



PAPER

Thermal neutron detection and track recognition method in reference and out-of-field radiotherapy FLASH electron fields using Timepix3 detectors

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E-mail: cristina.oancea@advacam.cz**Keywords:** FLASH electron radiotherapy, thermal neutrons, Timepix3 pixel detector, ⁶LiF converter, out-of-field dose from neutrons, particle type discrimination, equivalent doseSupplementary material for this article is available [online](#)**Abstract**

Objective. This work presents a method for enhanced detection, imaging, and measurement of the thermal neutron flux. **Approach.** Measurements were performed in a water tank, while the detector is positioned out-of-field of a 20 MeV ultra-high pulse dose rate electron beam. A semiconductor pixel detector Timepix3 with a silicon sensor partially covered by a ⁶LiF neutron converter was used to measure the flux, spatial, and time characteristics of the neutron field. To provide absolute measurements of thermal neutron flux, the detection efficiency calibration of the detectors was performed in a reference thermal neutron field. Neutron signals are recognized and discriminated against other particles such as gamma rays and x-rays. This is achieved by the resolving power of the pixel detector using machine learning algorithms and high-resolution pattern recognition analysis of the high-energy tracks created by thermal neutron interactions in the converter. **Main results.** The resulting thermal neutrons equivalent dose was obtained using conversion factor (2.13(10) pSv·cm²) from thermal neutron fluence to thermal neutron equivalent dose obtained by Monte Carlo simulations. The calibrated detectors were used to characterize scattered radiation created by electron beams. The results at 12.0 cm depth in the beam axis inside of the water for a delivered dose per pulse of 1.85 Gy (pulse length of 2.4 μs) at the reference depth, showed a contribution of flux of 4.07 (8) × 10³ particles·cm⁻²·s⁻¹ and equivalent dose of 1.73(3) nSv per pulse, which is lower by ~9 orders of magnitude than the delivered dose. **Significance.** The presented methodology for in-water measurements and identification of characteristic thermal neutrons tracks serves for the selective quantification of equivalent dose made by thermal neutrons in out-of-field particle therapy.

1. Introduction and goals

Particle therapy requires a well-defined characterization of stray radiation as the scattered radiation is directed towards healthy tissue and organs at risk. It is assumed that in electron fields produced in a linear accelerator (LINAC) most of the scattered particles are electrons, photons and neutrons. Out of all secondary and tertiary particles generated in high energy electron beams, the neutrons are the most difficult to quantify as they have the ability to travel further in tissue compared to other types of particles found in the stray radiation field. Therefore,

the utilization of high-energy electron beams invariably results in the production of undesired secondary radiation from neutrons (Jaradat and Biggs 2008, Konefał *et al* 2012). The generation of secondary neutrons by electron beams involves a two-step process (NCRP 1984). Initially, an electron undergoes inelastic scattering by the Coulomb field of an atomic nucleus, resulting in the creation of a bremsstrahlung photon (Attix 2008, Khan and Gibbons 2014, Mathew *et al* 2020). Subsequently, this photon interacts with atomic nucleus through the photodisintegration reaction, leading to the ejection of a neutron from the nucleus (Attix 2008, Khan and Gibbons 2014, Mathew *et al* 2020).

Unwanted secondary effects in patients undergoing external radiotherapy are often linked to out-of-field doses. The contribution of scattered neutrons is important to quantify especially for cases of pediatric patients (Peters *et al* 2010, Mukherjee *et al* 2017), individuals with electronic devices such as pacemakers (Konefał *et al* 2020, Koivunoro *et al* 2011), those with metallic implants (Oancea *et al* 2018), and pregnant women (de Saint-Hubert *et al* 2021, Wong *et al* 2023). In the case of external radiotherapy, the out-of-field equivalent dose from neutrons presents a significant issue for the aforementioned groups. It can lead to detrimental effects, such as damage to cardiac devices. These devices are vulnerable to damage from single ionization events caused by high-linear energy transfer radiation, so even if the flux is low, they are dangerous for these specific cases (Konefał *et al* 2020, Koivunoro *et al* 2011). In case of metallic implants, additional dose near implants was detected (Oancea *et al* 2018a, 2018b). Kids and pregnant women may experience various effects, depending on the dose received, tumor location, and fetal age. However, research in this particular area remains limited and it is currently under investigation by various groups (Cravo Sá *et al* 2020, de Saint-Hubert *et al* 2021, Knežević *et al* 2022, Wong *et al* 2023).

