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RECENT RESULTS ON NON-INVASIVE BEAM SIZE MEASUREMENT METHODS BASED ON POLARIZATION RADIATION

L. Bobb, Diamond Light Source, Oxfordshire, UK
M. Bergamaschi, R. Jones, R. Kieffer, T. Lefevre, S. Mazzoni†, F. Roncarolo, CERN, Geneva, CH
M. Billing, J. Conway, M. Forster, Y. Padilla Fuentes, J. Shanks, S. Wang, L. Ying, Cornell University, Ithaca, USA
P. Karataev, K. Lekomtsev, JAI at Royal Holloway University of London, Egham, UK
A. Aryshev, N. Terunuma, KEK, Tsukuba, Japan
V.V. Bleko, A. S. Konkov, A. P. Potylitsyn, Tomsk Polytechnic University, Tomsk, Russia

Abstract

We present recent results on non-invasive beam profile measurement techniques based on Diffraction Radiation (DR) and Cherenkov Diffraction Radiation (ChDR). Both methods exploit the analysis of broadband electromagnetic radiation resulting from polarization currents produced in, or at the boundary of, a medium in close proximity of a charged particle beam. To increase the resolution of DR, measurements were performed in the UV range at a wavelength of 250 nm. With such configurations, sensitivity to the beam size of a 1.2 GeV electron beam below 10 μm was observed at the Accelerator Test Facility (ATF) at KEK, Japan. In the case of the ChDR, a proof of principle study was carried out at the Cornell Electron Storage Ring (CESR) where beam profiles were measured in 2017 on a 5.3 GeV positron beam. At the time of writing an experiment to measure the resolution limit of ChDR has been launched at ATF where smaller beam sizes are available. We will present experimental results and discuss the application of such techniques for future accelerators.

INTRODUCTION

Non-invasive beam profile measurement techniques offer the advantage of providing beam size information without inserting an object in the beam path, as is required in more traditional methods such as profile measurement using wire scanners, Optical Transition Radiation (OTR) or scintillation screens. There are two main reasons for choosing such methods: being capable of measuring high intensity beams that would destroy any interceptive devices and avoiding any blow-up in emittance due to the interaction of the particles with material. Non interceptive methods can therefore allow a continuous monitoring of the transverse beam size during machine operation. This is the case of the proposed Compact Linear Collider (CLIC), where charge densities up to 10^8 nC/cm^2 can be reached in the main beam [1], a value that is approximately 100 times higher than the damage limit of the best thermal resistant materials such as Be or SiC.

We report here on the status of two projects that aim at studying Diffraction radiation (DR) and Cherenkov Diffraction Radiation (ChDR) as candidates for non-invasive beam profile measurement techniques. In DR, beam size information is obtained through the analysis of the far-field angular distribution of light produced when the beam passes through a narrow slit in a metallic screen [2]. In ChDR, light is produced at the boundary of a dielectric material (eg: fused silica) close to the beam path. Notwithstanding the differences in terms of geometry and properties of the emitted radiation, DR and ChDR are based on a similar physical mechanism, that of emission by polarisation currents induced at the surface of a medium [3] by the electromagnetic field of a relativistic particle. This electromagnetic field can be considered as quasi-transverse one, with an effective field radius given by

$$l = \gamma\lambda/2\pi \qquad (1)$$

where γ is the Lorentz factor and λ the wavelength of observation. As a consequence, measurement methods based on DR / ChDR work when the impact parameter h of the target (the half aperture of a slit in the case of DR, the distance between beam path and crystal edge for ChDR) satisfies the condition $h \le l$. If we consider the visible spectrum (e. g. $\lambda = 500$ nm) and relativistic electrons at 1 GeV ($\gamma \cong 2000$), we will obtain an appreciable DR/ChDR emission for $h \le 160$ μm, a condition that can be attained and controlled experimentally.

While DR is a more established technique, the first proposal using it for beam diagnostics dating back to 1998 [4], ChDR can still be considered to be at a proof of concept stage. We will therefore report on these two separately throughout this paper.

STATUS OF DR EXPERIMENT AT ATF2

A DR setup was installed in 2016 in the extraction line of the Accelerator Test Facility 2 (ATF2) in KEK. A description of the instrument and target can be found in [5]. In the course of 2017, the instrument has been upgraded to its final configuration (see Fig. 1).

