# Development and Advanced Characterization of an X-Ray Flash Benchtop

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2026 JULY 19–22 VANCOUVER, BC
JOINT AAPM | COMP MEETING

## ABSTRACT

**Purpose**

Ultra-high dose rate (FLASH) irradiation has demonstrated the potential to spare normal tissue while maintaining tumor control, yet its underlying mechanisms remain unclear, particularly for low-energy X-rays where radiation quality and linear energy transfer (LET) vary strongly with beam energy and depth. The purpose of this work is to develop and dosimetrically characterize an improved benchtop kV X-ray FLASH system based on a commercial small-animal irradiator, enabling systematic investigation of FLASH irradiation under both constant and variable LET conditions using conventional X-ray tube technology.

**Methods**

A commercial orthovoltage irradiator was upgraded to a high-power configuration, 6kW, and equipped with a newly developed fast mechanical shutter optimized for ultra-short irradiation times. Dosimetric characterization was performed for filtered and unfiltered beams at tube potentials of 119–200kVp. Absolute dose and dose-rate measurements were conducted using synthetic diamond detectors, newly commissioned ionization chambers, and radiochromic films. Percentage depth dose measurements were performed in water-equivalent material at millimeter-scale depths. Monte Carlo modeling of the X-ray tube and dosimeters was performed using BEAMnrc, EGSnrc, and egs++, including explicit modeling of ionization chamber components and backscatter effects. Spectral verification was additionally performed using SpekPy.

**Results**

The upgraded system achieved dose rates exceeding 40 Gy/s under filtered beam conditions and up to 72 Gy/s for unfiltered beams at short source-to-sample distances. Percentage depth dose (PDD) measurements demonstrated dose rates above 37 Gy/s at a water-equivalent depth of 1.3 mm. Monte Carlo simulations of the unfiltered X-ray spectrum showed good agreement with SpekPy predictions, with differences below 5%. Furthermore, LET simulations demonstrated a highly homogeneous LET distribution across the irradiated field. The newly developed shutter design enabled reproducible high-dose-rate irradiations with minimal temporal uncertainty.

**Conclusion**

A high-power benchtop X-ray FLASH system was successfully developed and rigorously characterized, providing a robust platform for future investigations of the role of radiation al

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## INTRODUCTION

This work presents an upgraded benchtop kV X-ray FLASH irradiation system based on a commercial orthovoltage platform. A newly developed high-speed mechanical shutter, designed for 6 kW beam power, enables reproducible ultra-short irradiations under FLASH-relevant conditions (Figure 1). The system geometry and target tracks (Figure 2) allow photon-based FLASH delivery using conventional X-ray tube technology, expanding access to FLASH research beyond accelerator facilities. Rigorous experimental dosimetry combined with detailed Monte Carlo modeling provides a robust framework for studying FLASH irradiation under variable radiation quality conditions. In addition to dose distribution homogeneity, the linear energy transfer (LET) distribution was investigated. LET is often used as a substitute for Relative Biological Effectiveness (RBE) and is therefore an important factor when assessing potential changes in the response of normal tissue. Based on the findings, it has been demonstrated in [1] that the restricted LET for X-ray beams from 10 to 300 kVp corresponds to regions with both constant and variable LET. This can be investigated using orthovoltage X-ray systems.

## METHODS AND MATERIALS

Monte Carlo simulations were performed using the EGSnrc code [2] and the SpekPy toolkit [3] to model the X-ray source under different operating conditions. The two applications BEAMnrc and egs++, part of EGSnrc, were used. The former is optimized on particle production and the latter on particle scoring, due to their specific variance reduction techniques. Therefore, combining the two provides highly accurate and efficient simulations. Experimental validation was performed using ionization chambers and radiochromic films to measure radiation doses. Dose rate assessment was performed for both filtered and unfiltered beams, corresponding to X-ray tube energy of 160 kV. The experimental setup was carefully calibrated according to the TRS-398 protocol [4] and correction factors were applied to account for the unfiltered beam characteristics. Inventor 2024 [5] was used for the 3D design of the FLASH table-top platform system.

