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VHEE HIGH DOSE RATE DOSIMETRY STUDIES IN CLEAR

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Abstract

The 200 MeV electron beam of the CERN Linear Accelerator for Research (CLEAR) user facility at CERN has been intensively used to study the potential use of Very High Energy Electrons (VHEE) in cancer radiotherapy. In particular, irradiation tests have been performed in the high dose rate regime, which has gained a lot of interest for the so called FLASH biological effect, in which cancer cells are damaged while healthy tissue is largely spared. High dose rate dosimetry, though, poses a number of challenges: to validate standard or new methods of passive dosimetry, like radiochromic films and alanine pellets, and especially to develop new methods for real-time dosimetry since the normally used ionization chambers suffer from non-linear effects at high dose rates. In this paper we describe the results of experimental activities at CLEAR aimed at developing solid, high-dose rate dosimetry standards adapted to VHEE beams.

INTRODUCTION

Real-time dosimetry methods used in radiotherapy are generally not well adapted for the high dose-rate regime. Both conventional ionisation chambers and solid-state detectors suffer from nonlinear saturation effects due to recombination at very-high dose-rates [1, 2]. For ionisation chambers, the charge collection efficiency has been reported to drop from more than 90 % for standard radiotherapy dose rates (in the order of tens of mGy/pulse) to less than 10 % for the Ultra-High Dose-Rates (UHDR, in the order of 10 Gy/pulse) used for FLASH. However, it could in theory be possible to mitigate such effects through careful calibration or a re-design of the detector geometry [3].

To this point, dosimetric measurements for UHDR have thus been performed using passive methods such as radiochromic films as their response is thought to be almost independent of dose rate. However as these require post-irradiation processing for reading the deposited dose, they are impractical for use in a medical facility [4]. Alternatives such as novel solid state detectors and calibrated dosimetry based on beam diagnostics are thus currently being investigated as potential real-time dosimetry solutions at CLEAR.

An important part of this development is the establishment of efficient, systematic and reproducible methodologies for testing and verification of the new developments using reliable methods, such as films. It is also essential to validate and obtain statistics on the response of the films under the particular conditions for which we aim to test new dosimeters, in particular for methods involving calibration against films. In this context, there have been developments in terms of a robot facilitating remote sample handling without manual interventions, as well as procedures for scanning and processing films.

VHEE FLASH AT CLEAR

Table 1: CLEAR Machine Parameters for Dosimetry Studies

Energy	200 MeV
Bunch charge	0.05 nC - 3 nC
Bunch frequency	1.5 GHz / 3 GHz
Bunches per pulse	1 - 150
Pulse repetition rate	0.8 Hz - 10 Hz

A list of beam parameters for the CLEAR facility is shown in Table 1. VHEE UHDR dosimetry studies are performed at CLEAR at an energy of 200 MeV [5, 6]. By varying the charge, train length and number of trains, one may operate at both conventional dose rates and the UHDR required to access the FLASH effect for various target doses [7]. The beamline is equipped with Yttrium Aluminium Garnet (YAG) scintillator screens linked to cameras, allowing observation of the beam size, position, and intensity distribution in real time. They exhibit excellent time and spatial resolution and do not suffer from non-linearities at high dose-rates. These screens play an integral part in the parametric high dose-rate dosimetry studies, aimed at correlating beam diagnostics with passive dosimetry.

SAMPLE HANDLING AND PROCESSING

C-Robot

A robot has been developed by the CLEAR team in order to facilitate the efficient irradiation of multiple samples, and reduce the number of accesses [8, 9]. It consists of a grabber, able to move in 3D, which can move samples from a slotted sample container, able to hold 24 standardised sample holders, to the path of the beam. It is possible to install a water phantom in the beam area. The robot is controlled using an open-source GUI [10]. The sample holders are 3D printed to ensure that they match the grabber and sample container, and can be adapted to various types of samples, such as films and Eppendorf tubes.