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† email: stefano.mazzoni@cern.ch

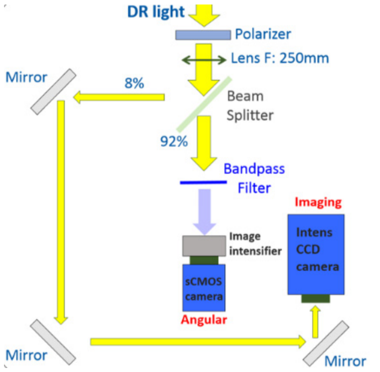

Figure 1: Sketch of the DR setup at ATF2.

DR is produced when the beam passes through a slit with a vertical aperture ranging from 50 to 200 μm and is emitted in the direction of the extraction viewport at an angle of 40º with respect to the beam. After passing through a motorised polariser positioned just outside the extraction viewport, DR is split into two separate optical lines. The “imaging” line creates a 1:3.6 magnified image of the slit onto a gated intensified camera (pco DICAM Pro with GaAs photocathode) which is used for monitoring and alignment purposes. This line is also used to check the position and shape of the beam on an OTR screen and to ensure that the beam is properly centred in the DR slit. The “Angular” line records the far-field DR signal. Far-field conditions are achieved by placing the sensor (a pco Edge 4.2 LT sCMOS coupled to a Hamamatsu C9547 gated image intensifier unit) at the back focal plane of a 2” diameter, 250 mm focus plano-convex lens (LA4538 from Thorlabs). A filter wheel equipped with bandpass filters is positioned between the lens and intensified camera, hosting visible (400 ± 10 nm ,400 ±- 40 nm, 600 ± 40 nm) and UV (250 ± 40, 230 ± 10) bandpass filters. The intensified camera is mounted on a motorised stage to compensate for the variation of back focal length as a function of the wavelength of observation.

Beam size measurement using DR is based on the correlation between the visibility (defined as $V = I_{min}/I_{max}$) of the projected vertical polarisation component (PVPC) of the angular distribution of intensity of DR with the transverse beam profile [6]. In the left hand side of Fig. 2 we show the vertically polarised signal with the characteristic main lobes and side fringes typical of DR. The PVPC is obtained by integrating the image between the two vertical red lines. The result, plotted on the right side of Fig.2, shows the I_{min} and I_{max} used to calculate the visibility. As the intensity of the peaks is not equal, I_{max} is calculated as the average value of the two main peaks.

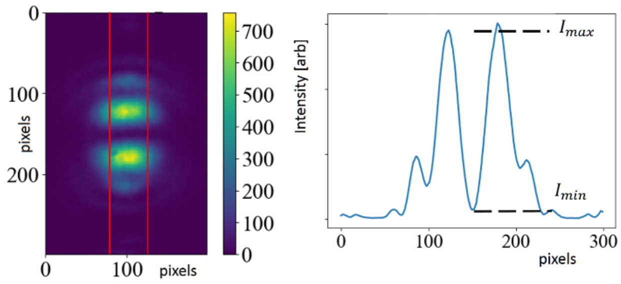

Figure 2: Vertically polarised DR pattern at 400 ± 40 nm (left) and corresponding PVPC (right).

With the present setup we took data at ATF2 during shifts in November 2017 and February 2018. In order to improve the resolution, measurements were performed in the UV range at 250 nm. Figure 3 shows the PVPC visibility of DR acquired with a slit width of 49.7 μm. A 100.0 μm wide mask was used to cut out the synchrotron radiation contribution. The expected vertical beam size (σ) measured with the imaging line and an OTR screen placed at the same position of the slit is 5 μm.

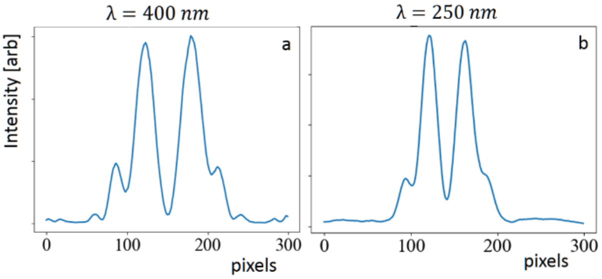

Figure 3: PVPC at 400 nm (a) and at 250 nm (b) using a 49.7 μm slit for a transverse beam size of 5 μm

It can be seen that the signal at 250 nm has a larger visibility, with $V_{250} = 0.145 \pm 0.013$ (statistical) and $V_{400} = 0.05 \pm 0.013$. The latter is close to the noise floor, with I_{min} is basically at the same level of the image background. DR at 400 nm is therefore not sensitive to such small beam sizes, as a change of beam size will not produce a change in visibility. This is not the case for 250 nm, where a non-zero visibility is observed for a beam size below 10 μm [7].

