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FIRST MEASUREMENTS OF CHERENKOV-DIFFRACTION RADIATION AT DIAMOND LIGHT SOURCE

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Abstract

Cherenkov-Diffraction Radiation (ChDR), appearing when a charged particle moves in the vicinity of a dielectric medium with speed faster than the speed of light inside the medium, is a phenomenon that can be exploited for a range of non-invasive beam diagnostics. By using dielectric radiators that emit photons when in proximity to charged particle beams, one can design devices to measure beam properties such as position, direction and size. The Booster To Storage-ring (BTS) test stand at Diamond Light Source provides a 3 GeV electron beam for diagnostics research. A new vessel string has been installed to allow the BTS test stand to be used to study ChDR diagnostics applicable for both hadron and electron accelerators. This paper will discuss the commissioning of the BTS test stand, as well as exploring the initial results obtained from the ChDR monitor.

INTRODUCTION

Diamond Light Source is a 3rd generation synchrotron light source storage ring facility in the U.K [1]. Recently the conceptual design report was published for the 4th generation upgrade to Diamond-II [1]. Such an upgrade would feature a Multi-Bend Achromat (MBA) lattice, requiring more dipole magnets with lower magnetic field strength. This creates new straight sections for more insertion devices to be installed, and also reduces the horizontal emittance as

$$\epsilon_x \propto \frac{1}{N^3_{\mathrm{Bending}}} \quad (1)$$

where ϵ_x is the horizontal emittance, and N_{Bending} is the number of dipole magnets [1]. From a diagnostics perspective, one drawback of such a design is that the shallower bends provided by the dipole magnets reduce the space available for synchrotron radiation extraction.

For ultra-low emittance rings, monitoring the beam position inside the dipole could be advantageous. Previous results have shown that Cherenkov Diffraction Radiation (ChDR) offers the ability to design non-invasive optical diagnostics that could be used for monitoring a variety of beam parameters, such as; position, size, and bunch length [2–5].

As part of the ChDR collaboration, research is being undertaken at Diamond into the feasibility of using a ChDR radiator as an optical Beam Position Monitor (BPM) pickup. These investigations could lead to an optical BPM design to be used on Diamond-II.

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BEAM TEST STAND

The Diamond accelerator chain has three accelerators: a linac, a booster synchrotron, and a storage-ring [1]. On the Booster to Storage-ring (BTS) transfer line is a test stand that is used for beam diagnostics research [6]. Figure 1 shows the vacuum vessel string recently installed on the BTS test stand, this features: three Optical Transition Radiation (OTR) monitors, an Inductive Beam Position Monitor (IBPM) [7], and a ChDR monitor. The OTR monitors and IBPM are used for cross referencing the results from the ChDR monitor. The IBPM is used for beam position and charge measurements [7], whereas the OTR monitors are used to obtain the size and position of the beam. By monitoring OTR monitors upstream and downstream of the ChDR radiator, the trajectory through the test stand, and the beam's distance from the radiator can be found.

Nominal beam parameters in the BTS test stand will set the booster to extract 3 GeV electrons in a train of 120 bunches at a rate of 5 Hz. These have approximately 0.2 nC of charge per train, and a bunch spacing of 2 ns. The transverse beam size in the test stand has a Gaussian distribution with a σ_x of 1.4 mm and a σ_y of 0.5 mm.

The beam parameters of the BTS test stand can be changed to enable a variety of experimental studies. For example, the transverse beam position can be changed, and a horizontal or vertical waist can be introduced onto the beam and moved along the test stand. The beam can also be extracted in either a multi-bunch train, or a single bunch train. The charge can be varied up to 1.3 nC for a multi-bunch train, or 0.3 nC for a single bunch.

THEORY

ChDR is a type of radiation emitted from a dielectric when a highly relativistic charged particle moves in the vicinity of the dielectric at a speed faster than the speed of light through that medium [8]. This happens due to the effect of the charged particles external field producing a polarisation effect on the material [9]. As with Cherenkov radiation, ChDR is emitted at the angle Θ_{Ch}, given by

$$\cos(\Theta_{Ch}) = \frac{1}{n\beta} \quad (2)$$

where n is the refractive index for the dielectric medium, and β is the particles velocity relative to the speed of light [8]. As the charged particle is not moving through the material, the distance between the charged particle and the dielectric, known as the impact parameter, h, must be considered [8].

