ISBN: 978-3-95450-236-3 ISSN: 2673-5350 doi:10.18429/JACoW-IBIC2023-MOP032

ONE DIMENSIONAL BEAM POSITION MONITOR PROTOTYPE USING INCOHERENT CHERENKOV DIFFRACTION RADIATION

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Abstract

This paper proposes a novel advancement in both the studies of Cherenkov diffraction radiation (ChDR) and beam instrumentation. The proposed beam position monitor (BPM) consists of two identical fused Silica prism radiators, with a fibre collimator attached to each one, which in turn are connected to a photodetector via a series of optical fibres. The setup will be implemented into the booster to storage ring transfer line at Diamond Light Source - an electron light source with 3 GeV beam energy. The prototype proposed aims to test the feasibility of a full BPM utilising ChDR. If proven to be fully realisable, optical rather than capacitive BPM pickups could be more widely distributed. The paper will include the complete design and preliminary results of a one-dimensional BPM, utilising the ChDR effect.

INTRODUCTION

Cherenkov radiation (CR) is the emission of electromagnetic radiation when a charged particle travels through a dielectric medium with a speed greater than that of light in that medium. Observed in 1934 by Cherenkov [1], it has since been expanded upon both theoretically and experimentally. Cherenkov radiation is emitted at a well defined angle denoted the Cherenkov angle θ, given by

$$\cos\theta = \frac{1}{\beta n} \tag{1}$$

where $\beta = v/c$ is the ratio of the charged particle velocity v to the speed of light c, and n is the refractive index of the medium the charged particle particle is travelling through [1]. The emission and directionality of Cherenkov radiation enables this phenomena to be a useful tool in many fields ranging from astrophysics [2] to radiotherapy [3].

The theory of CR has been expanded to account for the situation where the incident relativistic particle is instead travelling close by a medium acting in a manner similar to classical diffraction radiation [4] called Cherenkov Diffraction Radiation [5]. In addition to particle energy and the refractive index of the medium, ChDR is dependent on the impact parameter b which represents the distance between the incident charged particle and the medium. ChDR is produced by a hyper-relativistic particle travelling close to a medium, rather than through it, and given that ChDR is emitted at the well defined Cherenkov angle it is well suited for accelerator diagnostic applications where a non-invasive technique is of paramount importance.

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The intensity of light emitted increases the closer the particle is to the medium, as such it is necessary to ensure that the incident particle is within the condition

$$b \leq \gamma\lambda \tag{2}$$

where γ refers to the Lorentz factor of the incident particle and λ refers to the wavelength of emitted radiation. The quantity $\gamma\lambda$ refers to the effective electron field radius [6].

For optical wavelengths and an electron beam energy of 3 GeV b is $\leq$ 3 mm. ChDR has been investigated experimentally and had its applicability to diagnostics examined [7, 8].

BTS TEST STAND

The experiment is located on the Booster To Storage (BTS) transfer line at Diamond Light Source (DLS). The test stand consists of a six-way cross vacuum chamber with a four-dimensional manipulator system which allows for the insertion and removal of experiments. Vertical translation and rotation of the manipulator are automated. It was previously used for another ChDR experiment [9], which tested feasibility of beam position measurements and fundamental ChDR properties.

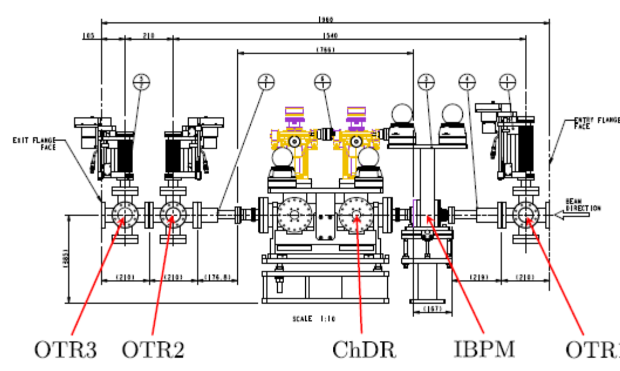

Figure 1: Schematic of BTS test stand.