In this investigation, the neutrons are mostly generated from the collisions between the primary electron beam and the LINAC beamline which is specifically designed to deliver ultra-high dose-rate (UHDR) beams. The quantity of generated neutrons varies depending on the characteristics of the beamline and its configuration. In our research LINAC setup, beam modifying devices were not employed. However, during patient treatment, additional collimators and beam shaping devices comprising high-Z materials are typically used. These supplementary components can lead to an elevated neutron flux. As shown in various publications (Bordy *et al* 2013, Miljanić *et al* 2014, Králík *et al* 2015, Harrison 2017, Cravo Sá *et al* 2020), neutrons were identified as a component in scattered radiation produced in conventional radiotherapy, as well as in particle therapy (Schneider and Hälg 2015, Safavi-Naeini *et al* 2018, Vykydal *et al* 2016). The contribution of thermal neutrons to the total dose is often less than 5% in conventional radiotherapy (Agosteo *et al* 1993), but this contribution to the out-of-field dose needs to be quantified when investigating the impact of scattered radiation on healthy tissue. Therefore, a complete characterization of the out-of-field radiation should be performed in high energy electron beams.

Neutron dosimeters frequently used are superheated emulsions and solid-state nuclear track detectors (Roy *et al* 1987, D'Errico *et al* 1998, Vanhavere *et al* 1998, di Fulvio *et al* 2013). They are very sensitive to neutrons, insensitive to photons, and can detect as low as few μSv with low uncertainties (Roy *et al* 1987, D'Errico *et al* 1998, Vanhavere *et al* 1998, di Fulvio *et al* 2013). However, they are passive detectors and data processing is time-consuming due to semi-automatic readout procedures. Furthermore, it is not possible to easily measure the particle flux or the dose rate. Ideally, a single compact detector would be used to measure the particle flux, the dose equivalent and the dose rate of scattered particles with the aim to characterisation of the stray radiation field of a high energy electron beam.

The Timepix detector, an active semiconductor pixel detector, is used for the detection of thermal neutrons in various applications including neutron imaging, calibrations, and the ATLAS experiment at CERN (Jakubek *et al* 2009, Campbell *et al* 2013, Krejci *et al* 2016, Granja *et al* 2023). Due to its proven detection efficiency for charged particles (Rosenfeld *et al* 2020) and gamma rays (Rubovič *et al* 2017), as well as its ability to perform online data processing (Granja *et al* 2018), this detector appears to be well suited for real-time characterisation (Charyyev *et al* 2023) of the mixed particle field characteristic for the stray radiation of a primary high energy electron beam.

The goal of this study was to provide absolute measurements of thermal neutron flux and equivalent dose inside the water tank. In that aim, customised detectors, based on the Timepix3 chip, were equipped with thermal neutron converters made out of a ^6LiF compound (Šolc *et al* 2022) to allow for measurements of thermal neutron flux in real time. To achieve the goal of this investigation, an enhanced method for particle field characterization with emphasis on thermal neutron imaging and detection using the highly-integrated miniaturized MiniPIX Timepix3 module in miniaturized customised architecture (Oancea *et al* 2022, Oancea *et al* 2023) was developed. In this investigation, a calibration of individual converters was performed in a reference field and the corresponding thermal neutron detection efficiency was determined. The neutron signals were recognized and discriminated against the other particle types such as gamma rays and x-rays using artificial intelligence and high-resolution pattern recognition analysis. Additionally, the thermal neutron fluence was converted into the thermal neutron equivalent dose using a conversion factor derived from Monte Carlo