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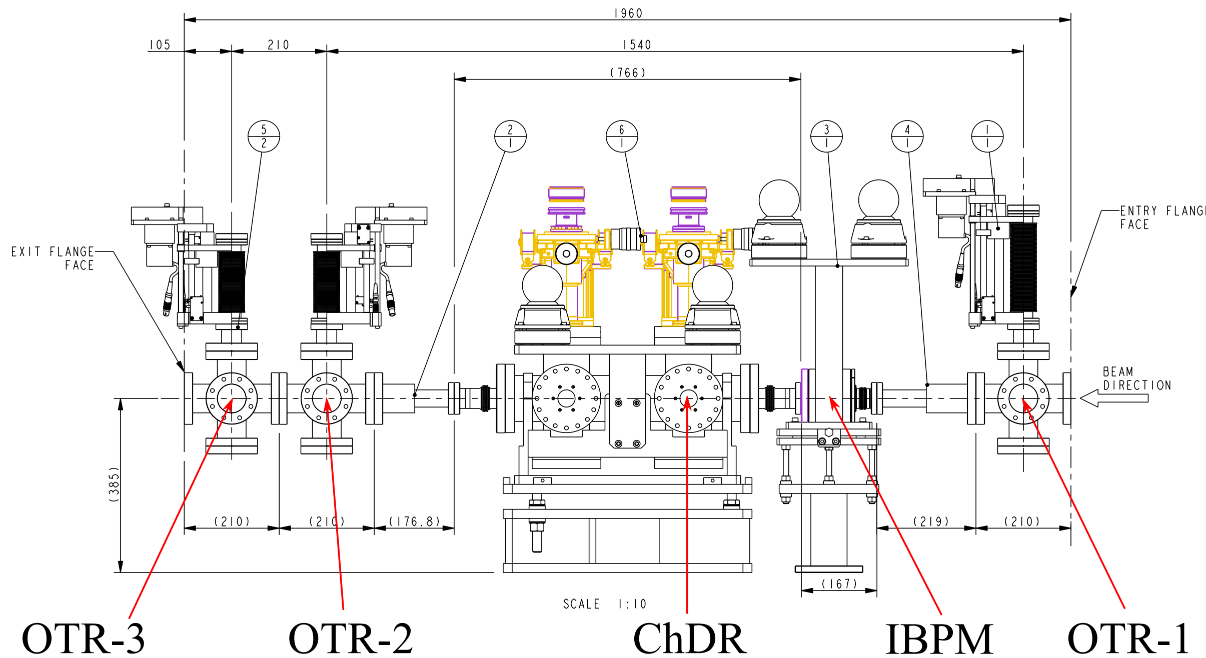

Figure 1: Vessel string of the Diamond BTS Test-Stand With Monitor Locations, Courtesy of A. Day.

The number of photons produced with ChDR, is less than that of Cherenkov radiation, though for any given wavelength the number of photons produced by ChDR, becomes comparable if the condition

$$h \leq \frac{\gamma\lambda}{2\pi} \tag{3}$$

is met, where γ is the Lorentz factor, and λ is the wavelength [10].

Due to the Gaussian profile of the beam and the possibility of beam halo, some charged particles will go directly through the radiator generating Cherenkov radiation, especially for small impact parameters. When measuring in the incoherent range this poses the issue of separating the light generated from ChDR, and Cherenkov radiation [2].

