ADVANCEMENTS AND DOSIMETRY OF A SINGLE-TURN EXTRACTION FOR FLASH RADIOTHERAPY STUDIES AT ELSA

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Abstract

Ultra-high-energy electrons are used to investigate their effects on cell samples in nanosecond to microsecond pulses at the electron accelerator facility ELSA. This may allow highly efficient treatment of deep-seated tumors through the FLASH effect. Previous studies at ELSA using an initial extraction mode with 250 ns long pulses from the 1.2 GeV booster synchrotron demonstrated the suitability for FLASH radiotherapy studies. A newly developed single-turn extraction scheme from the stretcher ring now enables access to beam energies of up to 3.2 GeV with pulse lengths of approximately 330 ns and improved beam stability. In preparation for upcoming cell irradiation studies with this new extraction mode, precise dose determination is carried out by combining radiochromic film measurements with Geant4 simulations over the full energy range from 1.2 GeV to 3.2 GeV. Depth-dose curves from the previous and current operation modes are compared. Additionally, studies of Cherenkov radiation are performed to evaluate its potential for beam characterization.

FLASH@ELSA

FLASH@ELSA is an experiment investigating the FLASH effect [1] at the electron accelerator facility ELSA located at the University of Bonn. ELSA consists of three acceleration stages. Electrons from either a thermionic or polarized source are first pre-accelerated to 26 MeV with a linear accelerator (linac). They are then accelerated by the booster synchrotron up to typ. 1.2 GeV. Afterwards the electrons are injected with a rate of up to 50 Hz into the stretcher ring, where energies of up to 3.2 GeV can be reached.

FLASH Operation Modes

To provide ultra high dose rates (UHDR) of $\geq 40\,\mathrm{Gy\,s^{-1}}$, which defines the FLASH regime [1], suitable extraction modes to provide short pulse durations are essential. Two operation modes have been developed for FLASH@ELSA to deliver ultra-high dose rates (UHDR) for irradiation studies at different beam energies.

Booster Extraction Mode: For this mode the beam is directly extracted from the booster synchrotron and guided to the experimental site. Part of the stretcher ring functions as a transfer beamline towards the irradiation site. This extraction method provides electron pulses with a pulse length of around 250 ns and charges of up to 2.5 nC at a beam energy of 1.2 GeV.

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Single-Turn Stretcher Extraction: This extraction mode features a full beam extraction within one turn from the stretcher ring, capable of storing up to 200 mA of current at low energies. Therein, injection kicker magnets are repurposed for extraction into the external beamline [2]. Figure 1 highlights the locations of the kickers, extraction septa and irradiation site. The single-turn extraction delivers electron pulses with a length around 330 ns. Pulse charges exceeding 2.5 nC are achievable within the investigated energy range from 1.2 GeV to 3.2 GeV, with a estimated limit of 9.5 nC at 2.5 GeV.

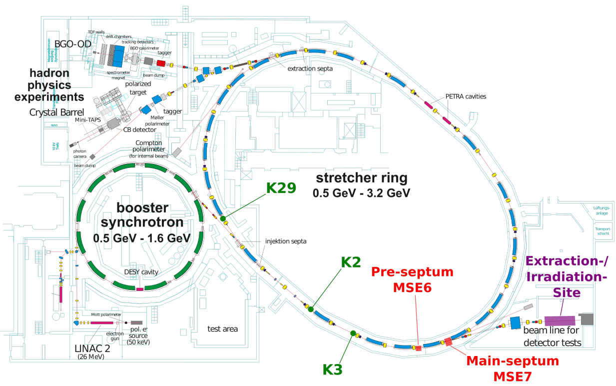

Figure 1: Accelerator facility ELSA with the marked locations of the injection kickers in green, pre- and main-septum in red and the FLASH experimental site in purple.