STATUS OF CHDR STUDIES

The first observation of incoherent ChDR was performed at CESR with a 5.3 GeV positron bunch of up to 2.5 nC, corresponding to a circulating beam current of 1 mA [8], in an experiment aimed at measuring the light yield in the visible range as a function of the impact parameter defined in eq. 1. The radiator used is a triangular prism made of high purity fused silica (see Fig. 4) mounted on a rotation stage to keep it parallel to the beam path so as to have a constant value of the impact parameter along its length. The side facing the beam is 2 cm long.

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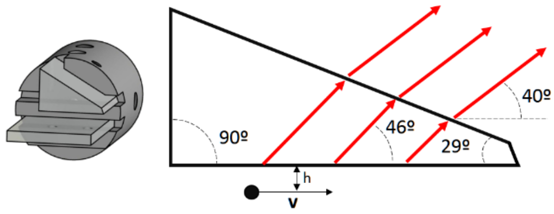

Figure 4: Section of the fused silica prism used in the ChDR setup at CESR.

The target was designed to send the ChDR to an optical system composed of a polariser, a bandpass filter at 600 ± 10 nm and a 500 mm plano-convex lens. This forms the image of the radiator face (beam side) onto a Proxivision proxikit gated intensifier with multialkali photocathode coupled to an AVT Manta 145G CCD camera.

The total absolute photon yield of ChDR has been measured as a function of the impact parameter [8]. As expected from polarization radiation theory, the light intensity increases exponentially for smaller impact parameters. At $h = 1$ mm, the yield produced by the 2 cm-long radiator at a wavelength of 600 +/- 10 nm corresponds to 0.8×10^{-3} photons per turn per particle, which is in good agreement with theoretical predictions [8]. This would bring the photon intensity radiated in the entire wavelength range of 200–2000 nm to 0.1 photon per turn per particle for the same impact parameter. This number is comparable to the light intensity generated by backward transition radiation and exceeds, by at least one order of magnitude, the light intensity emitted by DR from a conducting slit of similar aperture. This relatively large yield coupled to the non-invasive nature of ChDR opens the possibility of its use as a beam profile or position monitor.

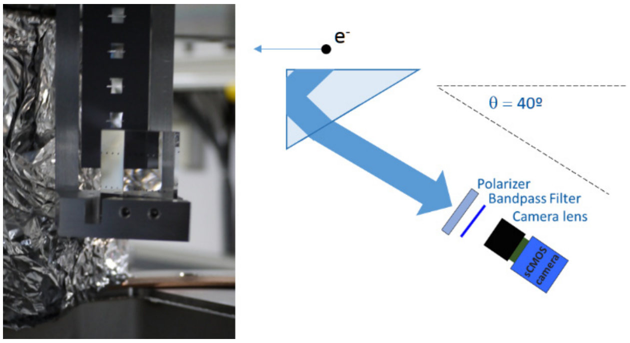

Figure 5: The ChDR prism radiator as seen from the camera (left) and a sketch of the setup (right).

With this motivation, in May 2018 the DR setup at ATF2 described in the previous section was modified to perform ChDR measurement. The extremely small, sub-micron [9] beam size that can be achieved at ATF2 is ideal to measure the ultimate resolution of ChDR and to compare it with predictions from ongoing theoretical work. The modification at ATF2 involved adding a fused silica triangular prism similar to the one of Fig. 4 at the bottom of the DR slit holder (see Fig 5). The target shape is such that ChDR is sent through a viewport positioned at 40° with respect to the beam path. The ChDR then goes through a polariser and a bandpass filter before being recorded with the DR sCMOS camera described in the previous section with a 2x extended hyperspectral 60 mm macro lens from Jenoptik.