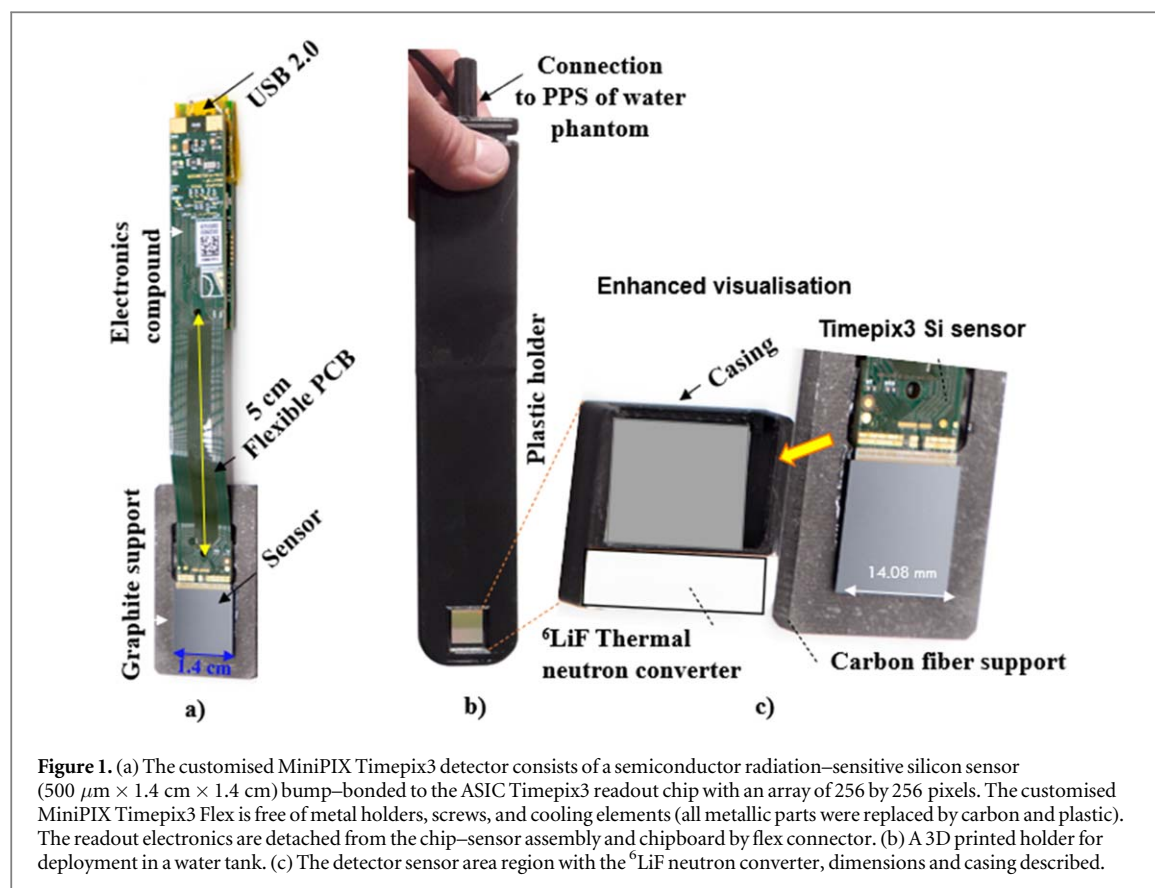


Figure 1. (a) The customised MiniPIX Timepix3 detector consists of a semiconductor radiation-sensitive silicon sensor ($500\ \mu\text{m} \times 1.4\ \text{cm} \times 1.4\ \text{cm}$) bump-bonded to the ASIC Timepix3 readout chip with an array of 256 by 256 pixels. The customised MiniPIX Timepix3 Flex is free of metal holders, screws, and cooling elements (all metallic parts were replaced by carbon and plastic). The readout electronics are detached from the chip-sensor assembly and chipboard by flex connector. (b) A 3D printed holder for deployment in a water tank. (c) The detector sensor area region with the ^6LiF neutron converter, dimensions and casing described.

simulations. The final goal was to apply the developed method to determine the quantity and the spatial distribution of the thermal neutron fluence and the corresponding equivalent dose in water generated out-of-field of the UHPDR high energy electron beams (Bourgouin *et al* 2022a).

