Real-time Plastic Scintillation Dosimetry of Ultra-High Dose Rate Very High Energy Electrons (VHEE) at CERN CLEAR Facility

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Abstract. Very High Energy Electrons (VHEE) that can theoretically treat deep-seated tumours and be delivered at ultra-high dose rates (UHDR) could be the solution to translate FLASH radiotherapy into the clinic. Standard dosimeters have limited application in those extreme conditions, but dose-rate independent and fast-response plastic scintillation detectors (PSDs) are a potential alternative to overcome this. In this work, response of a 4-channel PSD to the 200 MeV VHEE UHDR beam delivered with doses and dose rates in pulse up to 90 Gy and 4.6×10^9 Gy/s, respectively, at the CLEAR facility in CERN was characterized, using the Hyperscint RP200 platform. Scintillation light linearity with dose was observed for three scintillators from ~5-50 Gy, while clear fiber output was linear up to 90 Gy. While linearity on this dose range was conserved even after radiation damage by exposure to 37.2 kGy total accumulated dose, light output significantly decreased. This work proves the potential of plastic scintillators for real-time dosimetry of UHDR VHEE beams.

1. Introduction

Conventional external radiotherapy typically uses a beam of ionizing radiation, either electrons or photons, produced by a medical linear accelerator (linac) to kill cancer cells. Decades of research have allowed modern radiotherapy treatments to accentuate the differential response of healthy tissues and tumours to radiation. However, doses delivered are still limited by normal tissue tolerance, as severe side effects must be avoided. As shown in recent years, delivering radiation at ultra-high dose rates (UHDR), with single fraction doses in sub second treatment times, can trigger a normal tissue sparing effect while maintaining toxicity to tumour cells [1-3]. This effect, termed the FLASH effect, has been demonstrated in many animal models with different particle modalities and beam characteristics [4]. Low energy electrons are widely used right now to produce UHDR beams, but their ability to treat tumours is limited because of their low penetration in the body. Very High Energy Electrons (VHEE) beams (>100 MeV) offer an interesting avenue for external radiotherapy due to their superior penetration capabilities and favourable dose distribution that allows treatment of deep-seated tumours. They are less sensitive to inhomogeneities than protons and have the potential to treat tumours as effectively as or even better than photon beams [5], [6]. High-energy electrons, deliverable at high dose rates, are thus promising candidates for translating FLASH therapy into clinical practice.

UHDR VHEE beams pose new challenges for accurately measuring dose under conditions that are far removed from reference clinical measurements. Radiochromic films, extensively used in the clinic for 2D dose measurements, have excellent dose rate independence, but they do not allow real-time measurements [7]. The ionization chamber, the reference dosimeter in radiotherapy, suffers from significant charge recombination at high dose rates, which causes change in sensitivity, non-linearity and saturation [8]. A possible solution to overcome these limitations lies in the development of water equivalent plastic scintillation detectors (PSDs) that can be read in real-time. Comprised of a scintillating material emitting light when irradiated, PSDs proved to be promising detectors for dosimetry at ultra-high dose rates in UHDR low energy electrons and photons [9], [10], [11]. A recent study by Hart *et al.* demonstrated their utility for real-time dosimetry of 200 MeV UHDR electrons [12]. This work aims to further investigate the output linearity, radiation damage and recovery of PSDs when exposed to the UHDR VHEE beam delivered at the CLEAR CERN facility.

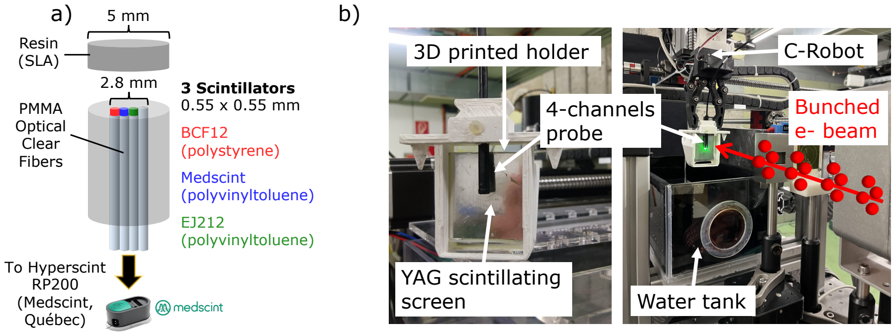

Figure 1. a) 4-channel PSD design. b) Experimental set-up in the in-air test area of the CLEAR beam line.

2. Materials and Methods

A 4-channel PSD (Figure 1a) was designed with polystyrene based BCF12, polyvinyltoluene (PVT) based EJ-212, PVT based proprietary Medscint scintillators and clear plastic fiber for stem effect light (Cherenkov and fluorescence) removal. The probe, installed on a 3D printed holder held by the C-Robot, was centred on the gaussian beam visually using the reflection of a YAG scintillating screen (Figure 1b). An integrating current transformer (ICT) recorded delivered charges per pulse, that were then converted to dose with Gafchromic MD-V3 films measurements performed on each day of experiments. The channels were connected to the Hyperscint RP200 platform to measure scintillation light output to dose pulses from ~5 to 90 Gy. Dose rates in pulse varied throughout but ranged from 2.2×10^{8} to 4.6×10^{9} Gy/s. Between measurements, the PSD was damaged with irradiations of ~5 kGy delivered with about 12 Gy pulses at 3.33 Hz for dose rates of ~40 Gy/s in average and ~1.4×10^{9} Gy/s in pulse. In total, 37.2 kGy was delivered to the probe. Linearity of response to dose was computed by plotting the area under the curve from the measured output spectra according to dose per pulse, after subtracting background and stem effect. Slopes of linear measurements, extracted from linear regressions, were taken as light output. Linearity limits were determined using visual inspection, the coefficients of determination (R^2) and residuals of the linear regressions. In between the linearity measurements, scintillators were allowed to rest for a given period of time, then re-irradiated to assess short-term recovery of light output and spectral changes. To evaluate long-term recovery, output and spectra measurements were conducted respectively with the 6 MV beam and the kV source of a TrueBeam clinical Linac at time points ranging from 24 to 237 days after radiation damage and compared to the same measurements done before CLEAR irradiations.

