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MEDICAL IRRADIATION STUDIES AT KIT ACCELERATORS

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Abstract

Radiation therapy is an important oncological treatment method in which the tumor is irradiated with ionizing radiation. In recent years, the study of the beneficial effects of short intense radiation pulses (FLASH effect) or spatially fractionated radiation (MicroBeam/MiniBeam) have become an important research field. Systematic studies of this type often require research accelerators that are capable of generating the desired short intense pulses and, in general, possess a large and flexible parameter space for investigating a wide variety of irradiation methods. The KIT accelerators give access to complementary high-energy and time-resolved radiation sources. While the linac-based electron accelerator FLUTE (Ferninfrarot Linac- Und Test-Experiment) can generate ultrashort electron bunches, the electron storage ring KARA (KArlsruhe Research Accelerator) provides a source of pulsed X-rays. In this contribution, first dose measurements at FLUTE and KARA, as well as simulations using the Monte Carlo simulation program FLUKA (FLUktuierende KAskade) are presented.

INTRODUCTION

Radiation therapy encompasses a large area in which research is being conducted into increasingly efficient radiation methods that are spatially more precise and less damaging to healthy tissue. Therefore, research accelerators usually have the advantage of a very large and flexible parameter range which can be operated variably. In general, due to their short pulsed radiation, they have a particularly high peak dose rate in the order of $10^{12}\,\mathrm{Gy\,s^{-1}}$ [1, 2]. Thus, they offer the possibility to study systematically effects such as the FLASH effect, which needs dose rates greater than $40\,\mathrm{Gy\,s^{-1}}$ [3], or even new irradiation methods with regard to their effectiveness and compatibility. The KIT accelerators FLUTE, a linac-based short-pulse electron accelerator, and KARA, an electron synchrotron storage ring, offer a unique opportunity to study for example the previous mentioned radiotherapeutic effect and the possible biological impact of high peak dose rates due to the short pulsed radiation [4, 5]. To properly design and optimize the experiments, a dosimetric characterization of the radiation is needed, therefore corresponding dose simulations in addition to experimental measurements of the dose are performed. The simulation is done with the program FLUKA, a multipurpose multiparticle code based on the Monte Carlo method. It is often used for calculations of particle transport and interactions with matter [6–8].

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Dose Concept

A relevant physical quantity for the discussion of irradiation effects on matter is the absorbed dose D since it is proportional to the biological effects [9]. It is defined as the total absorbed energy $\mathrm{d}E$ per mass element $\mathrm{d}m$ of the absorbing material with density ρ and volume $\mathrm{d}V$, namely

$$D = \frac{\mathrm{d}E}{\mathrm{d}m} = \frac{\mathrm{d}E}{\rho \cdot \mathrm{d}V}. \quad (1)$$

The SI-unit of the absorbed dose is the Gray ($[D] = 1\,\mathrm{Gy} = 1\,\mathrm{J\,kg^{-1}}$). Another important and often used quantity in radiotherapy is the dose rate

$$\dot{D} = \frac{\mathrm{d}D}{\mathrm{d}t} \quad (2)$$

which describes the time evolution of the dose. The unit of the dose rate in general is given as $[\dot{D}] = 1\,\mathrm{Gy\,s^{-1}}$.

FLUTE

A first dosimetric characterization and first proof-of-principle experiment was carried out in cooperation with the German Cancer Research Center (DKFZ) by measuring the electron depth dose curve at FLUTE.

