DIRECT MEASUREMENTS OF ENERGY SPECTRA UNDER ULTRA-HIGH DOSE RATE ELECTRON BEAM CONDITIONS*

A. Lenartowicz-Gasik [a,b], M. Wiktorowicz [a]
M. Dobrzyńska [a], T. Zakrzewski [a], K. Mazurek [a]
W. Soroka [a], S. Wronka [a], J. Rzadkiewicz [a]

[a]National Centre for Nuclear Research, Otwock, Poland
[b]Faculty of Physics, University of Warsaw, Warszawa, Poland

Received 31 October 2025, accepted 30 January 2026, published online 31 March 2026

Ultra-high dose rate radiotherapy (FLASH-RT) is a highly promising approach to cancer treatment, utilising ionising radiation. This innovative technique delivers the treatment dose in less than 200 ms, inducing the "FLASH effect", which spares healthy tissue while retaining tumour control. This type of dose delivery presents significant challenges for accurate dose and energy measurement, especially for a single radiation pulse. In this work, we present a method for direct measurements of the energy spectrum using a permanent magnet electron energy spectrometer, designed to evaluate the energy distribution of electron beams at a wide range of dose rates. The preliminary results obtained in the AQURE FLASH RT accelerator dedicated to FLASH research indicate differences in the energy spectra of beams, which differ in dose rate. This method makes it possible to obtain the energy spectra of even a single pulse, and to determine its most probable and average energy of the electron beams.

DOI:10.5506/APhysPolBSupp.19.1-A33

1. Introduction

Ultra-high dose rate radiotherapy (FLASH-RT) is an emerging technique delivering radiation doses above 40 Gy/s in milliseconds, inducing the FLASH effect — enhanced normal tissue sparing while maintaining tumour control. Despite promising preclinical results, the physical and biological mechanisms underlying the FLASH effect are not yet fully understood, and accurate characterisation of FLASH beams remains challenging [1]. Conventional dosimetry and magnetic spectrometers are designed for continuous or quasi-continuous beams and may produce artefacts or inaccuracies at ultra-high dose rates. Typically, beam energy is inferred indirectly through

* Presented at the XXXVIII Mazurian Lakes Conference on Physics, Piaski, Poland, August 31–September 6, 2025.

depth-dose measurements or Monte Carlo simulations, which may be inaccurate or insufficient under FLASH conditions [2, 3]. In this work, we present direct measurements of energy spectra under ultra-high dose electron beam conditions. The measurements were carried out using the AQURE FLASH RT accelerator. Preliminary results reveal measurable spectral differences between electron beams with different dose rates, confirming the need for precise spectrometric measurements under FLASH conditions.

2. Materials and methods

2.1. AQURE FLASH RT accelerator

AQURE FLASH RT was developed and built based on the clinical intraoperative radiotherapy (IORT) accelerator AQURE [4, 5]. An experimental verification of the possibility of using the AQURE IORT accelerator to obtain FLASH beams was carried out, which was the basis for the design and manufacture of the dedicated FLASH device [6]. The AQURE FLASH RT generates an electron beam with energies of 6 and 9 MeV. A dedicated beam-forming system shapes the ultra-high dose rate radiation into flat, symmetrical fields with diameters of 4–10 cm. Beam and pulse parameters, such as frequency, can be adjusted over a wide range. One of the key elements of the device is an innovative, continuously improved system for monitoring the dose deposited by the electron beam in real-time [7]. Current development efforts aim to increase the beam dose rate by delivering as much dose as possible within a single ultra-short pulse. Dosimetric measurements of ultra-high dose rate beams generated by the AQURE FLASH RT accelerator are performed using film dosimetry — Gafchromic EBT-XD radiochromic films [6, 8].

2.2. Permanent magnetic field spectrometer

In this study, we present a new method for measuring energy spectra, based on the approach proposed by McLaughlin *et al.* [9] and optimised for ultra-high dose rate beams. The spectrometer (Fig. 1) consists of a collimator forming a narrow pencil beam, two permanent neodymium magnets mounted in a ferromagnetic yoke to produce a magnetic field (0.8 T), a scintillation screen (terbium-doped gadolinium oxysulfide) to detect electron impact positions, a mirror to redirect scintillation light, and a CCD camera for imaging. The system was optimised for FLASH beams by selecting a scintillator with high light yield and fast response, tuning the parameters of the camera to capture signals with a high signal-to-noise ratio, optimising light collection, and enabling real-time data acquisition through dedicated software. Background noise was minimised and the system was calibrated to ensure precise energy reconstruction.