3. Results and Discussion

Figure 2 shows the scintillator and clear fiber signal according to dose per pulse for increasing total accumulated dose. Irregularities in the curves are likely caused by variations in beam size and positioning. For scintillators, integrated light signal is linear to dose per pulse until about 50 Gy/pulse (~8×10^8 Gy/s in pulse), while clear fiber output stayed linear over the whole dose and dose rate range studied. A saturation of scintillator response is observed for doses over 50 Gy/pulse, which was not caused by a saturation of the photodetector system. Dose rates varied non linearly with dose per pulse and higher dose rates were sometimes used for smaller doses due to combination of number of bunches and pulse length. Saturation cause is thus difficult to isolate, but could be caused by a decrease of scintillation efficiency at high dose per pulse due to a quenching effect normally seen for high LET radiation.

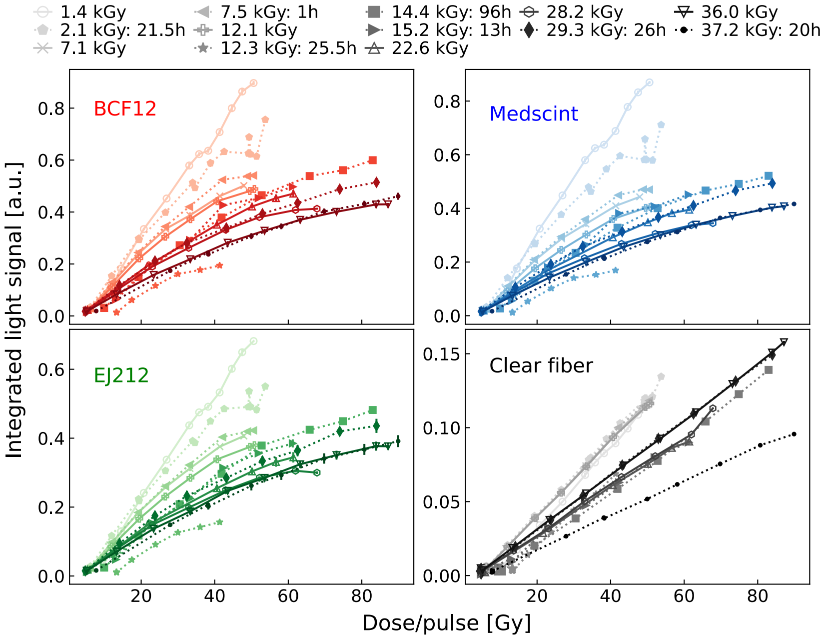

Figure 2. Integrated light signal (area under the curve) of scintillator and clear fiber spectra measured for different dose per pulse, at increasing total accumulated dose in the probe. Mean over 3 single pulses is shown. Full symbols represent short-term recovery measurements, with associated rest times specified in the legend. Errors in x, ranging from about ± 1 to 11 Gy and not shown for visual clarity, were calculated from standard deviation of dose pulses, uncertainty in dose calibration and uncertainty in probe positioning.

Light output (linear slopes) significantly decreased with accumulated dose in the probe, but stayed linear to dose for the ranges previously discussed. PSDs could thus still be used for relative dose measurements even when damaged by radiation. Mean losses of light yield of <1.85 %/kGy were measured for scintillators and clear fiber. Short-term output recovery reported at 1h, 96h, 13h and 26h following irradiation suggests that recovery depends on inter-irradiation time interval but also on accumulated dose. Scintillation and clear fiber spectra were shifted towards higher (yellower) wavelengths with dose, which is consistent with the yellow discoloration that normally appears in irradiated plastic scintillators and fibers [13].

Long-term recovery of light output loss was significant, but partial, and appears to stabilize after 39 days for BCF12, between 65 and 150 days for Medscint and EJ212 and after 32 days for clear fiber.

Conclusion

This study demonstrates that plastic scintillators and clear fibers respond linearly with dose in VHEE UHDR conditions for a clinically relevant dose range, even after exposure to 37.2 kGy. While scintillators lost linearity at about 50 Gy/pulse, clear fibers performed better with no loss of linearity on the whole dose range measured. Significant loss of light output <1.85 %/kGy and spectral shift with radiation damage was observed, as well as short-term (<100h) recovery. After less than 150 days of rest, output partially recovered. These results are a critical step toward the use of plastic scintillators for real-time dosimetry of UHDR VHEE beams. Future work will aim to use less variable FLASH beams to verify some of the conclusions of this work with less dose uncertainty. Recovery processes with scintillator compositions designed for increased radiation hardness will also be explored, as well as response saturation at high doses per pulse.

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