Radiochromic Films

Radiochromic films change colour macroscopically due to polymerisation caused by ionising radiation, with the change in colour related to the accumulated dose. The films are processed post-irradiation to read the dose. The films

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are optically scanned and the resulting image processed to determine the optical density (OD). The OD is then matched against a calibration curve, which must be obtained for each production batch at a calibration facility. At CLEAR, various types of Gafchromic films from Ashland are used: EBT3 (0.1 - 10 Gy), MD-V3 (1 - 100 Gy) and HD-V2 (10 - 1000 Gy) which are calibrated at the eRT6 linac at CHUV in Lausanne [1]. The films are cut to the exact dimensions (35×40.5mm) of the sample holder slots and engraved using a laser cutter [2]. This method also avoids the issue of layer detachment frequently caused by other means of cutting. To validate the scanning procedure, image processing methods and reproducibility of this method, a large number of films were irradiated under various conditions. Fig. 1 shows a Gafchromic film irradiated at CLEAR.

Figure 1: Gafchromic EBT3 film irradiated at CLEAR.

Following irradiation, the films are scanned using a 16-bit Epson Perfection V800 Photo scanner at 300 dpi. For this purpose, a scanning mask was designed to ensure consistency of the orientation and position on the scanner plate for each film, as well as to study the extent to which these variables affect the readout. The mask allows for 9 different positions and 8 orientations 45° apart, as shown in Fig. 2. The *standard* scanning position is herein referred to as the center position at 0°, i.e. with the edges of the film and scanner lengthwise parallel with one another.

The resulting .tif images are processed using a script which reads the RGB pixel values. The optical density of a single colour channel x is the channel's pixel value divided by the 16 bit RGB colour space: $OD_x = -\log(x/65535)$. The calibration data should be fitted to a function of the form,

$$OD_x = a + b/(D - c), \quad (1)$$

where D is the dose [11]. The dose distribution of the films may then be obtained by inversion of the calibration function. As the dose distribution is not uniform across the film, the relevant area must be selected for analysis. By performing a Gaussian fit of the processed image, one may also obtain an estimation of the relevant beam size.

RPL Dosimeters

Radio-photoluminescence (RPL) dosimeters are silver activated phosphate glass cylinders of 1.5 mm diameter and 8.5

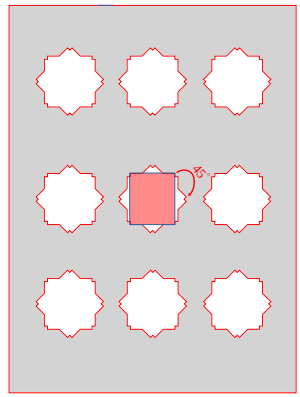

Figure 2: Mask used for film scanning and studies of orientation and position dependency. The centered red square refers to the standard scanning position.

mm length which work on the principle of radiation-induced luminescence centers[12]. RPLs are used for passive beam loss measurements in machines such as the Super Proton Synchrotron and Large Hadron Collider at CERN [13]. The luminescence emitted upon exposure to UV light is proportional to the absorbed dose, with a supposed linear response in the range 1 Gy - 5 MGy. RPLs have the advantage that measuring the luminescence centers is non-destructive and they do not fade over time. Although they do not provide the same spatial resolution as films, they may be a useful complementary tool for parametric dosimetry studies and bench-marking. To test their response to VHEE beams, RPL

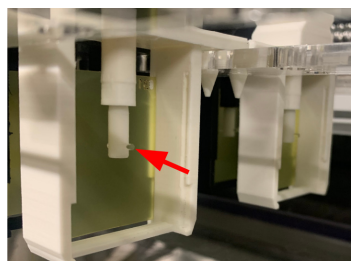

Figure 3: The RPL cylinders and films mounted in the sample holder of the C-Robot.

cylinders were mounted horizontally in the sample holders, as shown in Fig. 3. HD-V2 films were mounted upstream and downstream of the RPL for reference. The RPLs were then irradiated at a constant dose rate using 100 pC trains with a size of ~ 1.6 mm corresponding to an average dose rate of ~ 1 Gy/s. Following the irradiation, the films were marked and evaluated at the location of the RPLs [3]. These measurements yield uncertainties of ~ 10% due to inaccuracies in film and position readings. Further studies are planned to measure the effect of dose variation.