2. Instrumentation and measurements

2.1. Timepix3 flex detectors

2.1.1. MiniPIX TPX3 flex with thermal neutron converter and graphite backing

The MiniPIX and the AdvaPIX Timepix3 detectors (Poikela *et al* 2014) used during this investigation were provided by ADVACAM (Prague, Czech Republic) whereas the Timepix3 chip was developed within the Medipix Collaboration at CERN. The ASIC read-out chip contains a matrix of 256×256 pixels (total 65536 independent channels, where one pixel size corresponds to $55 \times 55\ \mu\text{m}^2$) and an active sensor area of $14.08 \times 14.08\ \text{mm}^2$ for a total sensitive area of $1.98\ \text{cm}^2$ (Poikela *et al* 2014). Timepix3 provides two signal channels per pixel which can be set in various modes such as energy and counting, or energy and time of interaction at the pixel level. The detector's sensors were manufactured from silicon (Si). An illustration of the MiniPIX TPX3 Flex detector can be found in figure 1. For this study, the Si sensors had a thickness of $100\ \mu\text{m}$, $500\ \mu\text{m}$, or $650\ \mu\text{m}$, as listed in table 3. A picture of the detector sensor (Timepix3) is shown in figure 1(c). In figure 1(c) can be seen the detector fixed on the extruded graphite support and its thermal neutron converter (white color) placed on a 3D printed frame to support it close to the sensor area (distance of less than 1 mm).

Compared to the rigid version of the MiniPIX Timepix3 (TPX3) detector (Gohl *et al* 2022, Granja *et al* 2022), the customised Flex version has a unique design: the sensor was moved 5 cm away from the electronic components using a flexible printed circuit board (PCB) (Oancea *et al* 2023). Moreover, to minimize the radiation field perturbation, all metal parts were replaced by plastic and the chip-sensor assembly was placed on an extruded graphite support chiller, see figure 1(a). The detector electronic's component was built into the 3D printed plastic holder, which was designed to facilitate the immersion of the detector under water. The plastic holder was designed to be compatible with the positioning system of the water tank (Oancea *et al* 2023) to ease the final assembly (figure 1(b)). The holder was placed into a silicon medicinal cover (thickness of $65\ \mu\text{m}$) for waterproofing purposes.

2.1.2. AdvaPIX TPX3 Flex with thermal neutron converter and graphite backing

The main reason and advantage for which AdvaPIX TPX3 Flex was designed is the data speed rate limit of up to 20×10^6 hits s^{-1} , whereas the MiniPIX TPX3 Flex allows for a maximum data speed rate of 2.3×10^6 hits s^{-1} . Also, this detector was built into an identical 3D printed holder and an extruded graphite support was used.