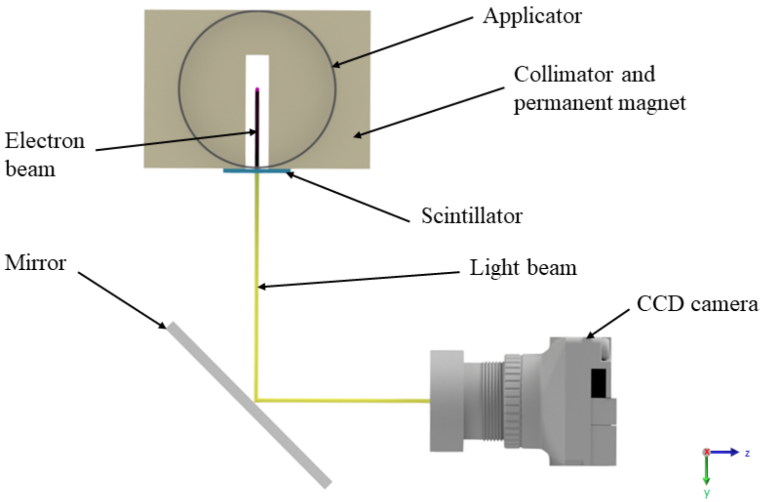


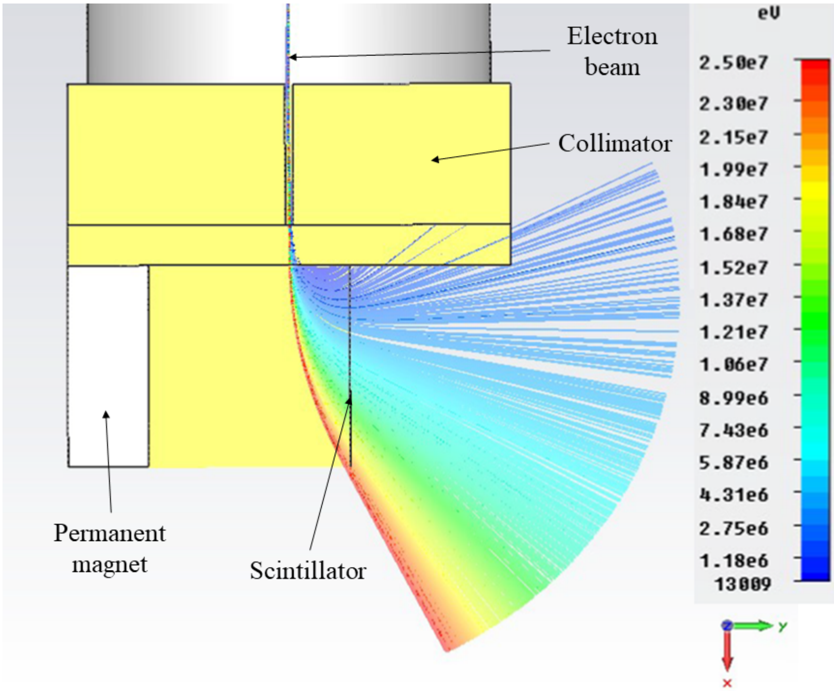
Fig. 1. Schematic cross section of the electron beam energy measurement system, showing the collimator, two permanent neodymium magnets, scintillation screen, mirror, and CCD camera used.

The spectroscopy system was simulated in CST Studio [8] to establish the relationship between electron energy and its position on the scintillation screen after magnetic deflection. The model corresponded to the actual measuring system through which electrons with energies of 0–25 MeV flowed. The simulation results (Fig. 2 (top)) show the energy-dependent positions of electron impacts on the scintillation screen, from which a calibration curve (Fig. 2 (bottom)) was derived to enable direct energy assignment.

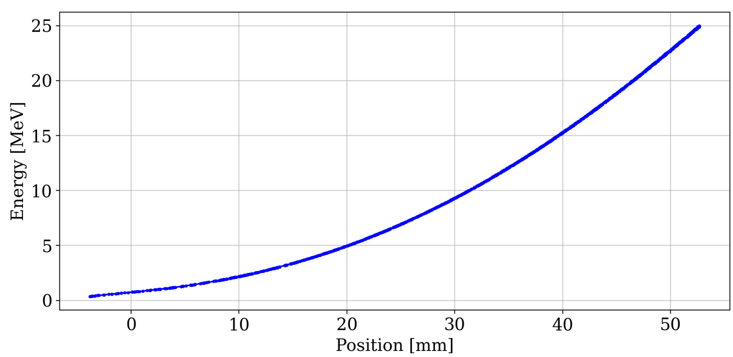
3. Results and conclusions

The proposed energy spectroscopy method has demonstrated the capability to determine electron beam energy spectra for multipulse delivery (150 pulses in 1 s) across a wide range of dose rates, from conventional to ultra-high (FLASH) conditions. Figure 3 shows the energy spectra of electron beams delivered at conventional dose rates (0.17 Gy/s), and at ultra-high dose rates of 110 Gy/s and 150 Gy/s, respectively. From the obtained spectra, the most probable energy (E_p) and the mean energy (E_0) were determined and compared with corresponding values derived from depth-dose (PDD) measurements. The comparison results are summarised in Table 1.