Irradiation Site

The electron pulses pass several detectors (Fig. 2) before reaching a water phantom for irradiation. After exiting the beam pipe through a thin kapton foil, the pulse charge is measured by an integrating current transformer (ICT). Afterwards the transverse beam profile and position is measured with a luminesce screen (Chromox). The image is analyzed by an in-house developed image analysis software package [3]. Samples and detectors are irradiated within a water phantom, simulating the interaction with the human body. To quantify the applied dose for irradiation studies, radiochromic films (GafChromic™-EBT3) are placed inside the water phantom. Overall, the setup provides comprehensive shot-by-shot information on the beam profile, position and dose distribution. This enables controlled irradiation with knowledge of the applied dose, independent of varying beam positions and profiles.

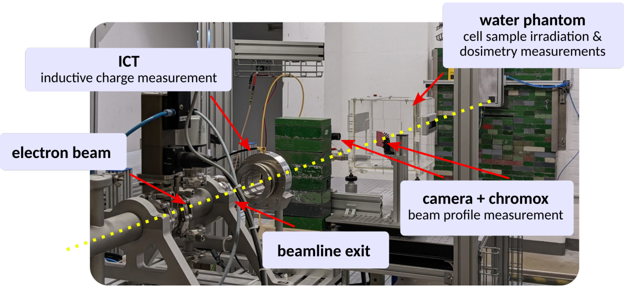

Figure 2: Setup of the experimental site for irradiation studies.

DOSE SIMULATION AND MEASUREMENT FOR ENERGIES UP TO 3.2 GeV

To monitor the efficacy of the biological effect of UHEE FLASH irradiation on cell samples, a precise dose monitoring is necessary. Therefore, tools and procedures that determine the applied doses were developed. In the current setup this is done by the evaluation of GafChromic™-EBT3 films and comparison with simulations in Geant4 [4–6].

Dose Simulation

For the simulation of the applied dose, the water phantom is modeled within Geant4 [7]. In comparison to previous studies on the dose measurements at 1.2 GeV using the booster extraction mode [8], the energy and the beam profile parameters were adjusted to match those of the new irradiation properties for the single-turn extraction mode. In preparation of the dosimetry studies for different energies, comprehensive simulations to estimate the expected dose distribution are performed. The depth dose curve for different energies produced by the simulation of the electromagnetic shower is shown in Fig 3. The simulations confirm the expected shifts of the dose maxima to larger depths and the increase in the charge-normalized dose with increasing energy.

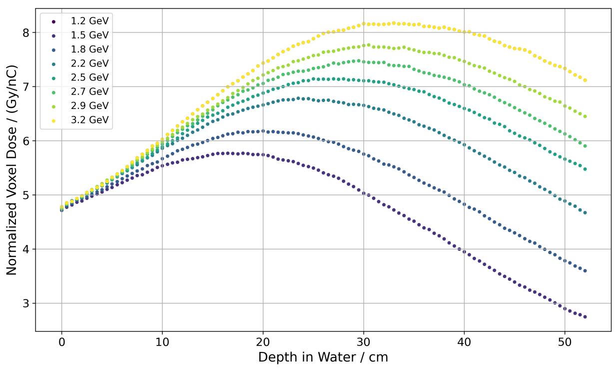

Figure 3: Simulation of the deposited dose inside a line of $5 \times 5 \times 5\,\mathrm{mm}^3$ voxels, centered to a Gaussian beam with the size of $2 \times 2\,\mathrm{mm}^2$ for different energies.

Depth Dose Curve Measurements

For the irradiation studies at increased energy up to 3.2 GeV the single-turn extraction mode is utilized. Depth dose curve measurements are performed for different beam energies using GafChromic™-EBT3 films to measure the applied dose. Therefore for each measurement multiple films are placed at different depths inside the water phantom and are irradiated with a single shot. For all subsequent simulations and measurements, the reported dose refers to the deposited dose within the central $3.5 \times 1 \times 3.5\,\mathrm{mm}^3$ voxels or the corresponding $3.5 \times 1\,\mathrm{mm}^2$ film area (horizontal×vertical), centered at the transverse beam maximum. From each depth dose curve measurement, the maximum normalized dose and its corresponding depth are determined. These values are summarized in Table 1, together with the measured beam pulse properties. The comparison shows an increase in the maximum normalized dose and a shift of the dose maximum towards greater depths with increasing beam energy, agreeing with the simulations. Due to the short pulse duration of 330 ns, the achieved dose rate is in the order of $10\,\mathrm{MGy\,s^{-1}}$ for all measurements.

