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BEAM INSTRUMENTATION FOR REAL TIME FLASH DOSIMETRY: EXPERIMENTAL STUDIES IN THE CLEAR FACILITY*

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Abstract

Real-time dosimetry for ultra-high dose-rates (UHDR) and very high energy electrons (VHEE) is a challenge which is currently being studied using the electron beam at CERN Linear Accelerator for Research (CLEAR). These studies are motivated by the demand for reliable dosimetry for FLASH radiotherapy. This mode of irradiation relies on UHDR, a dose rate regime where conventional dosimetry monitors such as ionization chambers saturate. One potential approach is the use of a calibrated beam-based dosimetry method. The existing beam instrumentation provides real-time information on charge and both transverse and longitudinal profiles of the pulses, and makes possible a measurement of the beam Twiss parameters. In the context of achieving a real-time prediction of the dose deposition, this paper presents experimental studies of the correlation of these parameters with the read-out of passive and dose-rate independent methods such as radiochromic films, and compares them with simulation results.

INTRODUCTION

The 200 MeV electron beam at CLEAR exhibits a Gaussian profile in both transverse planes. This effectively means that the dose-distribution across a given area of interest (AOI) is a function of not only the energy and charge, but also the 1σ beam size w.r.t. the peak. All these beam parameters are readily available at CLEAR, using well-established beam instrumentation such as scintillating screens made of yttrium aluminium garnet (YAG) and cameras to measure the beam size, beam charge monitors (BCM) and a spectrometer line to measure the beam energy [1].

In order to correlate these quantities with dose deposition, in particular at high dose rates, radiochromic films are a suitable instrument, due their passive nature and dose-rate independent response, combined with the fact that they exhibit two-dimensional spatial resolution. This allows for assessing both the beam size and the dose distribution from the films. The fact that they are passive however introduces a limitation on the number of measurements which can be managed, as well as a range of uncertainties which has been describe elsewhere [2]. This paper describes the first set of CLEAR experiments aimed at establishing a correlation between beam parameters and dose depositions in radiochromic films in water.

EXPERIMENTAL SETUP

Radiochromic films were irradiated at multiple depths within a water phantom, at both conventional (CONV) and UHDR/FLASH dose-rates. Each set of film irradiations were accompanied by longitudinal scans of the beam profile using a YAG screen and measurements of the Twiss parameters to be used as input in simulations. Some irradiations in air were also performed, but are not described here.

A robotic system for sample handling, the *C-Robot*, was used to move YAG screens and films in and out of the beam during the experiments. The robot and water phantom were installed at the in-air test-stand at the end of the CLEAR beam line [1]. Figure 1 shows the robot holding a sample holder in front of the beam, which is clearly visualized by the conical blue light from Cherenkov radiation emitted by the electrons in the water phantom.

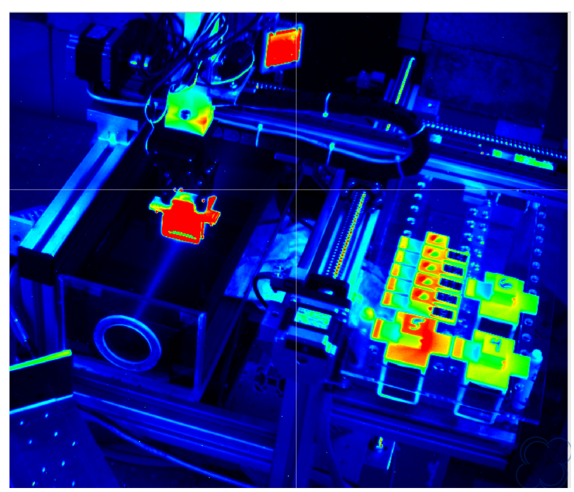

Figure 1: The C-Robot holding the YAG screen inside water in front of the beam. The Cherenkov light emitted as the beam passes through water is clearly visible.

The films were installed in robot holders with multiple slots in the longitudinal direction as seen in Fig. 2. This provides information of the beam size and dose evolution as a function of depth, which may then be correlated with the longitudinal scans performed with the YAG screen.

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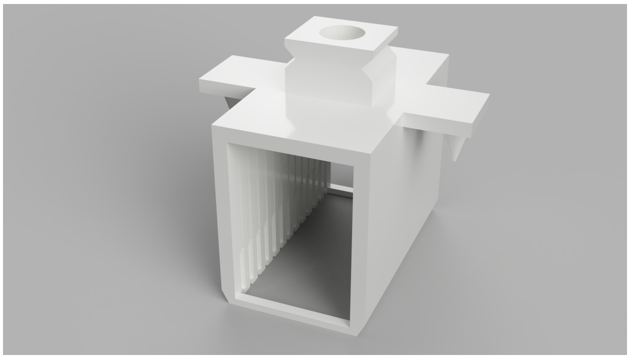

Figure 2: Robot holder for in-water film irradiations. It has a total of 14 slots placed ~ 5 mm apart, each having the capacity of holding 3 films placed back-to-back.