The preliminary results presented in this study demonstrate the feasibility of using a spectrometric system equipped with a permanent magnet and a scintillation screen for measuring electron beam energy spectra across a wide range of dose rates — from conventional to ultra-high FLASH dose



Simulation of the test electron beam in the spectrometer in CST Studio



Calibration curve of a spectrometer system

Fig. 2. CST Studio simulation of energy-dependent electron deflection (top) and the corresponding calibration curve relating scintillation screen position to electron energy (bottom).

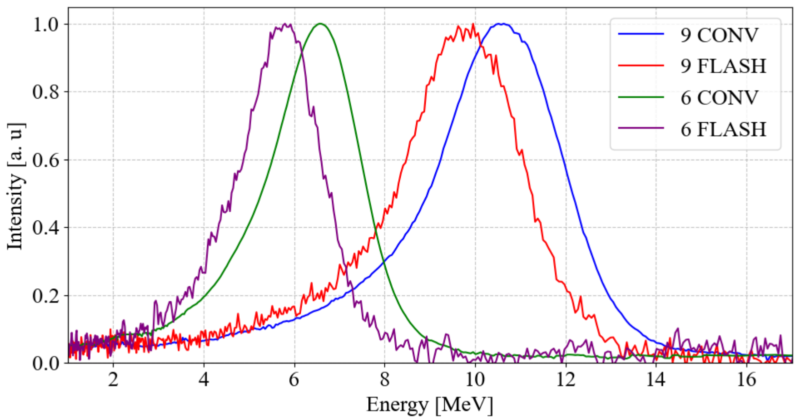


Fig. 3. Normalised energy spectra of 6 and 9 MeV electron beams at conventional (CONV) and ultra-high dose rates (FLASH).

Table 1. The most probable (E_p) and average (E_0) energies of electron beams with nominal energies of 6 MeV and 9 MeV, for both conventional and FLASH dose rates obtained from spectra and PDD measurements.

	PDD E_p [MeV]	PDD E_0 [MeV]	SPECTRA E_p [MeV]	SPECTRA E_0 [MeV]
9 CONV	11.8 ± 0.2	10.3 ± 0.2	10.6 ± 0.2	9.2 ± 0.1
9 FLASH	10.9 ± 0.2	9.7 ± 0.2	10.0 ± 0.2	8.5 ± 0.2
6 CONV	7.1 ± 0.2	6.0 ± 0.2	6.6 ± 0.1	6.0 ± 0.2
6 FLASH	6.9 ± 0.2	5.8 ± 0.2	5.8 ± 0.2	5.6 ± 0.2

rates. The obtained results (Fig. 3 and Table 1) indicate that the energy distributions of electron beams depend on the applied dose rate. Both the most probable (E_p) and the average (E_0) energies decrease with increasing dose rate, demonstrating a measurable dependence of beam energy characteristics on irradiation conditions. A comparison between the energies derived from PDD measurements and those obtained from the spectra reveals systematic differences in the absolute values of both E_p and E_0. The energies determined from PDD curves are slightly higher than those obtained spectrometrically, reflecting the intrinsic characteristics of the two techniques — the indirect estimation of energy from depth-dose relationships in PDD measurements *versus* the direct determination of energy distributions using the spectrometric method. The observed discrepancies are within the expected range for independent experimental approaches and will be the subject of further investigations aimed at understanding their physical origin and improving the accuracy of energy determination for FLASH beams. Future work will focus on measuring spectra at even higher dose rates, particularly for single pulses, which is essential for the clinical implementation of FLASH radiotherapy.

We acknowledge support from the project No. RPWP.01.01.00-30-0002/21-00 in "Wielkopolski Regionalny Program Operacyjny na lata 2014–2020".

REFERENCES

[1] J.D. Wilson, E.M. Hammond, G.S. Higgins, K. Petersson, *Front. Oncol.* **9**, 1563 (2020).

[2] D.J. Butler *et al.*, *Radiat. Meas.* **180**, 107330 (2025).

[3] J. DeFrancisco, S. Kim, *J. Appl. Clin. Med. Phys.* **2025**, e70051 (2025).

[4] A. Misiarz *et al.*, *Rep. Pract. Oncol. Radiother.* **29**, 329 (2024).

[5] A. Ryczkowski *et al.*, *Pol. J. Med. Phys. Eng.* **30**, 177 (2024).

[6] A. Lenartowicz-Gasik *et al.*, *Pol. J. Med. Phys. Eng.* **31**, 62 (2025).

[7] A. Lenartowicz-Gasik *et al.*, *Pol. J. Med. Phys. Eng.* **30**, 300 (2024).

[8] F. Romano *et al.*, *Med. Phys.* **49**, 4912 (2022).

[9] D. McLaughlin *et al.*, *Med. Phys.* **42**, 5517 (2015).