EXPERIMENTAL SETUP

Figure 2 shows the radiator geometry used for the experiments at Diamond. The radiator is constructed from poly crystalline diamond. One side of the radiator is positioned parallel to the electron beam trajectory, the intensity of the photons generated then scales proportionally with the length of this side, l [11]. ChDR is generated inside the radiator at the angle Θ_{Ch}, and internally reflected until the photons reach a reflective aluminium strip at the downstream end. The angle of the cut at the downstream end of the radiator is specified so that the photons will leave the target at 90° to the electron beam where it can be detected by an appropriate optical detection system. The emission angle of the photons is distinctly different to that of synchrotron radiation allowing for them to be separated [2].

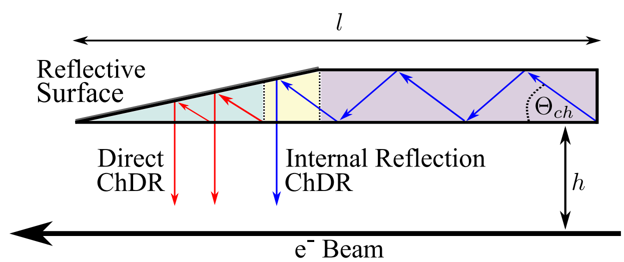

Figure 2: Diagram of ChDR generation inside the radiator.

Figure 3 shows a model of the ChDR radiator holder fitted with two ChDR radiators and an OTR screen. For the experiments at Diamond, only the far-side radiator and the OTR screen is installed. The target holder is mounted to two motor systems; translation in/out of the electron beam, and rotation.

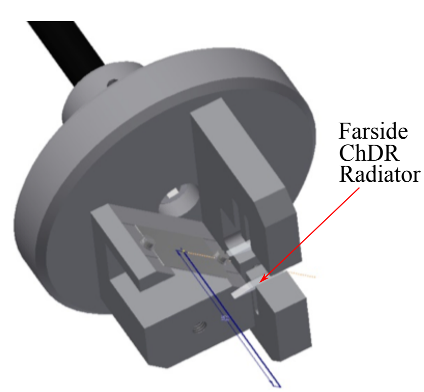

Figure 3: Dual ChDR and OTR target holder.

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The optical system is used to image the ChDR radiator (see Fig. 4). The entire system is mounted on an optical breadboard that can be moved laterally using a remote-controlled stage. Also on the optical axis are two mirror boxes to direct the light down from the viewport, and a filter wheel. The filter wheel is loaded with bandpass filters (400 ± 40 nm, 550 ± 40 nm) for monochromatic studies.

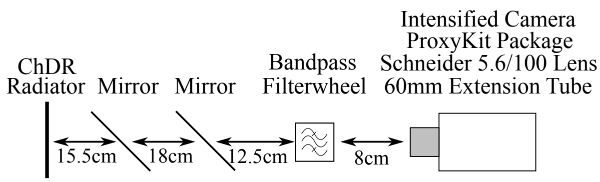

Figure 4: Optical imaging system.

The camera is a gated intensified ProxyVision ProxyKit Package [12]. This consists of an Allied Vision Manta G145-B, a fibre taper, and a Micro Channel Plate. Together these components form a highly sensitive imaging system that can gate around events as short as 100 ns [12]. The gain, exposure and triggering settings can be independently varied on the Manta G145-B and the intensifier, all of which can be set remotely. Mounted to the camera is a Schneider 5.6/100 lens with a 60 mm extension tube, this gives the ChDR imaging system a magnification of approximately 0.2.

COMMISSIONING

BTS Test-Stand Diagnostics

Initial testing was required to commission the new BTS vessel string including the OTR monitors and the IBPM. While the OTR monitors performed well under all tested beam conditions, when extracting in multi-bunch mode the Signal to Noise Ratio (SNR) on the IBPM was too low. By changing the accelerator to extract in single bunch mode, the SNR was increased dramatically allowing for the measurements on bunches with ≃ 0.025 nC of charge.

Initially, all the monitors were connected to the same TTL rising edge trigger, and set to acquire data for set beam conditions. The data acquired was then averaged over different accelerator shots. To improve this a single TTL rising edge can now be sent to the BTS test stand, and data from all diagnostics recorded before the next rising edge is allowed to fire. Data can now be reliably compared between the different monitors on a shot by shot basis.

