A NOVEL FIBRE OPTIC MONITOR FOR VHEE UHDR BEAM MONITORING: FIRST TESTS AT CLEAR

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Abstract

Beam monitoring for Ultra High Dose Rate (UHDR) radiation therapy using pulsed beams, i.e. Very High Energy Electrons (VHEE), is a major challenge. The lower pulse repetition of VHEE beams from linacs compared to other means of particle therapy, i.e., isosynchronous cyclotrons or synchrotrons means that in order to achieve high mean dose rates over sufficiently large cross sections to elicit the FLASH effect, ones needs high charge per pulse. The currently used transmission ion chambers suffer large recombination effects under these conditions. A proposed detector consisting of a 2D array of silica optical fibres connected to a photodetector which measures the Cherenkov radiation emitted by the VHEE beam as it passes through the fibres could be a promising alternative due to its high spatial and temporal resolution and its low material budget. First measurements with such a detector, consisting of silica optical fibres with a diameter of 200 μm, have been carried out at the CLEAR facility at CERN using 200 MeV electrons up to the UHDR required for FLASH. Measurements on the dynamic range of the fibre optic detector showed that it had a linear response at mean dose rates of over 300 Gy/s. Such results show that this fibre optic based beam monitor is able to provide fast direct real-time measurements of the VHEE beam dose and profile up to the UHDR. This makes it an excellent candidate for online dosimetry and beam diagnostics in future clinical FLASH machines with VHEE and other beam types.

INTRODUCTION

In order to enable a reliable translation of FLASH RT to the clinic, as well as provide accurate and reproducible preclinical results to facilitate this translation, accurate dosimetry and real-time beam monitoring needs to be carried out for UHDR [1, 2]. Currently in conventional radiotherapy, plane parallel ionisation chambers are the recommended dosimeter for secondary standard dosimetry of clinical electron beams, larger versions of these which are semi-transparent are also used for real-time dose monitoring within the clinical linac head. For ultrahigh dose-per- pulse beams, it has been shown that the ionisation chamber exhibits large recombination effects due to the high charge density in each electron pulse, which cause non-linearities in the response of the dosimeter at these dose rates [3, 4]. This effect is much more prominent for modalities where the delivery of the radiation is from a pulsed linear accelerator, for example VHEE, since the instantaneous dose rate within each pulse is extremely high in order to obtain the average dose rates required for FLASH [5,6]. Hence for these modalities alternative dosimetry technologies need to be investigated. Radioluminescence based detection is one of the oldest methods for detecting ionising radiation and the interest in fibre-coupled scintillating dosimeters has gained significant attention in recent years due to its ability to perform fast real-time measurements with high temporal and spatial resolution, making it particularly useful for in-vivo and small-field dosimetry [7]. A novel technique using a similar process has been implemented in the experimental areas at CERN for beam profile monitoring. The device consists of an array of scintillating plastic fibres that are read-out using multi-channel SiPMs which provide real-time measurements of the beam profile and intensity [8]. In fibre-optic coupled scintillation dosimetry Cherenkov radiation is often considered a source of contamination to the scintillation signal. But in recent years this radiation has been utilised for both fibre-based and optical imaging-based dosimetry, which is particularly useful for UHDR dosimetry since the increased beam intensity associated with this modality favours the detection of the optical photons produced in Cherenkov radiation [9]. Furthermore, Cherenkov light is produced instantaneously, on a timescale of 1×10^{-12} s, following the interaction between the charged particle and the dielectric medium, making it an ideal method for radiation detection at the fast time scales required for UHDR RT. A novel detector consisting of an array of optical fibre-based Cherenkov sensors connected to a photodetector is proposed as an alternative technology for UHDR real-time beam monitoring, particularly for use with VHEE beams.