The irradiations were performed at ~ 200 MeV, targeting 10 nC total delivered charge. The CONV irradiations were achieved at using ~ 300 pC single-bunch trains at 0.833 Hz repetition rate. For the UHDR/FLASH irradiations the train length was increased to 41 bunches, to be able to deliver the total charge in one pulse.

IMAGE PROCESSING

Gafchromic™ MD-V3 film, which has a dynamic range of 1 − 100 Gy, was used for dose- and beam size evaluation during this experiment [3]. The irradiated films were scanned at 300 dots per inch (DPI), and the digitized images processed according to the procedure described in [2]. The dose- and beam size evaluations were then performed as follows:

- The location of the peak on the images was determined via three different methods of Gaussian fitting; 2D Gaussian fit from the astropy library [4], and 1D Gaussian fits in the horizontal and vertical directions by projection and by evaluating strips centered around the peak as defined by the 2D fitting method.
- The peak dose was determined by taking the average over a square of 5x5 pixels centered around the peak.
- The beam size in the horizontal and vertical planes were defined as the standard deviations (σ_x and σ_y) of the Gaussian fit.

A similar process was performed on the YAG screen images saved by the digital cameras.

SIMULATIONS

The evolution of the beam size was investigated using two different simulation tools, namely TOPAS and RF-Track.

RF-Track is a tracking code developed at CERN, particularly for the optimization of particle accelerators [5]. It is flexible in that one can simulate beams of particles with arbitrary energy, mass and charge, including space-charge effects for both bunched and continuous beams, as well as scattering effects through matter. It uses a less complex model for particle-matter interaction and is written in optimized and parallel C++, yielding fast performance. It is however not possible to perform a complete dose evaluation with this tool, since it tracks only primary particles.

TOPAS is a particle transport simulation tool wrapped around the GEANT4 toolkit, but with its own parameter control system for ease of use. It has been particularly developed for radiotherapy applications and medical physics, and is flexible in terms of defining both beams and geometries precisely. Furthermore, TOPAS enables users to evaluate doses and particle coordinates and momenta, allowing a reconstruction of the beam phase space. However, the computational cost for the latter is higher compared to that of RF-track due to their different implementations [6].

In both codes, the beam was defined using the Twiss parameters obtained from quadrupole scans performed ~ 5.5 m upstream of the vacuum window of the beam pipe, using a quadrupole triplet and an in-vacuum YAG screen. The simulation geometry was then defined according to Fig. 3, where the vacuum beam pipe was treated as a drift space, and scattering from air and from the two kapton windows was taken into account. The beam-size was then evaluated throughout the water phantom. From TOPAS the dose distribution was recorded as well.

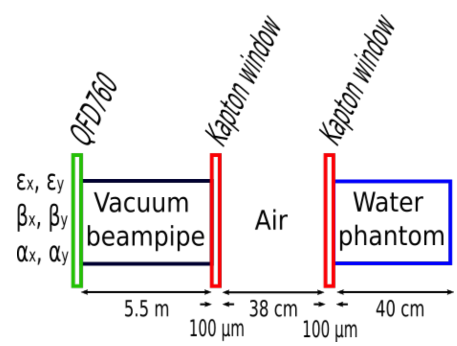

Figure 3: A schematic of the experimental setup. QFD760 refers to the entry of the quadrupole used as reference for the quadrupole scans.

RESULTS

The results of the quadrupole scans used for simulation input can be seen in Table 1.

In the graphs presented in this section, the errorbars represent the standard deviations between films irradiated in the same slots, or, in the case of YAG screens, the standard deviation between three consecutive measurements for each position. In the case of beam size measurements, the errorbars also incorporate the differences in beam size obtained using the different methods of Gaussian fitting. Figures 4 and 5 shows the beam-size evolution through the water phantom for the CONV and FLASH irradiations respectively, deduced from radiochromic films and longitudinal scans using the YAG screen. The simulation results from

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Table 1: The measured beam parameters for each irradiation. Each irradiation/holder (#) is denoted by CONV (C) or FLASH (F) corresponding to irradiation using single bunch trains at 0.833 Hz, and using a single train of 41 bunches respectively. Q is the total charge delivered to the sample, and ϵ_x, ϵ_y, are normalised emittances and β_x, β_y, α_x, α_y are the Twiss parameters measured at the entrance of QFD760, for the x and y planes.

