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TESTING THE PROPERTIES OF BEAM-DOSE MONITORS FOR VHEE-FLASH RADIATION THERAPY

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Abstract

Very High Energy Electrons (VHEE) of 50 - 250 MeV are an attractive choice for FLASH radiation therapy (RT). Before VHEE-FLASH RT can be considered for clinical use, a reliable dosimetric and beam monitoring system needs to be developed, able to measure the dose delivered to the patient in real-time and cut off the beam in the event of a machine fault to prevent overdosing the patient. Ionisation chambers are the standard monitors in conventional RT; however, their response saturates at the high dose rates required for FLASH. Therefore, a new dosimetry method is needed that can provide reliable measurements of the delivered dose in these conditions. Experiments using 200 MeV electrons were done at the CLEAR facility at CERN to investigate the properties of detectors such as diamond beam loss detectors, GEM foil detectors, and Timepix3 ASIC chips. From the tests, the GEM foil proved to be the most promising.

INTRODUCTION

The most widely used modality of RT is external beam therapy with high energy photons (6 - 15 MV) and low energy electrons (3 - 25 MeV). However, the maximum dose that can be delivered to the tumour is limited by the dose that the surrounding healthy tissue can tolerate. This is a particular challenge as these X- rays deliver their maximum dose at 1.5 - 3.0 cm depth in water-equivalent tissue and then have a near-exponential attenuation. Recent research suggests that delivering the prescribed dose to the patient's tumour at ultra-high dose rates (UHDR) elicits a larger differential response between the tumour cells and the healthy tissues, known as the FLASH effect [1]. The entire prescribed dose is delivered within less than a second at a mean dose rate of ≥ 100 Gy/s; compared to ≤ 0.03 Gy/s used in conventional RT. Due to recent advances in particle accelerator technology such as high gradient electron acceleration cavities, e.g. the ones developed as part of the CLIC study [2], it may be possible to treat deep-seated tumours with Very High Energy Electrons (VHEE) with energies of 50 - 250 MeV due to their increased longitudinal range and sharper lateral penumbra in comparison to current clinical electron beams [3]. Ionisation chambers have been the standard for electron beam dosimetry, however, studies have shown that at the ultra high dose rates required for FLASH-RT the response of the ionisation chamber suffers from non-linearities due to ion recombination within the cavity volume [4]. Therefore, new detectors and monitoring systems will need to be developed and tested in order to achieve accurate and reliable measurements of the delivered dose at UHDR for FLASH irradiations in both pre-clinical experiments to verify the FLASH effect, and for the eventual clinical implementation of FLASH-RT [5]. The requirements on such a system are:

- A response that does not saturate at the ultra-high dose rates of ≥100 Gy/s that are required for FLASH.
- A temporal resolution which is high enough to resolve individual bunches or trains.
- A response time that is fast enough to trigger a safety interlock in between pulses.
- Minimal perturbation on the beam.

The aim of the experiments described in this work is to understand the characteristics of the response of the detectors tested to the electron beam parameters at the CLEAR facility [6] and whether they exhibit any of the characteristics that suggest they would meet the criteria required for real-time dosimetry of VHEE at UHDR.

PCVD DIAMOND DETECTOR

The first detector tested was a B2-HV pCVD diamond beam loss detector which is currently employed as a fast beam loss monitor (BLM) at the LHC [7]. The diamond detector consists of a 10 mm × 10 mm × 0.5 mm pCVD diamond substrate coated on each side with a 200 nm thick gold electrode with a size of 8 mm × 8 mm. In the LHC, the detector is used alongside an AD-DC splitter and a 2 GHz amplifier, however for the FLASH dosimetry experiments only the detector was used since the beam intensity does not need amplification. This detector was considered due to its known ability to have a quick response time and resolve individual bunches when used as a BLM. However, since its primary usage is as a BLM and hence it is not directly installed in the path of the beam center, it has been expected that the detector response would reach saturation at FLASH rates.

Setup

The diamond detector was installed at the In-Air Test Stand at CLEAR, at approximately 25 cm away from the end of the beam pipe, and was aligned such that the pCVD

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diamond was on the axis of the beam. It was installed just behind an integrated current transformer (ICT) which was used to measure the delivered charge. The tests on the diamond detector were primarily to determine the beam intensities at which the response saturated.