Table 1: Properties of the depth–dose curve measurements, including the beam widths in both transverse directions (σ_x, σ_y), the normalized dose maximum (NDM), and the measured depth of dose maximum (DDM).

Energy [GeV]	σ_x **[mm]**	σ_y **[mm]**	**NDM [Gy/nC]**	**DDM [cm]**
1.2*	3.07	3.38	3.4 ± 0.4	≈ 17
1.8	2.26	1.80	8.1 ± 0.4	≈ 19
2.9	2.12	1.77	11.0 ± 0.6	≈ 21

*Measurement performed with booster extraction mode [8].

Figure 4 shows the measured depth dose profile in comparison with a corresponding simulation for an energy of 2.9 GeV. A good agreement between measurement and simulation is observed. This validates the suitability of the new single-turn stretcher operation for FLASH studies at ELSA.

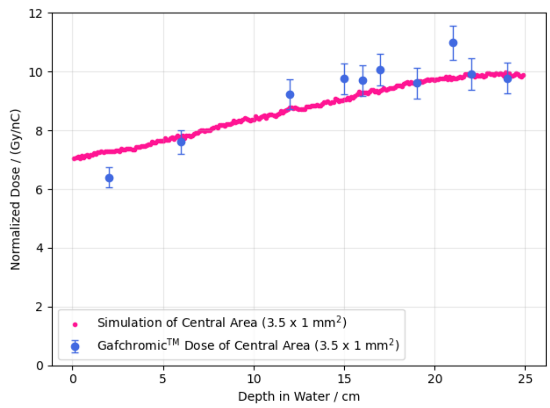

Figure 4: Measurement of the depth dose curve with GafChromic™-EBT3 films in comparison to a simulation via Geant4 at 2.9 GeV with beam properties given in Table 1.

INVESTIGATION OF CHERENKOV RADIATION

As an alternative to the established dose measurements performed with GafChromic™-EBT3 films, Cherenkov radiation is being investigated as an additional measurement technique. The Cherenkov light produced by the beam and the resulting particle shower inside the water phantom is studied as a potential tool for real time beam monitoring within the water phantom. In first quantitative measurements the emitted Cherenkov light was recorded by a camera positioned on the side of the water phantom, as shown in Fig. 5. The observed light is dominated by scattered Cherenkov light within the water phantom (which was slightly polluted to increase the effect). The scattering is increased from the dummy sample, leading to a local increased intensity. For the analysis of the Cherenkov light, the longitudinal light distribution is divided into multiple sections and corrected by background subtraction. A region of interest is defined (green segment in Fig. 5), where a clean beam signal is available.

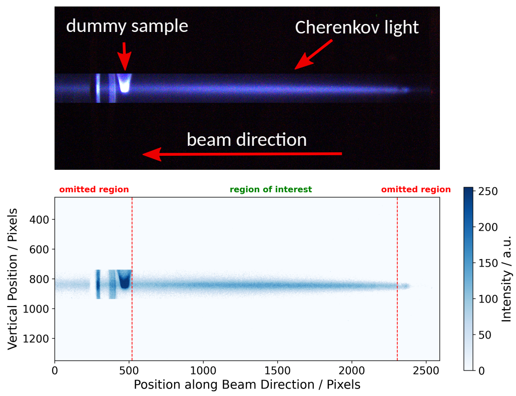

Figure 5: Top: Image of Cherenkov light produced by the electron beam inside the water volume, recorded by a camera viewing the water phantom from the side. Bottom: Longitudinal light intensity distribution after background subtraction for the region of interest (green) and the surrounding (red).