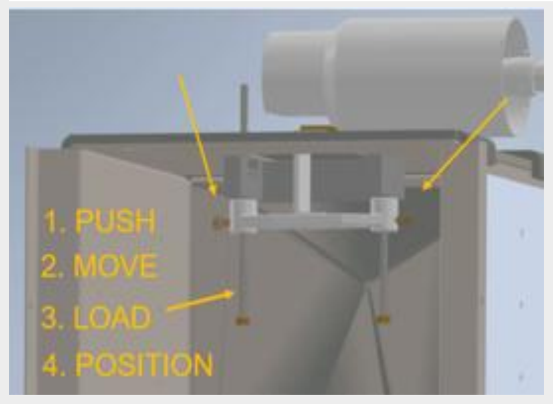


**Figure 1.** CAD rendering of the high-speed mechanical shutter designed for 6 kW ultra-high dose-rate operation.

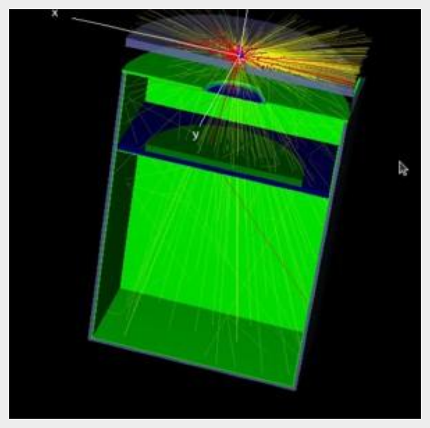

**Figure 2.** Target tracks and beam geometry of the benchtop kV X-ray FLASH irradiation system..

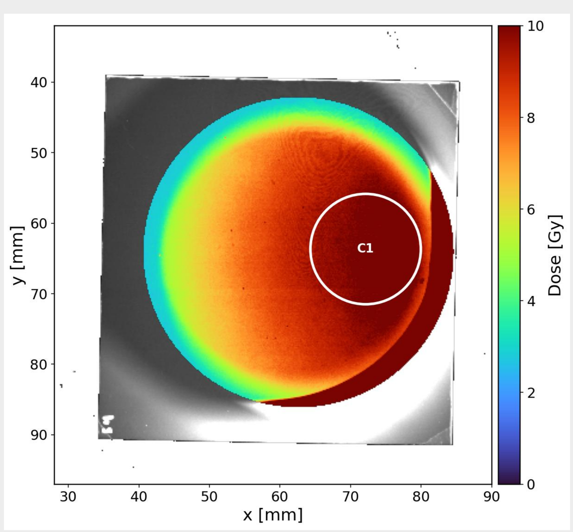


**Figure 3.** Dose maps without initial filtration to maximize the heel effect, with a circular well region of 7.0825 mm radius

## RESULTS & DISCUSSION

- Dose distributions were measured experimentally using Gafchromic film (Figure 3). A field homogeneity of 96% was achieved, demonstrating a highly uniform dose distribution under unfiltered beam conditions at a dose rate of approximately 72 Gy/s. These measurements confirm the suitability of the upgraded system for delivering homogeneous ultra-high dose-rate irradiations.
- To validate the Monte Carlo model, the simulated unfiltered X-ray spectrum was compared with the spectrum generated using the validated SpekPy toolkit (Figure 4). Since the X-ray spectrum determines key dosimetric characteristics, including beam quality, attenuation, depth-dose distribution, and LET, agreement between the two spectra provides confidence that the Monte Carlo model accurately reproduces the physical beam. This validation establishes the reliability of the model for subsequent dosimetric and LET calculations.
- The Figure 5 shows the dose attenuation as a function of water-equivalent depth. The red curve represents the Monte Carlo simulation, while the blue curve corresponds to the experimental measurements. As the photon beam traverses increasing water thickness, the dose decreases due to attenuation. The linear attenuation coefficient (μ) was obtained from the slope of the attenuation curve. A difference of approximately 10% was observed between the experimental and simulated values of μ, which is within the expected uncertainty considering both experimental and modeling limitations. The next step will be to further investigate the sources of discrepancy and refine the beam model to improve agreement between simulations and measurements.

