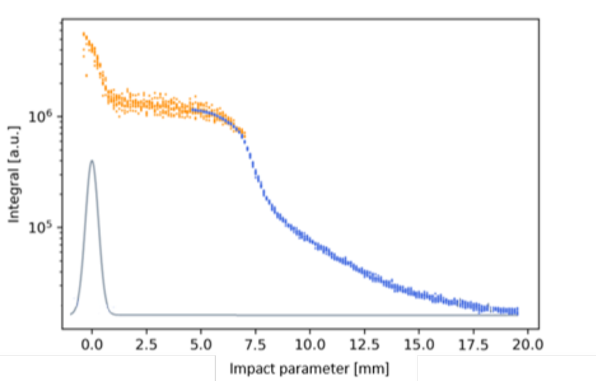

Figure 3: Impact parameter scan against total intensity of ChDR. The approximate beam profile is shown in grey.

The integrated intensity is plotted as a function of the impact parameter (i.e. the distance between radiator and beam). The blue values were obtained with maximum gain of the camera, the orange values with the minimum gain, and subsequently re-aligned. A Gaussian curve representing the beam size (σ = 300 μm) is also depicted as a solid grey line for comparison, measured with an Optical Transition Radiation (OTR) screen that could be inserted just upstream of the set-up. The non-linear dependence of total ChDR intensity on the impact parameter is clearly visible. The curve can be divided in two different part: the first, with impact parameter below 5 *mm*, is dominate by the contribution of standard Cherenkov of intercepting particle; the second, farther from the radiator where ChDR is dominant. Furthermore, there is measurable signal at a distance > 10σ (impact parameter > 3 *mm*). At such distances it is possible to exclude the contribution of direct Cherenkov radiation produced by the tails of the beam inside the radiator, such that the measurement can be considered truly non-invasive. Recording the image of the emitted ChDR also allows the vertical position of the beam to be measured, using the mean position of the vertical profile after fitting with a Gaussian. Fig. 4 shows the variation of this vertical position during the impact parameter scan.

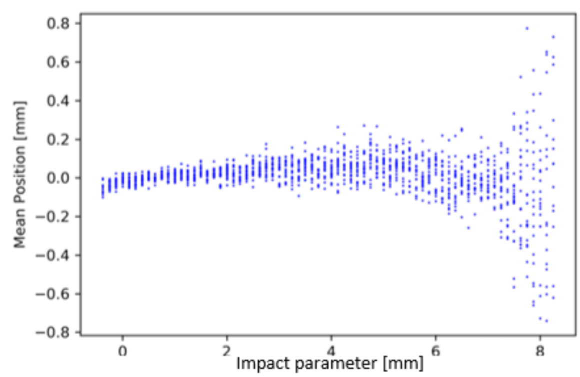

Figure 4: Vertical position of the beam during the impact parameter scan.

As expected, the vertical position does not change significantly during the scan with only the relative distance between the radiator and the beam in the horizontal plane varied. The measurement point for distances bigger than 6 *mm* shows a wider distribution due to the poor signal to noise ratio.

BEAM SIZE MONITOR BEASED ON DIF-FRACTION CHERENKOV RADIATION

Experimental Set-up

The radiator used for the beam size experiment based on ChDR at ATF2 is a prism with a triangular section made of high purity fused silica (Corning HPFS $SiO2$ 7980) as depicted in Fig. 5. This particular shape was chosen such that the ChDR could be sent through an existing viewport positioned at 40° with respect to the beam path. The ultra-relativistic electron beam (1.3 *GeV*) passes parallel to one surface of the radiator and generates ChDR photons at the Cherenkov angle $\phi \approx 46°$. The photons propagate inside the radiator before being reflected by the metallised back-face of the radiator. The photons are then refracted out of

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the radiator at an angle of 40° in the direction of the view-port thanks to the prism's wedge angle of 29°. The optical

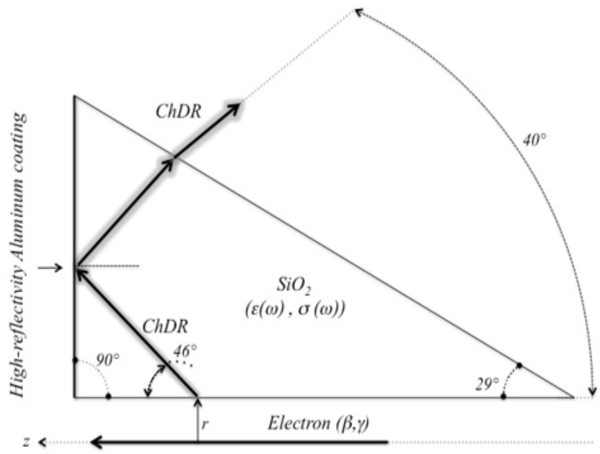

Figure 5: Radiator installed at ATF2.

line to observe the ChDR consist of a rotatable polarizer (LPVIS100 from Thorlabs), a band-pass filter with a centre wavelength of 700 *nm* (FB700-40 from Thorlabs), a camera lens (UV-VIS-IR 60 *mm* 1:4 APO Macro from Jenoptik) with a focal doubler to obtain a magnification factor $M = 2$. The dector used is a low noise CMOS camera (Edge 4.2 LT from PCO).