Measurement of Beam Intensity

To validate the feasibility of the Cherenkov monitor as an intensity monitor, the integrated light yield is evaluated for different pulse charges at a beam energy of 2.5 GeV. For this, the light yield is summed over the defined region of interest. Figure 6 shows a strong linear correlation of the measured Cherenkov light yield with the pulse charge. The observed excellent linearity confirms the suitability of the Cherenkov monitor as a useful tool for beam intensity measurements.

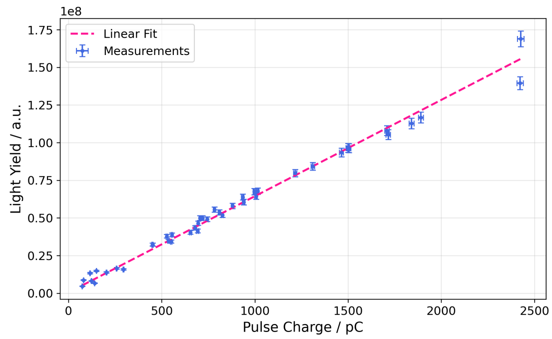

Figure 6: Correlation of pulse charge and measured intensity of Cherenkov light.

CONCLUSION AND OUTLOOK

Studies on the depth dose curve utilizing the new single-turn stretcher extraction mode have been performed successfully, demonstrating an increase in penetration depth and applied dose with increasing beam energy. The dose deposited in the GafChromic™-EBT3 films agrees with Geant4 simulations for a high beam energy. This provides evidence for the usability of GafChromic™-EBT3 under FLASH conditions for beam energies up to 2.9 GeV at ELSA. Additionally Cherenkov radiation observations are currently under investigation as a complementary diagnostic to improve the dosimetry for a precise cell sample irradiation. First measurements indicate good usability of Cherenkov radiation as an intensity monitor within the water phantom. Extended studies on the longitudinal intensity profile of Cherenkov radiation are ongoing, with the goal to obtain precise depth dose curve measurements via Cherenkov light and furthermore developing an online dose monitoring system for future irradiation studies.

REFERENCES

[1] M.-C. Vozenin *et al.*, “FLASH: New intersection of physics, chemistry, biology, and cancer medicine”, *Rev. Mod. Phys. 96*, p. 035002, 2024. doi:10.1103/RevModPhys.96.035002

[2] L. Thome *et al.*, “Development of a fast extraction method for short high intensity pulses at ELSA”, in *Proc. IBIC’25*, Liverpool, UK, Sep. 2025, pp. 142–144. doi:10.18429/JACoW-IBIC2025-MOPC032

[3] M. Switka *et al.*, “Progress on Distributed Image Analysis from Digital Cameras at ELSA Using the RabbitMQ Message Broker”, in *Proc. IBIC’23*, Saskatoon, Canada, Sep. 2023, pp. 449–452. doi:10.18429/JACoW-IBIC2023-WEP046

[4] J. Allison *et al.*, “Recent Developments in Geant4”in *Nucl. Instrum. Meth. A*, vol. 835, pp. 186–225, 2016. doi:10.1016/j.nima.2016.06.125

[5] J. Allison *et al.*, “Geant4 Developments and Applications”in *IEEE Trans. Nucl. Sci.*,vol. 53, no. 1, pp. 270–278, Feb. 2006. doi:10.1109/TNS.2006.869826

[6] S. Agostinelli *et al.*, “Geant4 - A Simulation Toolkit”in *Nucl. Instrum. Meth. A*, vol. 506, pp. 250–303, 2003. doi:10.1016/S0168-9002(03)01368-8

[7] K. Grunwald *et al.*, “Dose Simulation of Ultra-High Energy Electron Beams for Novel FLASH Radiation Therapy Applications ”, in *Proc. IPAC’23*, Venice, Italy, May 2023, pp. 4993–4995. doi:10.18429/JACoW-IPAC2023-THPM046

[8] L. Thome *et al.*, “Research on ultra-high energy electron beams for FLASH radiation therapy at ELSA ”, in *Proc. IPAC’24*, Nashville, TN, USA, May 2024, pp. 3610–3612. doi:10.18429/JACoW-IPAC2024-THPR45