Figure 1 shows a schematic of the vacuum vessel string on the BTS test stand consisting of three combined Optical Transition Radiation (OTR) and Yttrium Aluminium Garnet (YAG) monitors, and one Inductive Beam Position Monitor (IBPM) developed at CERN [10]. These diagnostic tools are used as references for the beam profile and trajectory through the BTS test stand when taking data with the ChDR BPM. The IBPM provides a reference beam position measurement, which the results from the ChDR BPM are compared against. The first OTR screen is used to measure

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the input beam profile and from this the input beam size into the BTS test stand. OTR2 (see Fig. 1) is used to check alignment of the ChDR BPM assembly with respect to the beam path. Shadowing of the beam profile on this screen indicates that the beam is in contact with the assembly and that correct horizontal/rotational alignment is not achieved. YAG screens have a higher photon yield allowing for beam shadowing to be easier to identify, whereas OTR screens provide better spatial resolution for beam size measurement.

The DLS storage ring has a vacuum rating of 10^{-10} mbar, the BTS transfer line is targeted at Ultra High Vacuum (UHV), therefore the ChDR BPM assembly must also be UHV compatible.

CHDR BPM DESIGN

The 1D ChDR BPM design utilises two pick-ups consisting of identical prisms positioned either side of the electron beam to produce horizontal beam position measurements using ChDR. The intensity of the emitted signal relies on the impact parameter, which from theory displays an exponential decay with increasing impact parameter. For the case of DLS using ChDR emitted at visible wavelengths, the impact parameter should be less than 3 mm. This means that if the beam moves out of this range, the detected signal will be within the noise, providing no useful information on current beam position. Therefore the ChDR BPM pick-ups should have a separation $\leq$ 3 mm to ensure that simultaneous signals from the two pick-ups can be detected.

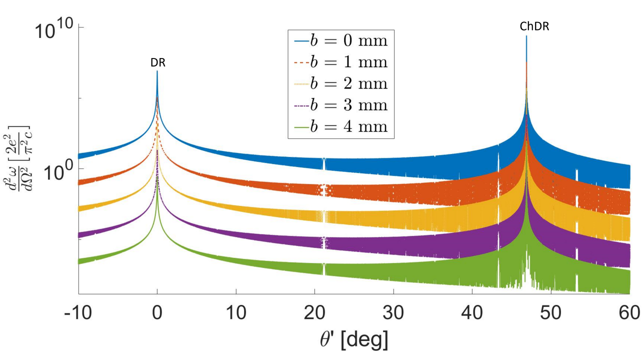

Figure 2: Intensity curve for the fused silica prism, showing the diffraction radiation (DR) peak centered at zero and the ChDR peak centered at the Cherenkov angle.

The ChDR BPM has an adjustable separation to allow for flexibility in measurements. The ChDR output signal intensity was calculated using the single target intensity equation from [11] and is shown in Fig 2. The emitted ChDR signal from one of the pick-ups will be at a maximum when the impact parameter between the electron beam and that pick-up is zero. The minimum separation between two pick-ups should be such that when the electron beam is in the centre of both pick-ups and has an equal impact parameter with both, the emitted ChDR signal is at 1% of the maximum value. This minimum separation was found by creating an

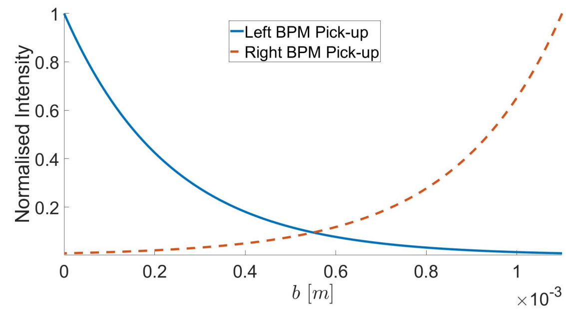

Figure 3: Graph showing the decay of two identical pick-ups either side of a beam with a separation of 1.1 mm.

intensity decay curve, shown in Fig. 3, for the two pick-ups using the results from Fig. 2.