MATERIALS AND METHODS

Initial tests were conducted at the CLEAR facility at CERN [10] with a single fibre as a proof-of-principle to determine the dynamic range of this proposed beam monitor and its ability to measure the beam profile. A 200 µm diameter silica fibre with 20 cm length sensitive region was installed at the In-Air Test Stand of the accelerator, shown in

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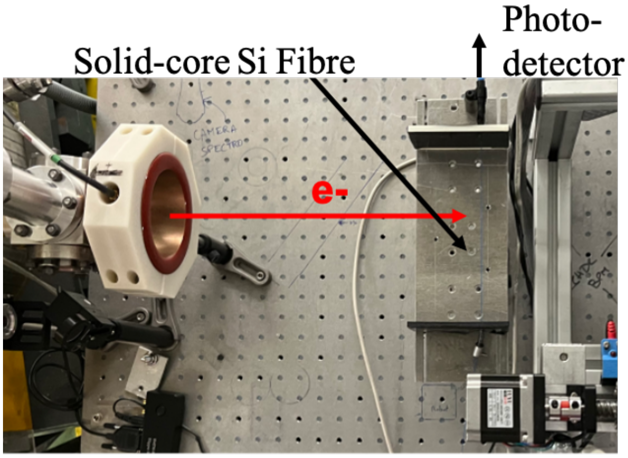

Figure 1: Setup of the fibre optic detector at CLEAR for the SiPM and PMT photodetectors (for the CCD camera the sensitive region of the Si fibre was oriented at 45° to the direction of the beam).

Fig. 1. In the first set of tests one end of the sensitive region of the fibre was connected directly to an SiPM or fast PMT, and for the second set of measurements a 28 m transport fibre was readout using a CCD camera. For the measurements with the SiPM and PMT, the sensitive region of the silica fibre was oriented perpendicular to the beam. For the CCD camera readout setup, the sensitive region of the silica fibre was oriented at 45° to the direction of the beam, this was to increase the signal, since the CCD camera is much less sensitive than the other photodetectors. The fibre was irradiated with 200 MeV electrons with a Gaussian transverse beam size that varied between $\sigma = 1 - 2$ mm RMS with a range of beam time structures in order to investigate the response of the fibre and photodetector to different intensities and dose rates; from those equivalent to conventional RT up to rates into the UHDR regime. The linearity of the response of the fibre monitor to an increasing the pulse charge, and hence the dose per pulse, was investigated by operating at the maximum charge per bunch and increasing the number of bunches per pulse (at a bunch spacing of 666 ps) i.e. increasing the pulse width, keeping the instantaneous dose rate the same for greater than one bunch per pulse. In order to evaluate the response of the fibre detector in terms of dose instead of charge a Monte Carlo simulation was written in TOPAS simulation software [11] to determine the equivalent dose deposited in a 1 cm^3 cube of water. This was 1.91 Gy/nC for 200 MeV electrons.

RESULTS

SiPM and PMT Photodetector Setups

The first fibre detector setups involved the sensitive region of the silica fibre being directly connected either to an SiPM which was in turn connected to a digitiser, or to a fast photomultiplier tube (PMT) with an ND = 6.0 optical filter (1×10^{-4} % transmission). For investigating the dose response by varying the charge per pulse, at each different charge measurements were taken for 100 consecutive pulses, from which a mean of the photodetector signal was calculated and then the response of the fibre and detector at each pulse charge was obtained from integrating the mean signal.

The linearity of the detector response was measured by increasing the charge, and hence dose, per pulse by operating at the maximum stable bunch charge (100 pC at CLEAR at the time of the SiPM measurements and 400 pC for the PMT measurments), and increasing the pulse width by increasing the number of bunches. The number of bunches was varied between 1 and 200. The results of these measurements are shown in Fig. 2 and 3 for the SiPM and the PMT, respectively. They can be seen to be linear up to an equivalent dose per pulse of 38 Gy/pulse for the SiPM and show near linearity up to a maximum achievable dose per pulse of 36 Gy/pulse for the PMT. The response of the fibre connected to the SiPM appears shows saturation above 50 bunches on the