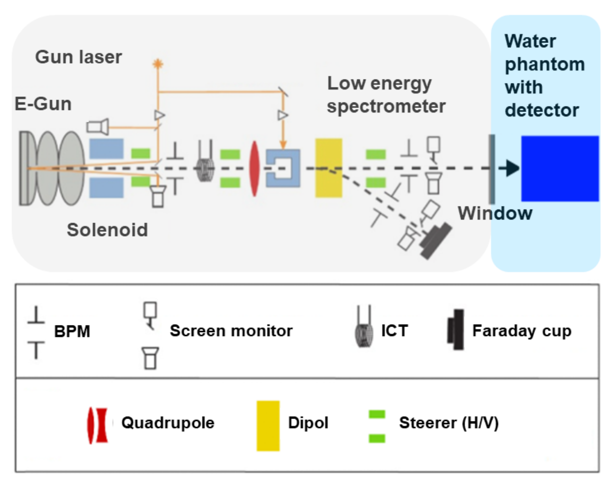

Figure 1: Schematic low energy section setup of FLUTE. The section with ultra-high vacuum (10^{-9} mbar) is marked in light gray and the section with ambient air in light blue. Adapted from [10].

Setup and Measurement

In Fig. 1, the schematic setup of the dose measurement is shown. The measurement was carried out in the low-energy

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section of FLUTE, behind the low-energy spectrometer on the straight arm, while the Faraday cup was replaced by a 150 µm thick exit window made of stainless steel. After passing the window, the electrons, with a measured initial total energy of $E \approx 5$ MeV, had to pass a 1 cm thick air gap before reaching the phantom. The detector for dose measurement, a commercial ionization chamber (Roos Chamber) from the company PTW, was located embedded in different depths of water-equivalent plates (RW3), a so-called solid water slab phantom (Fig. 2). Each single dose measurement for one depth was measured four times, each over a time period of $t = 40$ s. The measurement time t was taken manually.

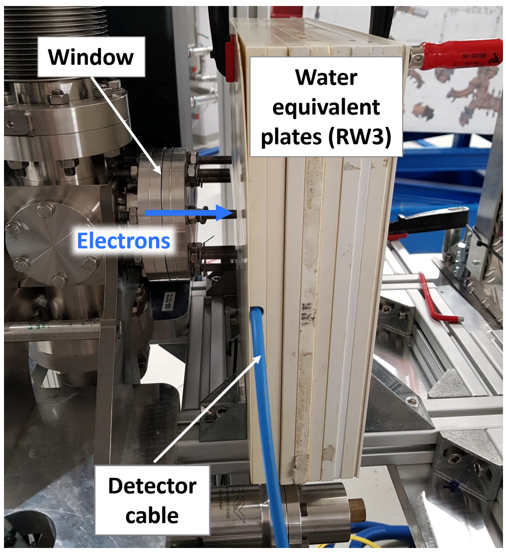

Figure 2: Depth dose curve measurement setup at FLUTE. The electrons pass through a 150 µm stainless steel window into air, where they then traverse a water phantom with the embedded detector.

FLUKA Simulation and Results

A comparison was made between simulated doses with FLUKA and the measured one. The beam parameters of the measurement were used in the simulation, but with an initial simulated total electron energy of $E = 5$ MeV. The result of the measured and simulated absorbed doses as a function of the phantom depth is shown in Fig. 3.

The curve shows the so-called build-up effect as the maximum measured absorbed dose D_{max} is reached at a depth of around 2 mm with $D = D_{max} \approx 8.06$ Gy. This corresponds to a maximum dose rate of $\dot{D}_{max} \approx 0.2\,\mathrm{Gy\,s^{-1}}$. In general, the FLUKA results have roughly the same shape including the build-up effect, but show a somewhat steeper drop between about 7 mm and 15 mm depth. Furthermore, the mean absorbed dose differs by a factor of almost nine.