Cherenkov Diffraction Radiation Monitor

In order to test the use of a ChDR radiator as a BPM pickup, the impact parameter, h, must be well characterised. By bumping the beam horizontally towards the ChDR target holder, the shadow of the holder could be seen on the downstream OTR-2 (see Fig. 1). Knowledge of the shadow location on OTR-2, the beam centroid measured on OTR-1, and the target holder geometry, was then used to define a beam trajectory with respect to the ChDR radiator. Using this trajectory, the impact parameter can be calculated for any trajectory given data from OTR-1 and OTR-2.

Figure 5 shows an image recorded from the ChDR system. The radiator can be seen to have three distinct areas previously highlighted (see Fig. 2): The section on the right is the bulk of the radiator, the square in the middle is the reflector that outputs the photons generated through the entire radiator, then the sector on the left is the cut end of the radiator, called the chamfer, which outputs photons generated in the chamfer only.

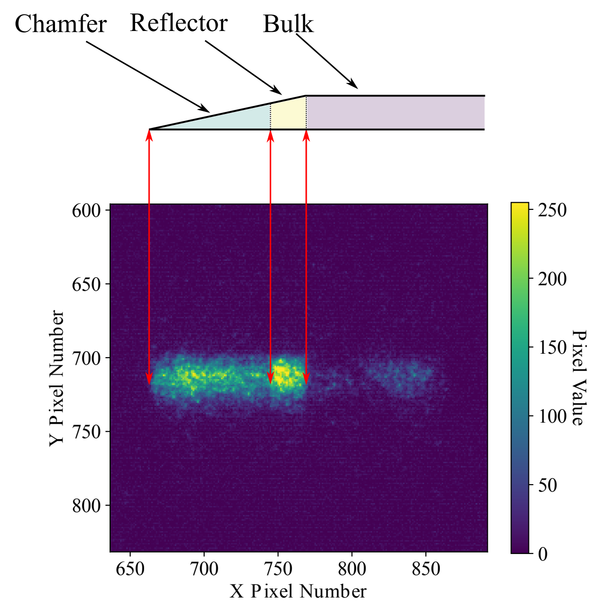

Figure 5: Image of ChDR from radiator.

To investigate the dependence of photon yield on impact parameter, an impact parameter scan is performed. The beam is aligned vertically with the radiator, then bumped horizontally towards the radiator where images are taken at each bump location. A Region Of Interest (ROI) is then set around the Chamfer, Reflector and Bulk. Each ROI then has its pixels summed together, this can then be compared at different impact parameters, showing a photon yield to impact parameter dependence.

RESULTS

A series of impact parameter scans have been taken, both with and without bandpass filters (see Figures 6, 7 and 8). All three ROIs are plotted on the graphs showing how the photon yield increases as the beam gets closer to the radiator. The photon intensity appears to be constant for all results until $h \lesssim 3500\,\mu$m. The area of each ROI is different, for the Chamfer, Reflector and Bulk, they are 4250, 1500, and 4750 pixels respectively where the results have been normalised to these areas. Unexpectedly Figure 6 shows the results from the chamfer being slightly higher from those of the radiator, this may be due to blackening of the radiator caused by direct interaction with the electron beam. As the reflector produces the highest photon yield for scans involving bandpass filters

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(see Figures 7 and 8), it may also be due to a background source interacting with the radiator.

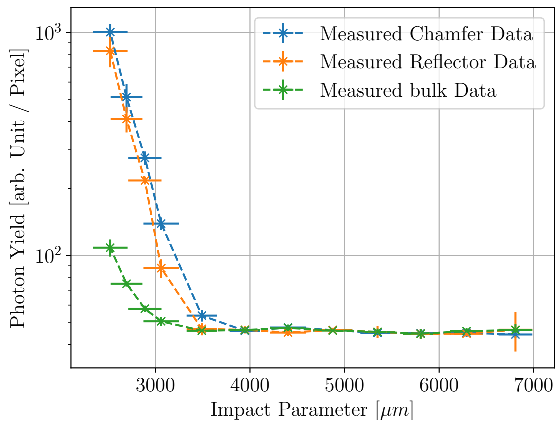

Figure 6: Normalised ChDR impact parameter scan.