Beam Size Measurement and System Upgrade

Preliminary measurements of transverse beam profiles, specifically the vertical beam profile, have been obtained from the ChDR signal using the setup previously described. The ATF2 beam optics was configured to have a small horizontal size, of the order of few tens of micrometres, at the location of the ChDR monitor. Such configuration allows minimising the horizontal beam size as ChDr images can be distorted when distance of beam core is significantly different than distance from the tails. The vertical polarisation component of the ChDR observed across the side of the radiator facing the beam is presented in the top part of Fig. 6. The associated profile is calculated between the two red lines. This region is chosen to minimize the profile width so to find the focal point. The measured vertical beam size of $\sigma_y = 63.2\ \mu m$ is in fair agreement (±6%) with the beam size measured using a neighbouring OTR screen ($\sigma_y = 67.2\ \mu m$).

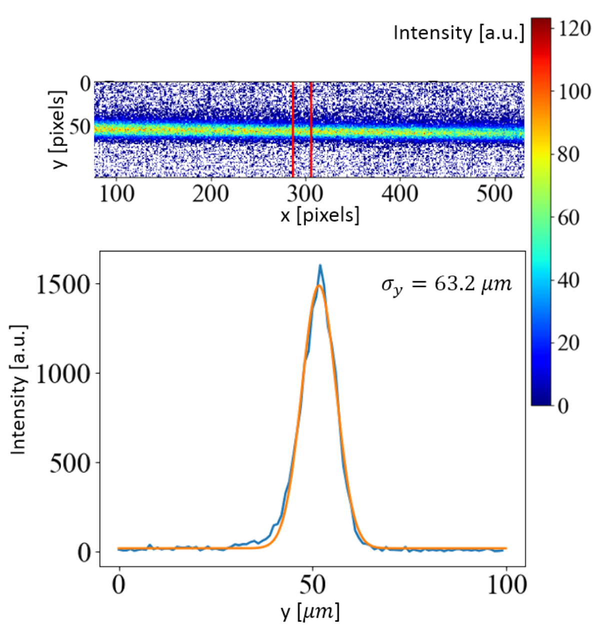

Figure 6: Diffraction Cherenkov 2D image and profile.

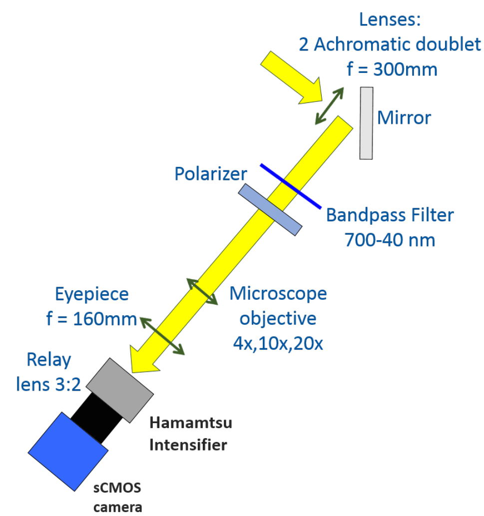

Figure 7: New optical line at ATF2. The yellow arrows represent the ChDR light path.

To improve the resolution of this monitor a new optical line is being designed and installed (Fig. 7). This consists of two achromatic doublets ($f = 300\,mm$) used to create an intermediate image that is then magnified with an infinite conjugated microscope made using a microscope objective and an eyepiece. The object plane of the microscope is the input surface of an image intensifier (C9547-04 from Hamamatsu) that is optically coupled to a low noise sCMOS camera (pco edge 4.2 LT) through a 3:2 relay lens. The effective magnification M can be chosen to be 2.4, 6 or 11.5 thanks to 3 selectable microscope objectives. A rotatable polarizer and band-pass filter are also present. This new set-up at ATF2 is foreseen to be test during 2019.

CONCLUSION

We have presented an overview of recent results of non-invasive beam diagnostics using ChDR. The application of ChDR for beam position monitoring using a long dielectric is a very recent idea, with the first results presented in this paper. Compared to other non-invasive technologies such as diffraction radiation, ChDR has the advantage of a relatively large light yield in the visible range, a simple experimental setup and a target geometry that requires a relatively uncomplicated alignment. Being a very recent

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technique, ChDR for position measurement still requires a number of studies to understand which experimental and instrumental factors might limit its use as an operational technique. For this purpose, further experimental studies with different radiators and detector will be performed at CLEAR in the second half of 2019. Regarding ChDR as a beam size measurement technique, the monitor installed at ATF2 has already shown a sensitivity to beam sizes smaller than a few tens of micrometres. To probe the resolution limit further, the existing instrument has been modified to in-crease the sensitivity (intensifier) and the magnification (optical components) with the aim of detecting micrometric beams later this year.

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