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DOSE SIMULATION OF ULTRA-HIGH ENERGY ELECTRON BEAMS FOR NOVEL FLASH RADIATION THERAPY APPLICATIONS*

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Abstract

The synchrotron-based ELSA facility delivers up to 3.2 GeV electrons to external experimental stations. In a new setup the irradiation of tumour cells with doses of up to to 50 Gy by ultra-high energy electrons (UHEE) in time windows of microseconds up to milliseconds (FLASH) is currently investigated. This technique may enable highly efficient treatment of deep-seated tumours alongside optimal sparing and protection of healthy tissue. In a preliminary setting electrons with an energy of 1.2 GeV are used to irradiate cell samples which are located inside a water volume, representing the human body. The relative biological effectiveness (RBE) can be determined by assessing the cell survival of healthy and tumour tissues. For precise dose determination, simulations by Geant4 reproduce the electromagnetic shower process, taking the extracted electron pulse properties into account. The water volume consists of voxels of different sizes for precise investigation in the volume of interest. Various properties such as particle types, deposited energy and the energy spectra of the particle shower can be extracted. The method and first results in comparison to measured data will be presented.

ELECTRON STRETCHER FACILITY

ELSA at the University of Bonn is a three stage accelerator. In the first accelerator stage, a linear accelerator (LINAC) accelerates electrons up to 26 MeV provided by either a thermal or a polarized electron source. Then the electrons are injected into the booster synchrotron. After the acceleration of up to 1.6 GeV, the electron beam is injected into the stretcher ring with a rate of 50 Hz. In this last accelerator stage the electrons can be accelerated up to 3.2 GeV. The electron beam is typically extracted to one of the three experimental sites.

Operation Mode for Irradiation

In a newly developed mode of operation, short electron pulses of 250 ns duration and charges of up to 2.5 nC are extracted from the booster synchrotron and guided through only a part of the stretcher ring, acting as a beamline, directly to one of the experimental sites (lower right in Fig. 1). At this location a water volume is set up, in which an electromagnetic shower builds up and cell samples can be irradiated. This shower is subject to being simulated using Geant4 [1–3] to estimate the applied dose to the cell samples.

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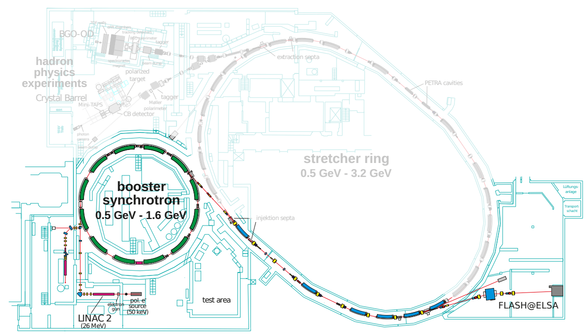

Figure 1: Overview of the facility highlighting the sections relevant for FLASH irradiation.

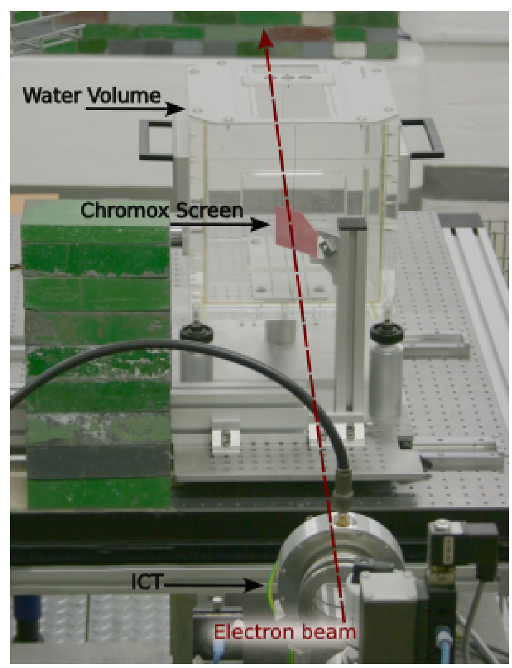

Figure 2: Experimental setup.

SIMULATION IN GEANT4

Geant4 is a toolkit that enables simulations of the passage of particles through matter by utilizing Monte Carlo methods. Geant4 is written in the object-oriented programming language C++.