KARA

Complementary dosimetric characterisation experiments were conducted at the beamlines of KARA with X-rays. Ra-

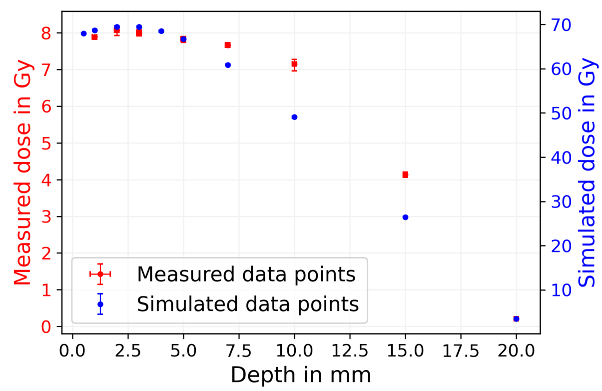

Figure 3: Accumulated average dose over 40 s with a repetition rate of $f = 5$ Hz and bunch charge of $Q \approx 350$ pC. Measured electron depth dose data points (red, left axis) with the absorbed dose error as maximal and minimal deviation of the absorbed dose mean value out of each four single dose measurements with the same detector depths. An error of $\delta d = 0.1$ mm for the detector depth is assumed. The simulated electron depth dose data points are also shown (blue, right axis). The error bars are barely visible on this scale.

diochromic films (EBT-XD) from the company Gafchromic were tested at the IMAGE beamlines.

Setup and Measurement

At the IMAGE beamline particularly intense synchrotron radiation is produced by the superconducting CLIC damping wiggler. A photon energy of 16 keV for a wider beam was selected by a monochromator. The principle of the experimental setup is shown in Fig. 4. Here, we used PMMA (polymethyl methacrylate) as a phantom. The exposure was repeated with a new film and different PMMA plate thicknesses in front of the EBT-XD film (no plate denoted 0 mm, 5 mm, and 10 mm).

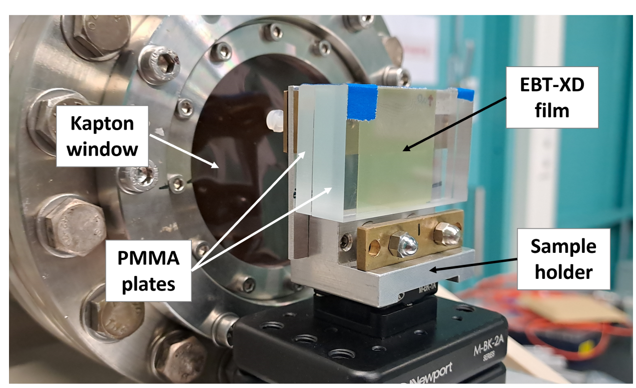

Figure 4: EBT-XD irradiation setup at the IMAGE X-ray beamline at the synchrotron KARA. Films placed between PMMA plates serve as a water phantom substitute.

After the films were irradiated for 0 s to 60 s (measurement time t taken manually), they were digitized using a calibrated

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scanner after 24 h, to ensure that the chemical reaction in films is almost complete. The digital images were then evaluated by a Python script that analyzes the optical density of the films, see Fig. 5. The calibration data was obtained from a conventional X-ray tube (MultiRad225). Since the films were unfortunately not hit in the center by the beam and this is not homogeneous, a region of interest (white box) was defined in which all dose values per pixel were averaged in order to extract a value. Plotting the averaged absorbed dose values as a function of irradiation time reveals a linear trend, see Fig. 6. The slope in Gy/s obtained from the linear fit of the individual data points provides the dose rates of the respective measurement series. Depending on the setup, the average dose rates were $1.7 \pm 0.1\,\mathrm{Gy\,s^{-1}}$ without PMMA plates, $0.72 \pm 0.02\,\mathrm{Gy\,s^{-1}}$ for 5 mm PMMA and $0.35 \pm 0.04\,\mathrm{Gy/s}$ for 10 mm PMMA in front of the films [11].