Results and Discussion

The initial bias voltage for the detector was set to its nominal value of 500 V. The beam energy used was 200 MeV. The initial charge used was 40 pC per bunch, however for just one bunch, this was already causing the detector response to saturate. The applied bias voltage was then adjusted down until the response no longer saturated which was at a voltage 160 V. For the remainder of the irradiations, one bunch per pulse was used, whilst the charge per bunch was increased. Then the bias voltage was altered to a value at which the signal no longer saturated. The results are shown in Table 1. A bias voltage of 17 V was required for an unsaturated response for a single bunch of 80 pC, but this led to a weak signal with a stretched out FWHM. Furthermore, at such a low bias voltage the detector has a much lower response time and resolving ability due to a drop in the collection efficiency of the electrodes, hence it would not be suitable for use at such a low voltage [8]. Therefore, from these initial studies it can be determined that the B2-HV pCVD Diamond Beam Loss Detector, as expected, would not be suitable as a real-time dosimeter for beam monitoring with UHDR VHEE beams for FLASH RT. This result is in agreement with other studies which show this diamond detector only has a linear response in the range 0.01 pC - 0.06 pC [8]. For ionizing electrons, a charge of 1 nC deposits a dose of 2 Gy in 1 cm^3 of water. Therefore, at the highest pulse repetition frequency (p.r.f) at CLEAR - 10 Hz [6], this equates to the diamond detector saturating at an average dose rate of 1.6 Gy/s, so would not be feasible for FLASH-RT.

Table 1: pCVD Diamond Detector Response Saturation Values

Bunch Charge	**Bias Voltage at Saturation**
40 pC	160 V
60 pC	30 V
80 pC	17 V

GEM FOIL DETECTOR

The second detector tested was a Gas Electron Multiplier (GEM) Foil Detector. The detector consists of a thin polymer foil, which is pierced with a high density of holes, and sandwiched between two thin sheets of metal, clad to each face. The electric field in the pierced holes creates an avalanche of multiplied electrons upon interactions from the incoming radiation with the gas on one side of the structure, which then transfer to a collection region [9].

Setup

The GEM foil in the detector used for this experiment had an active area of 5 mm × 5 mm and consisted of a foil 50 μm thick of kapton pierced with holes of 30 μm diameter and clad with 5 μm thick sheets of copper. It was positioned approximately 40 cm away from the exit of the beam pipe at the In-Air Test Stand of CLEAR. These tests were to determine the beam intensities at which the response saturated, as well as the detector's resolving ability and the perturbation it has on the beam.

Results and Discussion

All of the irradiations were done at a beam energy of 200 MeV. The first set of tests were with a charge of 50 pC per bunch at 1, 10, 50 and 100 bunches per train, respectively. The results showed that at these intensities the detector response does not saturate and has some temporal resolving ability on the bunches within the train. A subsequent set of irradiations was done with 100 pC per bunch with trains of 1, 10, 50 and 100 bunches, respectively. The response of the latter is shown in Fig. 1, and shows that at 10 nC per train (i.e. 100 pC per bunch with 100 bunches per train), the response of the GEM foil detector does not saturate. This equates to an average dose rate of 200 Gy/s at a 10 Hz p.r.f and therefore could be compatible with the UHDR required for FLASH-RT.

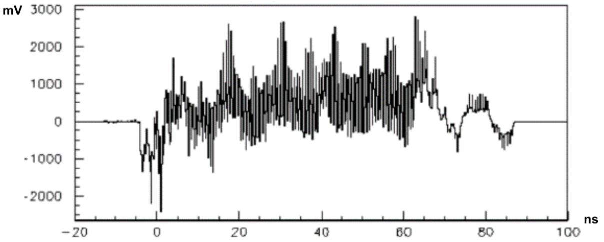

Figure 1: Signal detected from GEM foil with 5 mm × 5 mm active area for 100 bunches per train and a charge of 100 pC per bunch.

The temporal resolving ability of the GEM foil detector can be seen in Fig. 2. Here, the response of the detector to the individual bunches can be seen (the CLEAR electron bunch spacing was 666 ps [6]).

To measure the perturbation the detector had on the beam, the intensity and size of the beam was measured by a scintillating YAG screen 30 cm downstream of the detector, both with and without the detector inserted in the path of the beam. The measurements showed that the GEM foil detector scattered the beam to increase its size by 2.4 ×, and decreased the intensity of the beam by 38%.

These initial results from the GEM foil detector are promising as it shows that the response of detector does not saturate at charges of up to 10 nC per train. The results show that the detector is also able to resolve the bunches within the train, and appears to have slight perturbations on the beam.