The decay curve in Fig. 3 found that the desired minimum pick-up separation is at 1.1 mm. The separation between the two pick-ups can be increased up to 6.1 mm through the use of spacers. This maximum separation corresponds to an impact parameter of $2\gamma\lambda$ for 500 nm emission or $\gamma\lambda$ for 1000 nm emission.

To couple the ChDR light out from the prisms to optical fibres, collimators are used. To maximise the collected signal, the collimator lenses have been angled such that they are parallel to the output face of the prisms and are positioned by the assembly in close proximity. Figure 4 shows a 3D rendering of the BPM assembly.

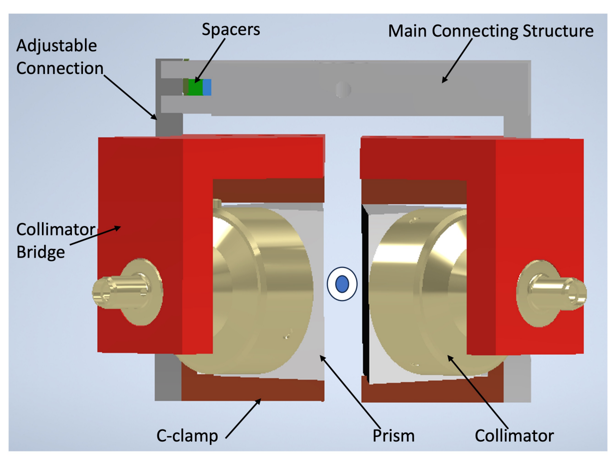

Figure 4: Autodesk inventor 3D rendering of the BPM assembly. Colours are used to differentiate the components: silver is used to denote the prisms; the two collimators are in gold; the C-clamps are in dark orange; collimator bridges are in red; the adjustable connection is in dark grey; the main connecting structure in the light grey and; the spacers in the green and blue.

The assembly itself is made of stainless steel with stainless steel screws. All screw holes are either through or have had a small hole drilled to ensure no cavities are formed to ensure the assembly is UHV compatible. The C-clamps feature a step angled at the Cherenkov angle, this aligns the target to

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ensure the generation face of the prism is flush with clamp and is not angled with respect to the electron beam trajectory.

The main structure is connected to the central actuator, which allows for the assembly to be lowered into the beam path when conducting ChDR experiments. For user beam operation of the storage ring the assembly is retracted beyond the nominal beam pipe diameter to ensure the presence of the assembly does not impact beam injection to the storage ring (see Fig. 5).

Figure 5: 3D rendering of the assembly in its retracted position inside the vacuum chamber from an upstream view.

The generated ChDR light is coupled from UHV compatible fibres inside the vacuum chamber to an external detector via a UHV-to-air fibre feedthrough. The detector is an amplified photodiode with a direct fibre input. The detector has a short rise time of 1 ns and a wide spectral range of 400 – 1000 nm which is ideal for ChDR experiments as it allows for a wide range of experiments to be explored.

PRISM DESIGN

Each ChDR pick-up utilises a prismatic radiator as shown in Fig. 6. The prism is made of UV grade fused Silica. Prisms have been optimised for 500 nm ChDR emission by setting the angle of the output face at 43.2° with respect to the electron beam path, to ensure that light emitted at this wavelength has an outgoing wavefront parallel to this interface. The upstream face is angled at the Cherenkov angle for 500 nm at 46.8° such that all light at this wavelength travels to the output face without encountering any reflections. To reduce signal interference from synchrotron radiation inside the beam pipe, the upstream face and the two triangular faces are coated in a 0.5 µm layer of aluminium.