In order to make an absolute measurement of the photon intensity, a white light source was passed through bandpass filters and then focused onto the ProxyVision camera using the same gain settings used in the scans. The same source was then focused onto a ThorLabs PM100USB with SV120VC photodiode instead of the camera [13, 14]. By repeating this for each bandpass filter, and a number of different intensities, a relation of pixel counts to number of photons was obtained.

Figures 7 and 8 show impact parameter scans using 550 nm green, and 400 nm blue bandpass filters respectively. These have been scaled with the bunch length in the BTS of 8.33 ps.

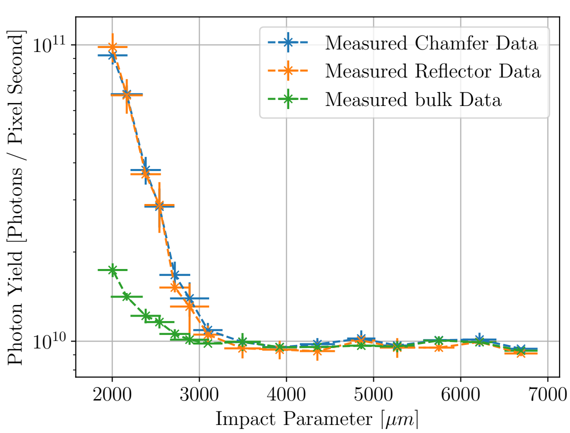

Figure 7: Normalised green bandpass filter (550 nm) ChDR impact parameter scan.

The scan using the 550 nm green bandpass filer shows an intensity that is nearly a factor ten higher than the scan using the 400 nm blue bandpass filter. According to [10], the photon intensity should be higher at longer wavelengths. While these results agree with theory, in order to make a direct

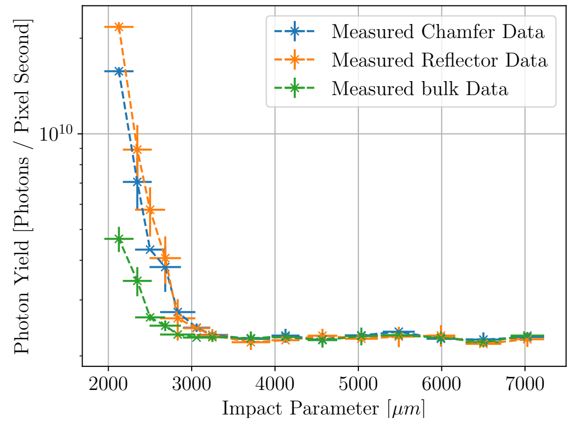

Figure 8: Normalised blue bandpass filter (400 nm) ChDR impact parameter scans.

comparison, the contribution of direct Cherenkov radiation also needs to be known.

CONCLUSION AND FUTURE DEVELOPMENTS

The ChDR radiator was installed onto the BTS test stand in November 2018. Since then, the diagnostics on the test stand have been commissioned, and the first initial ChDR measurements taken. These results have proved to be encouraging, and have given a strong base for future experiments to be built upon.

While the initial impact parameter scans show promising data, for ChDR to be used as a non-invasive pickup, signal should be measurable when $h \gtrsim 5\sigma_x$. Here the effect can only been seen at $h \lesssim 2.5\sigma_x$. An optical system has been installed that will measure the angular distribution of the ChDR. This is vital, as the angular distribution is needed in order to compare the measurements with the theoretical model [10]. As this requires the ChDR light to be focused down, this should also be measurable from further away.

Another question is that when the impact parameter becomes small, there will certainly be some contribution from Cherenkov radiation in the measurements. With the setup in the BTS test stand the photon contribution from ChDR and direct Cherenkov radiation is difficult to differentiate. Given that the spectral distribution of Cherenkov Radiation is well known, a spectrometer could be used to measure and separate the contribution of ChDR and Cherenkov radiation.

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