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Implementation of the Setup in the Simulation

The experimental setup is shown in Fig. 2. After leaving the beam line, the electron beam passes through an Integrating Current Transformer (ICT) and traverses the Chromox screen afterwards. The Latter is used to measure the beam profile and position. The beam then enters the water phantom which is made of perspex and filled with water. Within said water, the irradiation of cell samples takes place. The geometry of the simulation is based on this setup. In the simulation an electron source is placed 1.22 m in front of the Chromox screen which is also considered in the simulation. Further downstream, the geometry of the $26 \times 28 \times 26\,\text{cm}^3$ water volume is set up. It is sliced into voxels with a size of $5 \times 5 \times 5\,\text{mm}^3$ each. The voxel size corresponds approximately to the size of the cell samples used during irradiation experiments. This size is also compromise between computation time and resolution. Around the water volume, 2 cm thick perspex plates are placed, in the simulation (Fig. 3, in white). The entry window for the electron beam has a thickness of 3 mm.

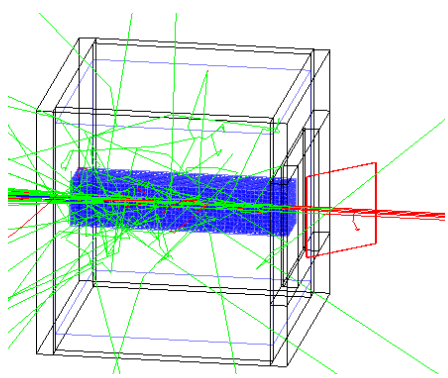


Figure 3: Visualisation of the geometry used in Geant4.

Physical Interaction

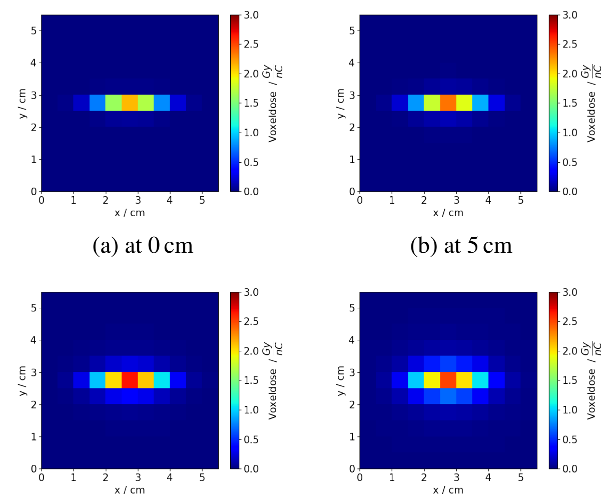
The voxels are implemented as actively monitored volume called a sensitive detector in Geant4. For each physical interaction inside a voxel, caused by the electromagnetic shower, the deposited energy, the particle type, its energy and the position of the voxel is stored in a hit collection. The physical processes to be simulated can be defined by the user or selected from a predefined physics list. Currently, the predefined electromagnetic interactions are used, which are the main processes at these energies.

Electron Beam Properties

A plane-parallel beam with a Gaussian profile with beam widths in the order of mm is used in this simulation. In addition, a particle source is being implemented which uses the Twiss parameters for the initial conditions of the electron beam. The Twiss parameters for the new operation mode are currently being determined.

Results of the Simulation

Figure 4 shows the simulated dose within the voxels for different depths. At a depth of 0 cm, only the beam profile ($\sigma_x = 6.8$ mm and $\sigma_y = 1.0$ mm,) is visible. At deeper depths an increase of the dose in the adjacent voxels due to the electomagnetic shower is visible. In the following the shown dose is normalized to 1 nC, as the charge of the electron pulse can be predetermined by the accelerator settings. In the experiment it is measured using an Integrating Current Transformer (ICT).



(a) at 0 cm (b) at 5 cm

(c) at 15 cm (d) at 25 cm

Figure 4: Dose distribution of the $5 \times 5 \times 5\,\text{mm}^3$ voxels within layers at different depths.

Two depth dose curves of the central voxel for different beam profiles are shown in Fig. 5. It can be seen that with a smaller beam profile a shift of the maximum to lower depths occurs. The dose of the entire depth dose curve is higher for the narrower beam widths which is illustrated by the different y-axis scales. The higher dose originates from the higher electron density resulting from the higher focussed beam. This results in a higher energy deposition per voxel.

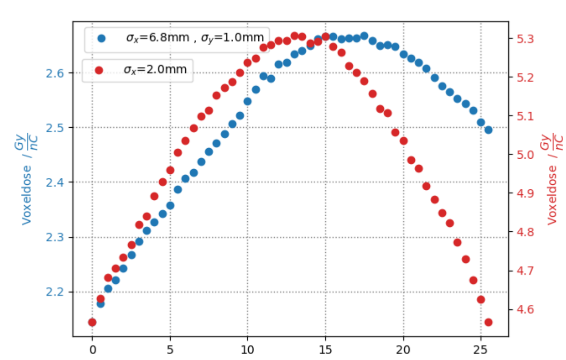


Figure 5: Simulated depth dose curve of the central voxel for two different beam profiles (neglecting divergence).