#	Q **(nC)**	ϵ_x, ϵ_y **(mm·mrad)**	β_x, β_y **(m)**	α_x, α_y
C	10.0	29.61, 21.89	3.37, 36.67	-0.08, -0.56
F	10.4	89.06, 41.13	7.61, 19.31	-0.18, -0.54

RF-Track and TOPAS using the measured Twiss parameters from Table 1 are added for reference.

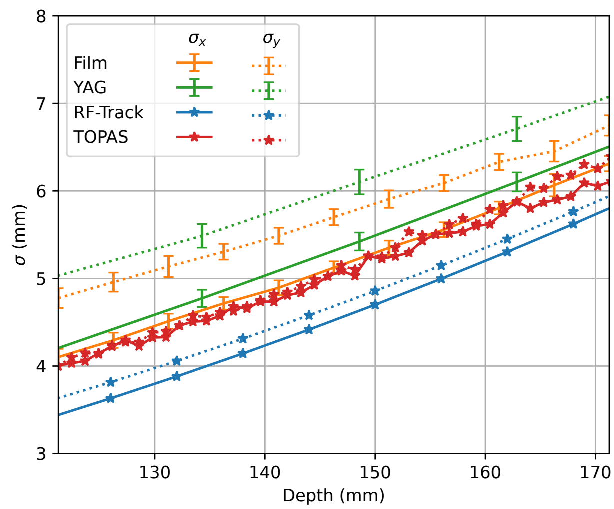

Figure 4: The evolution of the 1σ beam size as a function of depth, as measured by the films and YAG screens irradiated under CONV conditions.

The corresponding peak dose as a function of depth for both FLASH and CONV irradiations can be seen in Fig. 6. The results from the corresponding TOPAS simulations are added for reference.

CONCLUSIONS

The results achieved indicate that there is a systematic difference in the beam size measured on the YAG screen compared with the films, and the discrepancy is particularly prominent for FLASH conditions, with deviations reaching as much as $\Delta\sigma \sim 1$ mm. The simulated beam sizes from RF-Track seems to lie consistently below those retrieved by the other methods, while TOPAS yields fairly consistent results compared with the films. The source of these discrepancies must be further investigated before a reliable predictive model for beam-based dosimetry can be established. Further

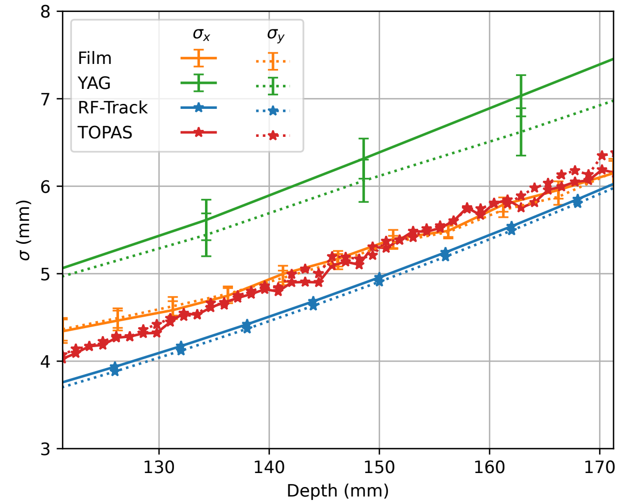

Figure 5: The evolution of the 1σ beam size as a function of depth, as measured by the films and YAG screens irradiated under FLASH conditions.

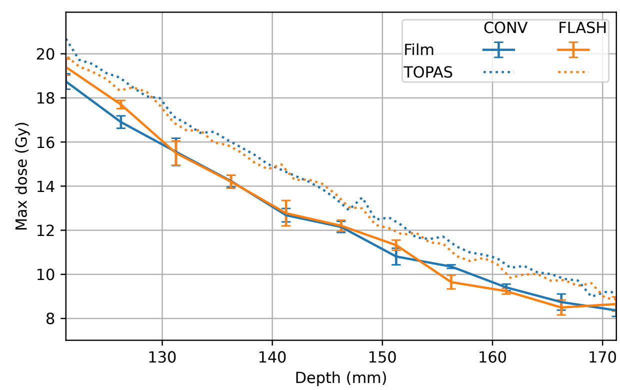

Figure 6: The evolution of the maximum dose as a function of depth, as measured by the films irradiated under both CONV and FLASH conditions.

work involves assessing if calibration, resolution and/or saturation of the YAG screens are contributing to the apparent enlarged beam size relative to the films, as this has been reported to happen [7]. In addition, more advanced simulation models which accurately captures the observed behaviour and discrepancies should be envisaged. In particular for the asymmetric beam captured by the films and YAG in Fig. 4, it is evident that there is a clear discrepancy compared with the simulations. Finally, comparisons between the various fitting algorithms used to deduce the beam size from transverse particle- and dose-distributions should be investigated in order to establish a robust and consistent approach.

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