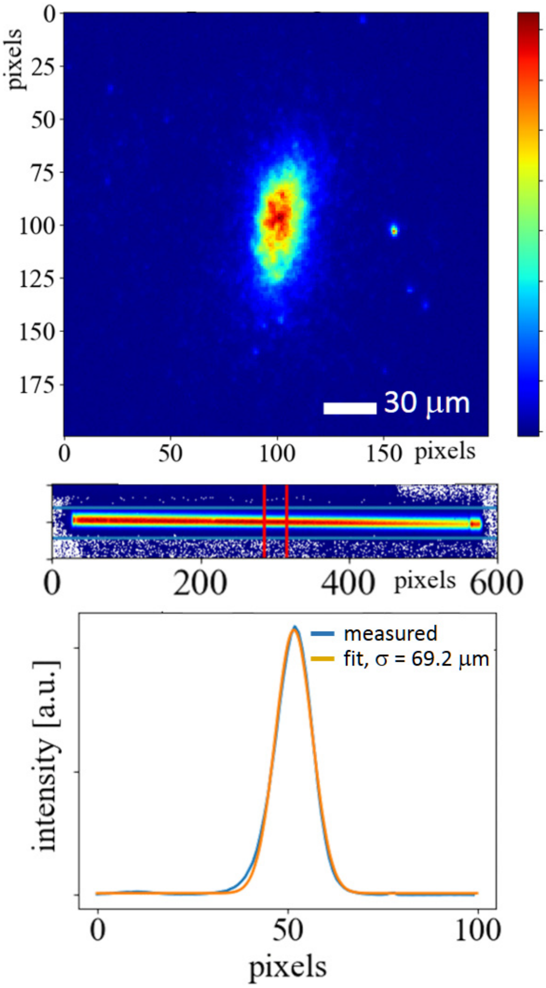

Figure 6: Preliminary ChDR beam size measurements: OTR beam profile (top), ChDR radiator image (middle), vertical beam profile (bottom).

With this setup, the vertical transverse beam profile was capable of being measured using the ChDR signal. The beam was configured to have the smallest possible horizontal beam size, of the order of a few tens of micrometres. Such a configuration allows the impact parameter to be defined with minimum uncertainty, as the transverse size of the beam is small compared with its average distance from the target edge. This means that the results can be better compared with theoretical predictions for photon yield and the ChDR intensity profile at the target surface.

. In our case, at the minimum impact parameter $h_{min} \cong$ 250 µm, we obtain a maximum uncertainty of 12 % (σ). When the instrument is properly aligned and set-up, the vertical polarisation component of the ChDR beam is clearly visible across the side of the crystal facing the beam (see centre image of Figure 6). It can be seen that the width of the ChDR signal has a slight dependence on the transverse position across the target.

This is due to a combination of factors that are currently still under investigation, including a residual angle between the crystal face and the beam trajectory, the depth of field of the imaging system and possible off-axis aberrations of the optical systems. From the analysis of the central part of the crystal (between the two vertical red lines in the central image of Figure 6) a vertical beam profile with $\sigma = 69.2$ μm is measured. This is in good agreement with an OTR based measurement performed under the same beam conditions, which gave an rms beam profile of 67.22 ± 1.36 μm. While a detailed analysis of the results is still ongoing, this preliminary result already shows that the ChDR technique is capable of measuring beams as small as 70 μm.

CONCLUSIONS

An overview of recent results with non-invasive transverse beam profile measurement techniques based on DR and ChDR has been presented. In the case of DR, sensitivity to below 10 μm (σ) beam has been demonstrated when observing in the UV regime below 250 μm. Notwithstanding this remarkable performance, DR still requires some effort in the measurement preparation (centering of the beam in the target slit) and data analysis. In addition, DR is quite sensitive to parasitic light (typically synchrotron radiation) that can affect the visibility. For these reasons, additional studies should be dedicated to the optimisation of DR for operational use.

The application of ChDR to beam size measurement is a very recent idea, with this paper presenting the very first results on small < 100 μm beam. 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 when compared to DR. Being a recent technique, ChDR still requires a number of studies to understand its theoretical resolution limit and any additional experimental or instrumental factors that might limit it. To this purpose, the instrument currently installed at ATF2 will be modified for future high resolution studies with micron sized beams

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