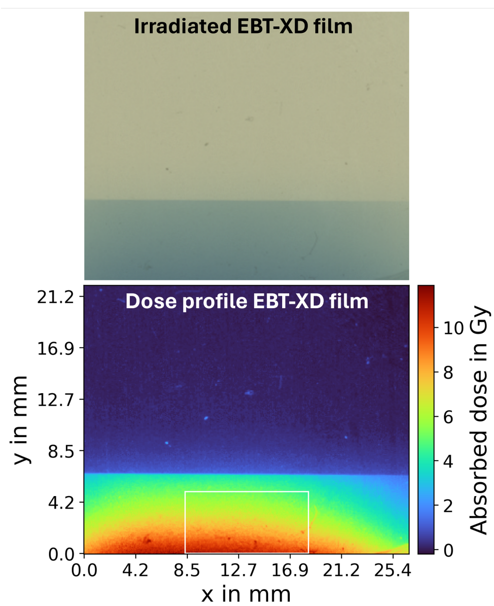

Figure 5: Irradiated EXT-XD films after an irradiation time of $t \approx 11$ s and corresponding 2D absorbed dose profile.

FLUKA Simulation and Results

To further compare and gain insights into the measurement results, equivalent FLUKA simulations were performed also for all three setups at KARA in accordance with the experimental setups. A tissue-equivalent material (A-150) was used in the FLUKA simulations for the active layer of the Gafchromic films. In this layer, the dose is determined, and a 2D dose plot is generated, see Fig. 7. The profile looks similar to the experimental profile, but the dose values differ by a factor of 20, which suggests that the films were probably not well suited for that photon energy range, according to the manufacturer, or the large deviation can be explained by the calibration measurement carried out with not pulsed 225 keV photons, which possibly makes a difference in the film reaction process.

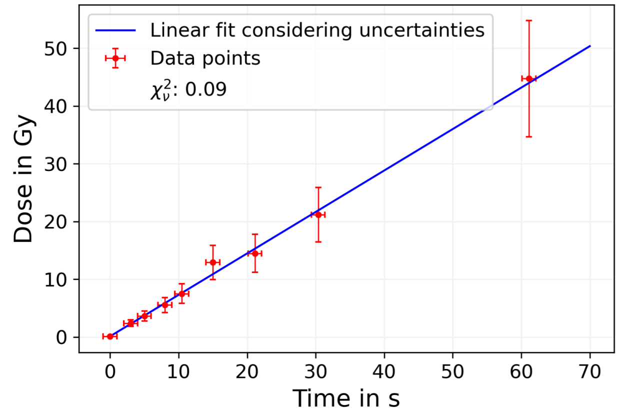

Figure 6: Measured dose at the IMAGE X-ray beamline at KARA. On the ordinate, the average dose D per EBT-XD film is plotted against the corresponding film exposure time t on the abscissa.

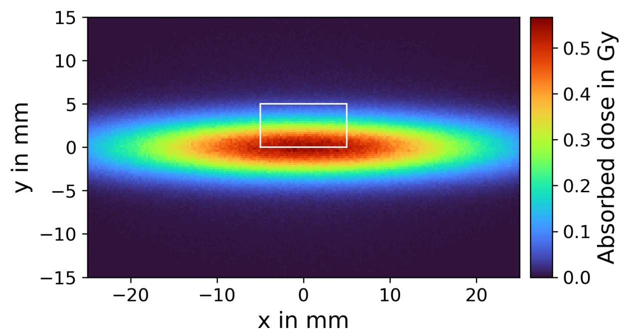

Figure 7: Simulated 2D absorbed dose profile for an exposure time of $t = 11$ s and a photon beam with Gaussian shape and an energy of 16 keV.

CONCLUSION AND OUTLOOK

First proof-of-principle radiological experiments at the KIT accelerators FLUTE and KARA are presented and show possibilities in the field of radiation therapy. To explain the large discrepancy between measurement and simulation, more measurements and improved simulations, regarding setup and material details, are needed. At the same time, it is necessary to test detectors for saturation and to improve the implemented evaluation programs. In the case of FLUTE, a new only 20 µm thin Havar window (leading to less scattering and absorption losses) is already installed for further experiments and other detectors from PTW will be tested in combination with radiochromic films from Gafchromic.

ACKNOWLEDGEMENTS

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