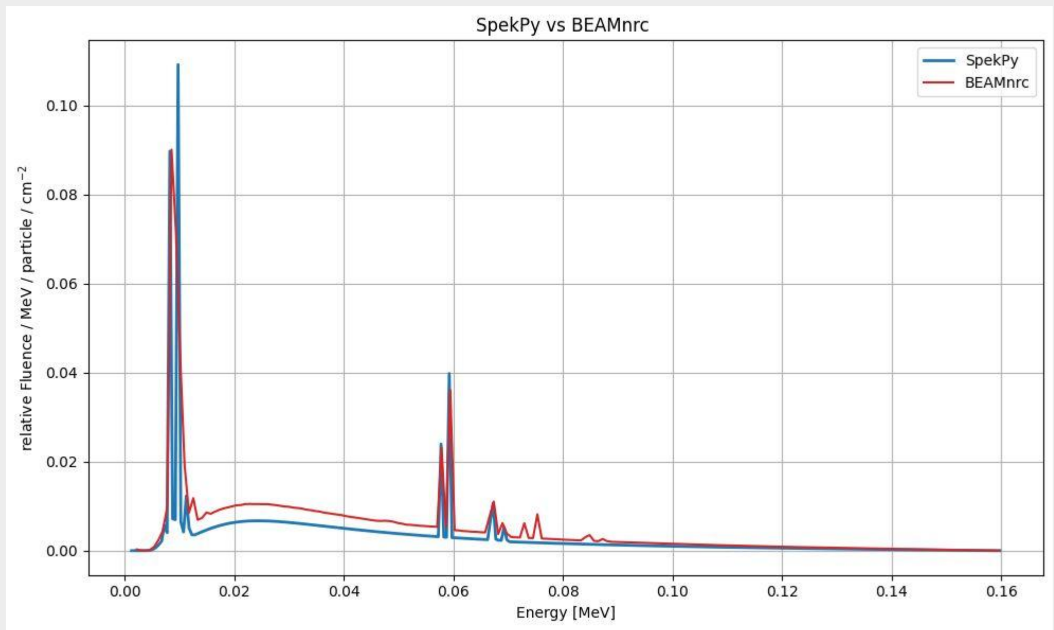


**Figure 4.** Spectral distribution comparison between SpekPy and BEAMnrc. No added filtration was used for these simulations.