The vertical size of the target with respect to the electron beam path is 32 mm. To match current theory [11], the vertical size is required to be an order of magnitude larger than the electric field radius $\gamma\lambda$ to ensure that the target appears to be infinitely tall compared to the electric field. This predicts that the intensity decay due to increase in impact parameter, will match that seen in Fig. 3.

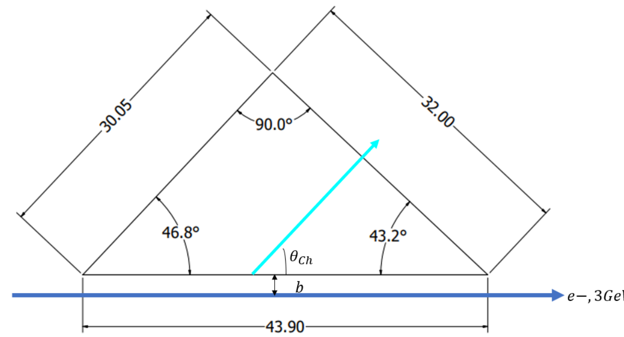

Figure 6: Prismatic Radiator.

CHARACTERISATION OF THE CHDR PICK-UP

To allow for an an accurate measurement of ChDR emission power, all components have been bench tested with a 638 nm laser and a power meter. Starting from the prisms the laser was directed through the the component and then focused into the power meter to accurately measure the power loss through that particular component. Each component was tested individually and the assembly was gradually built up such that the power loss through each section was accurately determined. The two most significant points of power loss were the 0.5 m long UHV fibre and the 2 m long in-air fibre.

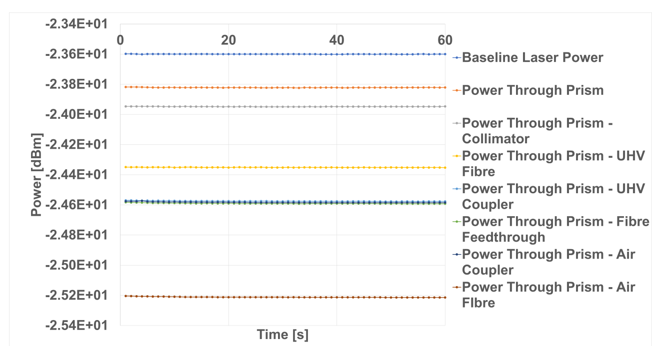

Figure 7: Power loss results of the components inserted into the BTS chamber.

As Fig. 7 shows the overall signal loss through the system is 1.6 dB, which corresponds to a percentage decrease of ~ 30.8%.

PRELIMINARY RESULTS USING ONE CHDR PICK-UP

For initial testing of the assembly, only one pick-up is installed (see Fig. 8). This allows for fundamental measure-

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ments to be undertaken which will then better optimise the insertion of the full two-pick-up BPM. A one pick-up system is far easier to properly align with respect to the electron beam. The initial shifts consisted of finding the correct vertical and rotational positions for the ChDR BPM assembly with respect to the electron beam path.