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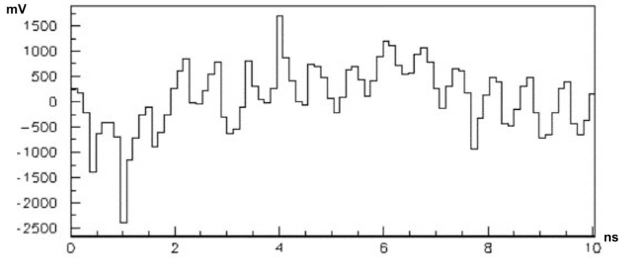

Figure 2: Signal detected from GEM foil for 100 bunches per train and a charge of 100 pC per bunch over a shorter timescale to observe resolving ability.

TIMEPIX3 ASIC

A Timepix3 Application-Specific Integrated Circuit (ASIC) readout chip was also tested. Timepix3 is a hybrid pixel detector readout chip which can record the time-of-arrival (ToA) and time-over-threshold (ToT) in each pixel [10]. The ASIC was used bare without a solid-state or gaseous sensor mounted as it was theorised that the intensities from the UHDR beam required for FLASH irradiations would be high enough to activate the readout pixels.

Setup

The Timepix3 ASIC was also installed at the CLEAR In-Air Test Stand at a distance of around 50 cm from the exit of the beam pipe. The detector consists of four Timepix chips which together provide a 512 × 512 array of pixels and a total sensitive area of 28 mm × 28 mm. The beam was targeted onto one of the four Timepix quad chips, in which the response was measured. The tests were to determine the beam intensities at which the response saturated. The measurements were carried out with the detector in ”Medipix” mode, in which all of the incoming particles are counted and in ToT mode, in which the incoming particles are measured with an incrementing counter as long as the signal is over the threshold [11].

Results and Discussion

The response was measured for a beam energy of 200 MeV at three different beam intensities, 50 pC per train (1 bunch per train), 100 pC per train (5 bunches per train, 20 pC per bunch) and 250 pC per train (5 bunches per train, 50 pC per bunch). The response of the detector in ToT mode to the 100 pC train and the 250 pC train can be seen in Fig. 3 a) and b), respectively. As can be seen in Fig. 3b), the response of the detector already saturates at 250 pC per train, and would hence be unsuitable for the detection of any larger intensities. This saturation was also seen at the same beam intensity when measuring the response in ”Medipix” mode. This is equivalent to an average dose rate of 5 Gy/s for a 10 HZ p.r.f, therefore confirming the detector would saturate at UHDR conditions required for FLASH-RT. Whilst the response of the detector had saturated at these beam intensities, a measurement of the response of the detector after the experiment to no beam showed that the detector was not damaged by the irradiations.

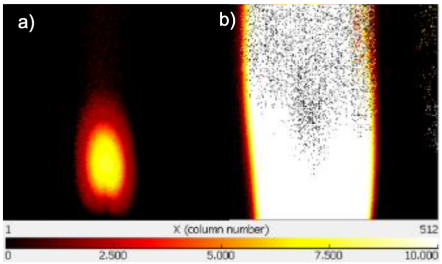

Figure 3: Pixel intensity response of Timepix3 ASIC to: a) 5 bunches of 20 pC per bunch, and b) 5 bunches of 50 pC per bunch, in ToT mode (X = Radiation Signal [a.u]).

CONCLUSIONS

The aim of the experiments described in this work was to determine whether the pCVD diamond detector, GEM foil detector or Timepix3 ASIC exhibited the properties required for real-time dosimetry for VHEE beams at UHDR required for FLASH RT. We concluded that neither the diamond detector nor the Timepix3 ASIC would be suitable for such use, since their response saturated at a charge per train of 80 pC and 250 pC, respectively. Considering the dose deposited in 1 cm^3 of water, this corresponds to dose rates of 1.6 Gy/s for the diamond detector and 5 Gy/s for the Timepix3 ASIC, demonstrating neither are able to operate at the dose rates required for FLASH-RT. Conversely, the GEM foil detector exhibited promising results since its response did not saturate at the highest charge per train used, 10 nC, which equates to a dose rate of 200 Gy/s. Hence showing that it would be able to operate at the dose rates required for FLASH-RT. Furthermore, this detector was able to show the bunch spacing within the train, and was demonstrated to have a slight perturbation on the beam. However, further tests would be need to be conducted on the GEM foil detector to determine whether it’s fully suitable for use as beam-dose monitor for FLASH RT using VHEE at UHDR, such as its behaviour with the larger beam sizes required for RT.

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