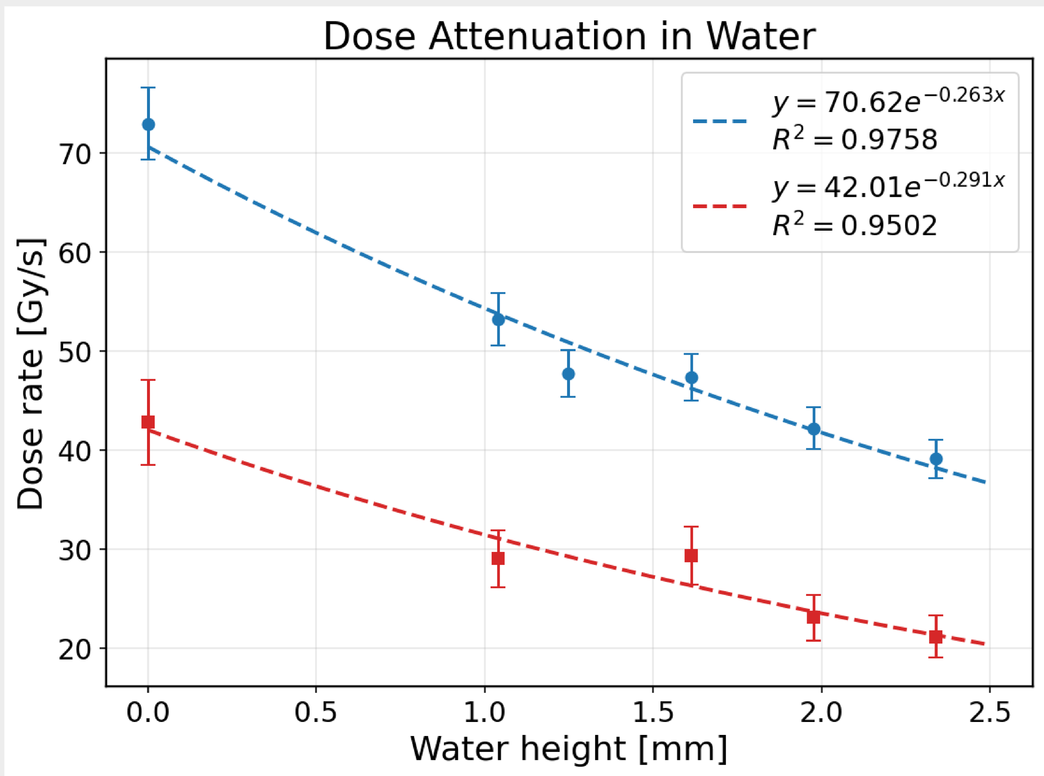


**Figure 5.** Dose attenuation as a function of water-equivalent depth. The linear attenuation coefficient can be obtained from the experiment and the simulations by finding the slopes.

## RESULTS & DISCUSSION

Figure 6 shows that LET remains relatively constant between 50 and 250 kVp, but increases sharply at lower energies. To investigate this further, Monte Carlo simulations were performed to determine the LET in the region of irradiation of our experimental measurements. The non-primary electrons were scored in voxels at regular intervals. The electron spectra (a) along the different positions showed high similarity inside the region of interest (b). Further, the LET values were calculated for each voxel and plotted per row in regards to each other. The results provide insight into the high homogeneity of the LET values in the region of interest (c), as expected by Makrigiorgos study.