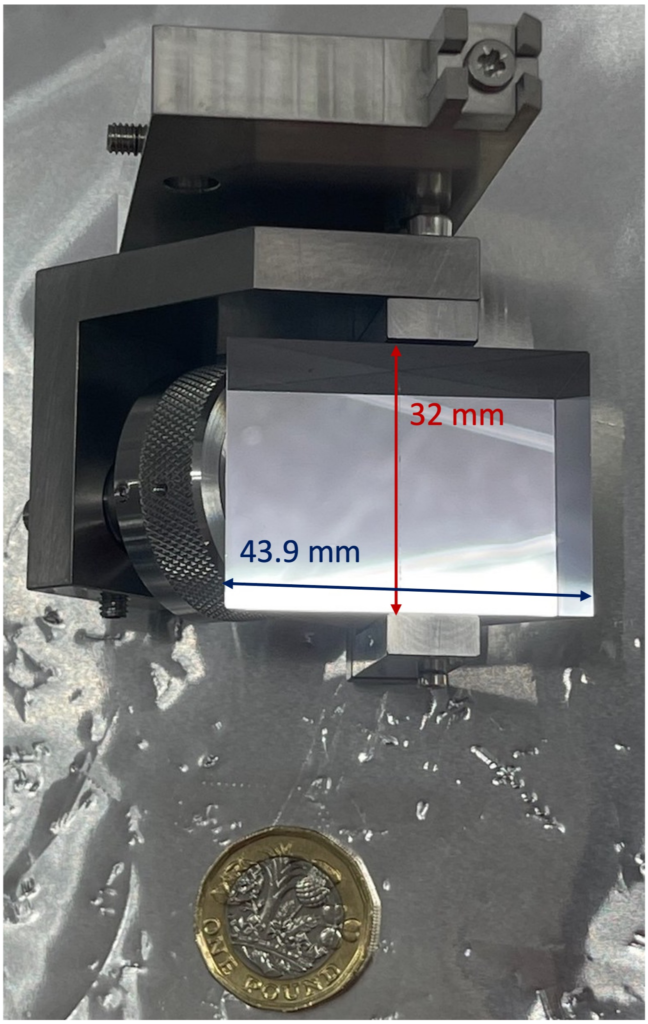

Figure 8: Image of one pick-up ChDR BPM assembly from an angle perpendicular to expected beam path, with a £1 coin for scale.

Initial commissioning of the one pick-up ChDR BPM assembly is underway. Figure 9 shows the beam profile on the YAG screen located at OTR2 (see Fig. 1) shadowed from the ChDR pick-up. This confirms that the beam can be moved sufficiently such that an impact parameter of zero between the electron beam and the ChDR pick-up can be achieved.

Figure 10 shows the output signal given by the interaction between the electron beam and the ChDR pick-up in Fig 9. The shadowing of the electron beam means that the signal from the ChDR detector will be a combination of CR and ChDR. This confirms that radiation emitted at the Cherenkov angle is successfully captured and transmitted through the BPM assembly.

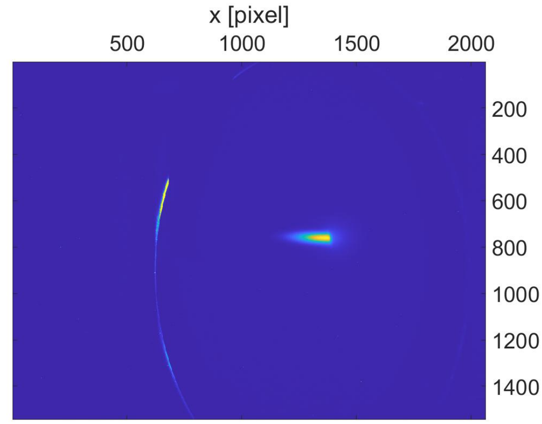

Figure 9: YAG image showing clear shadowing of the beam profile due to ChDR assembly.

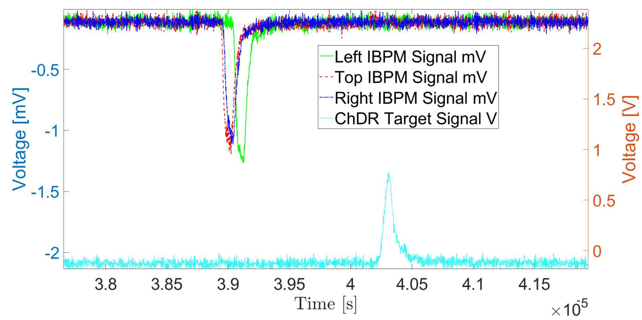

Figure 10: Oscilloscope signal showing the three IBPM signals and the ChDR signal. Voltage divisions of: 50 mV and 0.5 V for the IBPM and ChDR signals respectively.