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RESULTS

Film Dosimetry

The dependency of evaluated dose on film orientation on the scanner is shown in Fig. 4. It is evident that the orientation of the film on the scanner plate is significant for the output. This originates from differences in the scanner's polarised light transmission through the orientation of the film polymers [14]. Consistency in scanning orientation between experimental and calibration films is thus crucial.

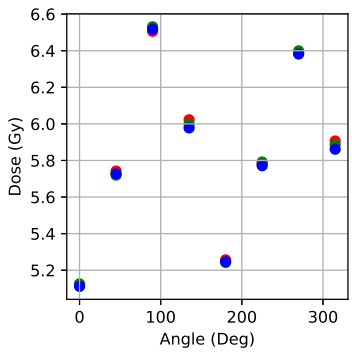

Figure 4: Measured dose of a film as a function of its orientation on the scanner. The 0° point refers to the standard orientation. The different colours correspond to the respective RGB colour channels.

An example of a film calibration curve can be seen in Fig. 5. Discussions on the colour channel to use, or whether a multichannel method for dose estimation should be implemented are ongoing. A colour plot indicating the dose distribution of the processed image is shown in Fig. 6. The evaluation of the total dose is evidently a matter of selecting a suitable region of interest to calculate the mean.

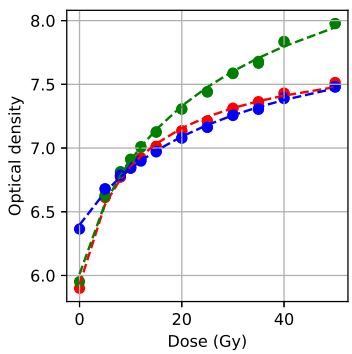

Figure 5: Calibration curves for the EBT3 Gafchromic films. The different colours correspond to the respective RGB colour channels.

RPL dosimetry

Seven RPL cylinders were irradiated at a constant dose rate with different target doses. The dose recorded using RPL luminescence is compared to the average of the dose

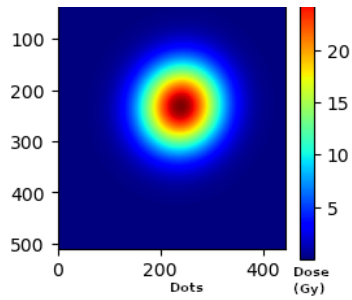

Figure 6: Colour plot of the dose distribution on the film, calculated based on the optical density and fitted to a Gaussian function. The vertical and horizontal units correspond to the number of evaluated image dots (i.e. film size × dpi)

recorded upstream and downstream with calibrated HD-V2 films in Fig. 7. There is good agreement over the range covered. Further studies of RPL responses to low total doses (~ 10s of Gy) and varying dose rates compared with the corresponding response of EBT3 films are ongoing.

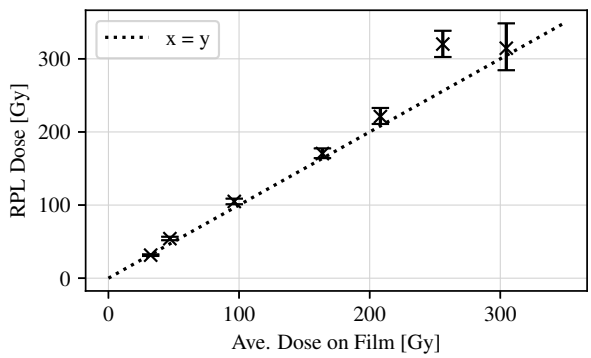

Figure 7: Dose readout for each RPL vs corresponding film readout. The errorbars represent estimates for the upper and lower dose values based on the standard deviation of the RPL calibration curve [15].

CONCLUSION

A framework for extensive dosimetric studies has been adapted and developed according to the constraints and requirements at CLEAR and the associated research projects. Further work to establish a best practice for film processing remains, and passive methods such as alanine pellets and RPL dosimeters may be used for bench-marking. These developments are important as a stepping stone towards the development of a real-time dosimetry modality for the high dose-rate regime.

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