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DEPTH DOSE MEASUREMENT

Radiochromic Gafchromic-EBT3 films are used to verify doses. The films are placed at different depths in the water volume and irradiated with an electron pulse to measure the depth dose. In order to position the films correctly aluminium holders are used on which the films are placed (Fig. 6). Unwanted interaction of the electromagnetic showers with the holder is prevented by a cut-out window in the holder. To obtain a dose from the irradiated Gafchromic films the film is scanned and calibrated. The calibration is performed by a calibration film, were different, but known doses are applied. With the calibration the color profile of the irradiated Gafchromic films is mapped to a dose profile. The films (depth dose measurement as well as calibration) are scanned each after a period of 14 days, due to a time dependent darkening after the exposure. For a preliminary prediction of the dose for the biological samples, a 5 mm × 5 mm square (as a measure of sample size, also matching the voxel size in simulation) is considered around the profile maximum as shown in Fig. 7. Since the dose is not constant over the entire irradiated area, the dose is averaged respectively and hereafter referred to as the voxeldose. Therefore, a Gaussian profile is fitted to the calibrated dose profile of the film and then analytically integrated over the area of interest. In that evaluation method an offset in the Gaussian fits occurs, that due to a systematic error in the calibration and is seen in Fig. 8 as an asymmetric error in the measurement.

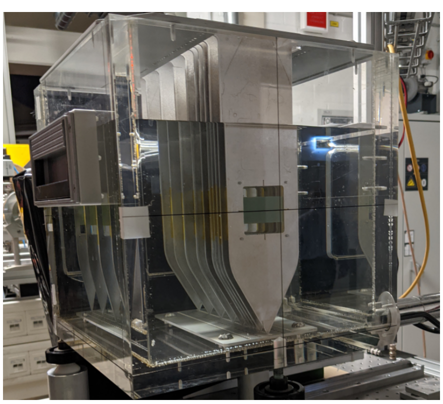

Figure 6: Water volume with Gafchromic holders inserted.

COMPARISON OF THE SIMULATION WITH THE MEASUREMENT

If one compares both the measured curve and the simulated curve (Fig. 8), it is noticeable that the shape of the two curves is in good agreement. As the position of the maximum of the measured curve can only be estimated in the range between 14 to 17 cm, this is also compatible with the simulation. However with the current simulation, there is a deviation in the absolute dose values by a factor of 2.3. A possible source of error is the beam divergence, currently being not implemented in this simulation. A particle gun with realistic beam properties utilizing the measured twiss parameters of the beam is under development. Nevertheless the measurement confirms the progression predicted by the simulation.

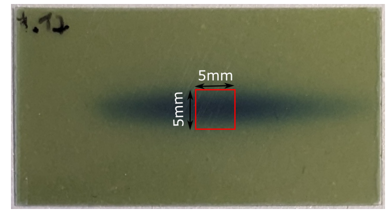

Figure 7: Photograph of a Gafchromic film form the depth dose measurement in water at 17 cm.

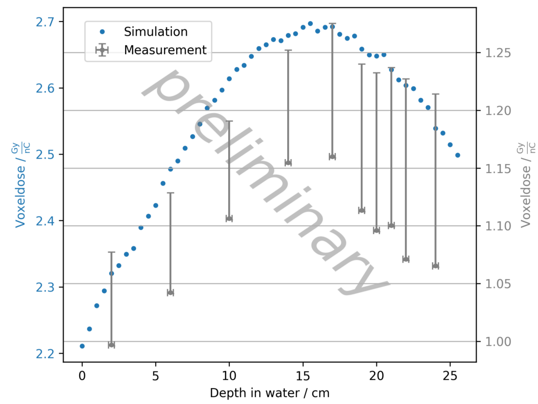

Figure 8: Comparison of simulated and measured doses. Beam properties: $\sigma_x = 6.8\,\mathrm{mm}, \sigma_y = 1.0\,\mathrm{mm}$, E = 1.2 GeV.

CONCLUSION AND OUTLOOK

The experimental setup was successfully implemented in Geant4 and first simulation results were achieved. However, further investigations such as the influence of divergence and evaluation of the Twiss parameter are still necessary. A first measurement of the dose could be performed as well. The comparison shows a good agreement between the curves, although further investigations are needed to determine the difference in dose between simulation and measurement. The first dose values should be sufficient to detect an effect in the irradiated cells.

ACKNOWLEDGEMENTS

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