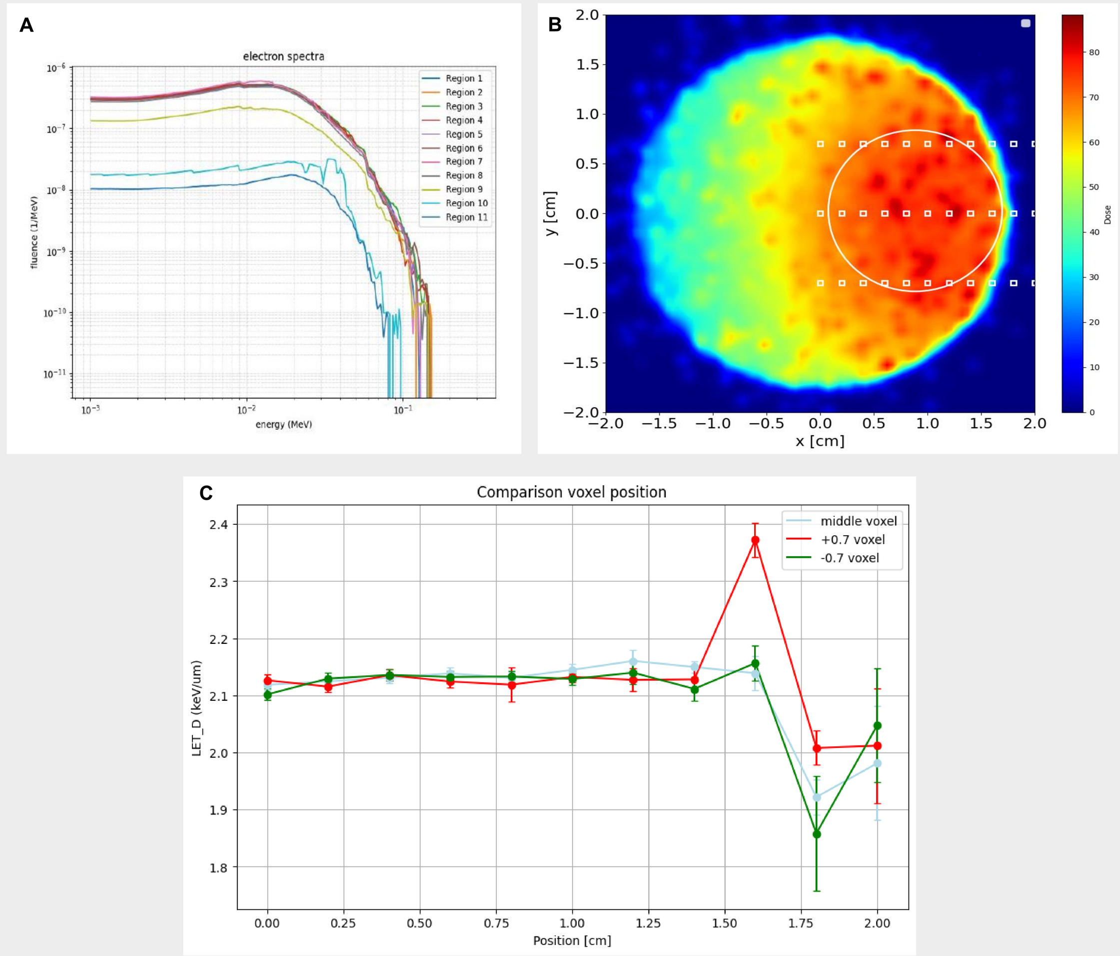


**Figure 6.** a) Electron spectra for middle voxel row; b) voxel and well position; c) LET values per position for the three rows

## CONCLUSIONS & OUTLOOK

An existing orthovoltage X-ray irradiator was successfully upgraded to deliver ultra-high dose rates suitable for FLASH radiotherapy research. The developed system achieved dose rates of up to 72 Gy/s under unfiltered beam conditions while maintaining excellent field homogeneity (96%). Experimental PDD measurements showed good agreement with Monte Carlo simulations, demonstrating the accuracy of the developed model. In addition, the simulated X-ray spectrum agreed well with SpekPy predictions, validating the beam model used for dosimetric calculations. LET simulations revealed a homogeneous LET distribution throughout the irradiated field, providing a reliable basis for future investigations of LET-dependent biological effects. The validated platform will be used for biological investigations, including cell and zebrafish embryo irradiation studies, to evaluate the effects of ultra-high dose-rate X-ray exposures. Future work will focus on correlating dose rate, LET, and biological response to improve the understanding of the FLASH effect.

1. Makrigiorgos, G., & Chin, L. M. (1991). Measurement of the restricted LET of orthovoltage and low-energy X-rays in tissue-equivalent plastic. Physics in Medicine and Biology, 36(6), 835–841. https://doi.org/10.1088/0031-9155/36/6/011LET
2. BEAMnrc Users Manual," EGSnrc, 2025. https://nrc-cnrc.github.io/EGSnrc.
3. G. Poludniowski, A. Omar, R. Bujila, and P. Andreo, "Technical Note: SpekPy v2.0—a software toolkit for modeling x-ray tube spectra," Medical Physics, Jun. 2021, doi: https://doi.org/10.1002/mp.14945
4. Absorbed dose determination in external beam radiotherapy. AUSTRIA: INTERNATIONAL ATOMIC ENERGY AGENCY, 2024
5. Autodesk Inventor 2024, Autodesk Inc., San Rafael, CA, USA. Available at: https://www.autodesk.com/products/inventor/

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