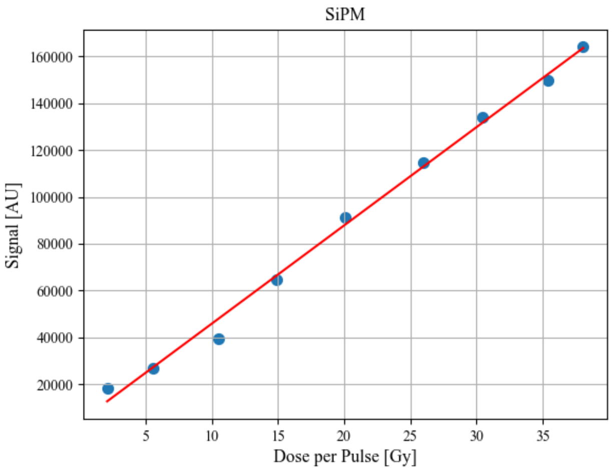

Figure 2: Dose per Pulse response of the Si fibre and SiPM to increasing bunches per pulse with maximum bunch charge of 400 pC.

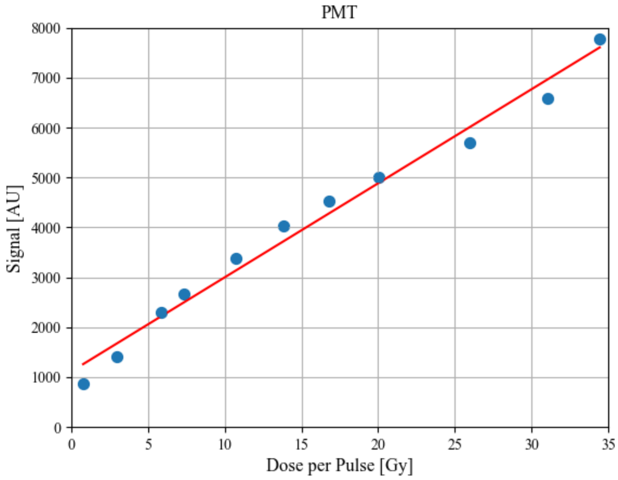

Figure 3: Dose per Pulse response of the Si fibre and PMT to increasing bunches per pulse with maximum bunch charge of 100 pC.

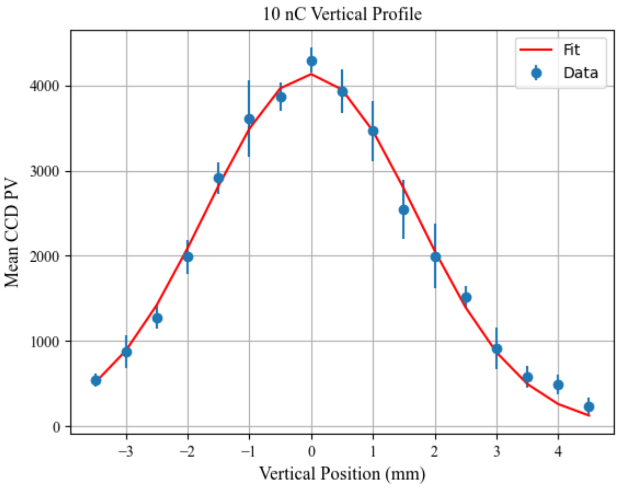

Figure 4: Projection of the vertical profile of the VHEE beam with a pulse charge of 10 nC measured with the CCD camera setup.