CONCLUSION

A 1D BPM utilising incoherent ChDR has been designed and characterised in the lab. The assembly has been installed with one pick-up in place on the BTS transfer line at DLS. Initial commissioning tests have been performed and first signals have been detected.

ACKNOWLEDGMENTS

The authors would like to thank the efforts of the engineers from Royal Holloway University of London for creating the stainless-steel assembly and the help of the DLS vacuum group with installing the ChDR assembly into the BTS transfer line.

REFERENCES

[1] P. A. Čerenkov, "Visible Radiation Produced by Electrons Moving in a Medium with Velocities Exceeding that of Light", *Phys. Rev.*, vol. 52, no. 4, pp. 378–379, Aug. 1937. doi:10.1103/physrev.52.378

[2] T. Kajita, "Discovery of atmospheric neutrino oscillations**", *Ann. Phys.*, vol. 528, no. 6, pp. 459–468, May 2016. doi:10.1002/andp.201600086

ISBN: 978-3-95450-236-3 ISSN: 2673-5350 doi:10.18429/JACoW-IBIC2023-MOP032

[3] D. A. Alexander, A. Nomezine, L. A. Jarvis, D. J. Gladstone, B. W. Pogue, and P. Bruza, "Color Cherenkov imaging of clinical radiation therapy", *Light Sci. Appl.*, vol. 10, no. 1, Nov. 2021. doi:10.1038/s41377-021-00660-0

[4] H. K. Avetissian, G. F. Mkrtchian, M. G. Poghosyan, and K. V. Sedrakian, "Coherent diffraction radiation diagnostics for charged particle beams", *Nucl. Instrum. Methods Phys. Res.*, vol. 528, no. 1–2, pp. 215–219, Aug. 2004. doi:10.1016/j.nima.2004.04.050

[5] A. Savchenko, A. Tiishchenko, and M. Strikhanov, "THz Cherenkov Diffraction Radiation From A Traingular Prism", 11th Int. Symposium (RREPS'15), St Petersburg, Russia, Sept. 2015. https://earchive.tpu.ru/bitstream/11683/22369/1/conference_tpu-2015-C64-C64.pdf#page=110

[6] I. M. Frank, "Coherent Radiation of the Fast Electron in Medium", USSR, 1971. https://www.osti.gov/biblio/4742626

[7] T. Lefevre *et al.*, "Non-invasive Beam Diagnostics with Cherenkov Diffraction Radiation", in *Proc. IPAC'18*, Vancouver, Canada, Apr.-May 2018, pp. 2005–2008. doi:10.18429/JACoW-IPAC2018-WEPAF074

[8] A. Curcio *et al.*, "Noninvasive bunch length measurements exploiting Cherenkov diffraction radiation", *Phys. Rev. Accel. Beams*, vol. 23, no. 2, Feb. 2020. doi:10.1103/physrevaccelbeams.23.022802

[9] D. M. Harryman *et al.*, "First Measurements of Cherenkov-Diffraction Radiation at Diamond Light Source", in *Proc. IBIC'19*, Malmö, Sweden, Sep. 2019, pp. 624–628. doi:10.18429/JACoW-IBIC2019-WEPP037

[10] J. J. G. Garrigos, "Development of the Beam Position Monitors for the Diagnostics of the Test Beam Line in the CTF3 at CERN", PhD Thesis, University of Valencia, 2013.

[11] M. Shevelev and A. S. Konkov, "Peculiarities of the generation of Vavilov-Cherenkov radiation induced by a charged particle moving past a dielectric target", *J. Exp. Theor. Phys.*, vol. 118, no. 4, pp. 501–511, Apr. 2014. doi:10.1134/s1063776114030182