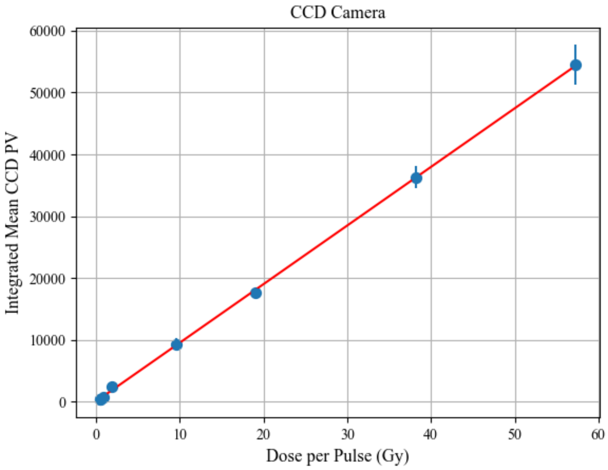

Figure 5: Dose per Pulse response of the Si fibre and CCD camera to increasing bunches per pulse with maximum bunch charge of 250 pC.

response traces, therefore the apparent linearity that is seen in Fig. 2 is likely to be from the increasing temporal width of the signal associated with the increase in pulse width. For the PMT, the data points around 20 Gy/pulse begin to drop below linearity and then the latter data points corresponding to longer pulse widths appear to deviate slightly from the linear trend of the other data points. This is likely to be from a combination of saturation of the PMT response around 20 Gy/pulse, which causes the response to start to become non-linear. Then at the longer pulse widths the relation between the dose per pulse and pulse width changes due to the limitations of delivering higher pulse charges at CLEAR from beam losses. This then decreases the instantaneous dose rate within the pulse; appearing as a larger integrated signal in Fig. 3, since the charge is delivered to the fibre over a longer duration.

CCD Camera Setup

The setup using a CCD camera involved the sensitive region of the silica fibre oriented at 45° to the direction of the electron beam and connected to a 28 m transport fibre leading to the CCD camera. The response linearity of this fibre monitor configuration to an increasing dose per pulse was measured by scanning the vertical position of the fibre over the beam at intervals of 500 µm (the diameter of the silica fibre and its coating). Taking 20 measurements of consecutive pulses at each position. From these data the projection of the vertical profile of the beam was plotted and fitted with a Gaussian, and the integral of this Gaussian was taken as the response of the fibre detector for a given dose per pulse. Measurements were taken with a charge per bunch of 250 pC, corresponding to pulse charges of up to 30 nC. The vertical projection of the profile of the beam measured with the silica fibre and CCD camera for a pulse charge of 30 nC is shown in Fig. 4. For this pulse charge the beam size obtained from the standard deviation of the Gaussian fit was measured to be 1.70 ± 0.064 mm, compared to 1.83 ± 0.059 mm measured on a YAG screen just behind the fibre installation. The response of this fibre monitor setup using a CCD camera to increasing dose per pulse is shown in Fig. 5, and can be seen to be linear all the way up to a dose per pulse of 57 Gy/pulse. Whilst unlike the SiPM and PMT the CCD camera showed no signs of saturation up into the UHDR regime, the response at pulse charges of less than 1 nC suffered from having a low signal-to-noise ratio. To attempt to overcome this issue further tests with this setup are planned but with a shorter transport fibre in order to retain the signal being transmitted to the CCD camera.

CONCLUSIONS

The results from these initial tests on the linearity of the response of the fibre optic beam monitor are very promising since they show that fibre is able to given an apparent linear response well into the UHDR regime, up to 38 Gy/pulse with an SiPM photodetector, up to 36 Gy/pulse with a PMT photodetector setup and up to 57 Gy/pulse for the CCD camera. From these experiments the CCD camera appears to be the most promising for UHDR beam monitoring due to the lack of saturation of response and the possibility of imaging an array of fibres with a single CCD camera. However, with the low signal-to-noise ratio at lower charges is an issue that can hopefully be overcome adapting the setup and using a shorter transport fibre. The CCD camera also has a lower temporal resolution than the other photodetectors. To overcome this issue, a proposed fibre optic beam monitor for UHDR RT could consist of multiple readout systems, i.e. a CCD camera to benefit from the large dynamic range and an SiPM or PMT connected to a single fibre in the array to take advantage of its temporal resolution.

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