2.2. Thermal neutron converter

Thermal neutrons from the stray radiation field are detected through their interactions with the ^6Li nucleus present in the converter layer which is facing the detector's sensor. The disintegration of created ^7Li nucleus generates tritium and helium ions. One of these ions can be then observed as distinct circular clusters on the sensor of the detectors. The converter layer (see figure 1(c)) was placed just above the upper section of the sensor, whereas the other area of the sensor remained unmasked and it was used for other purposes within the same experiment (e.g. beam imaging, dose measurements). Lithium was previously used as a converter for thermal neutrons (Voytchev *et al* 2003, Campbell *et al* 2013, Finocchiaro *et al* 2018, Granja *et al* 2023). In this investigation, the converter consisted of a thin layer ($\sim 10 \mu\text{m}$) of LiF compound with lithium enriched to 86% of ^6Li which has a high absorption cross section of 938(6) barns for thermal neutrons with kinetic energy of 0.025 eV (Meadows and Whalen 1970). The ^6LiF was mixed with dispersive glue and sprayed on the inner surface of 25 μm thick aluminum foil positioned 300(50) μm above the sensor surface. As converter layers were not perfectly uniform through all detectors, each detector-converter pair was calibrated in a thermal neutron reference field. The calibration constant, i.e. thermal neutron detection efficiency, was defined as the ratio between the number of detected circular clusters in the defined area behind the converter layer and the reference thermal neutron fluence. During the calibration, the settings (e.g. detector bias, per-pixel discharging parameter, called *ikrum*, etc) were kept as during the measurements of thermal neutron flux in the UHPDR electron beam. More details on the thermal neutron reference field and the calibration method will be presented in section 2.5.

2.3. Detector operation and readout modes

Timepix3 detectors operate each pixel simultaneously in *time* and *energy* mode. The time of arrival (ToA) can be identified with a resolution of 1.6 ns, whereas the time over threshold (ToT) of the respective pixel can be measured (Turecek *et al* 2016). For higher fluxes, the detector can be operated in frame mode (Event + iToT) and measures the integrated per-pixel deposited energy (iToT, which provides dosimetry information) and the number of hits in each pixel (events, which provide information regarding the beam intensity) (Granja *et al* 2022). In this investigation, for the purposes of calibration, all detectors were operated in data-driven mode (ToA+ToT) with a 5 keV threshold and a bias so as to have a fully depleted volume (e.g. +200 V for the 500 μm Si sensor) (Granja *et al* 2021). For the experiments in electron beams, the detector was operated in frame mode due to a high flux with an acquisition time of 0.1 s. The per-pixel threshold calibration and per-pixel energy calibration was performed at Advacam Laboratory (Jakubek 2011). The per-pixel calibration procedure (Jakubek 2011) relies on measurements of x-ray fluorescence photons resulting from excitation of In (24.7 keV), ^{55}Fe (5.9 keV), low-energy gamma rays from radionuclide source of ^{241}Am (59.5 keV). These measurements serve as the basis for the subsequent derivation of calibration function parameters through the fitting of the ToT spectral peaks that have been measured. Consequently, employing the appropriate calibration matrices allows to obtain the per-pixel energy deposited by each detected particle ranging in this case from 5 keV to over 2200 keV.

Moreover, a detection efficiency calibration was performed for thermal neutron detection with a reference thermal neutron source.

2.4. Method for particle-event recognition and particle flux quantification

2.4.1. Features of cluster track parameters

The 'data processing engine' (DPE) is an extensive data processing tool (Marek *et al* 2023) developed by ADVACAM and it processes all types of data formats measured by the Timepix3 detectors (Oancea *et al* 2023). It includes software that is able to: (i) process the pixelated information and convert it into clusters and their cluster features/parameters, (ii) plot the histograms of each cluster parameter (via integrated Python scripts), (iii) calculate the absorbed dose, particle flux, and other physical quantities, (iv) discriminate the particle type in mixed radiation fields (Granja *et al* 2018 showed examples of resolved tracks of single particles in a mixed radiation field), and (v) calculate the integrated sum of deposited energy and number of events in a frame. In addition, this tool supports the customization of data analysis by the implementation of filters and masks. The filters are a set of cluster parameters exclusion intervals that can be set to remove background or unwanted events (Novak *et al* 2023). The cluster features were used as inputs for training a neural network for particle classification, and a complete list of the used parameters is provided in table 1. In figure 2(a) can be seen the histogram of the spectrometric parameter height for recognized thermal neutron interactions (black line) and photons (red line), demonstrating a clear separation between the two types of particles. Conversely, in figure 2(b)

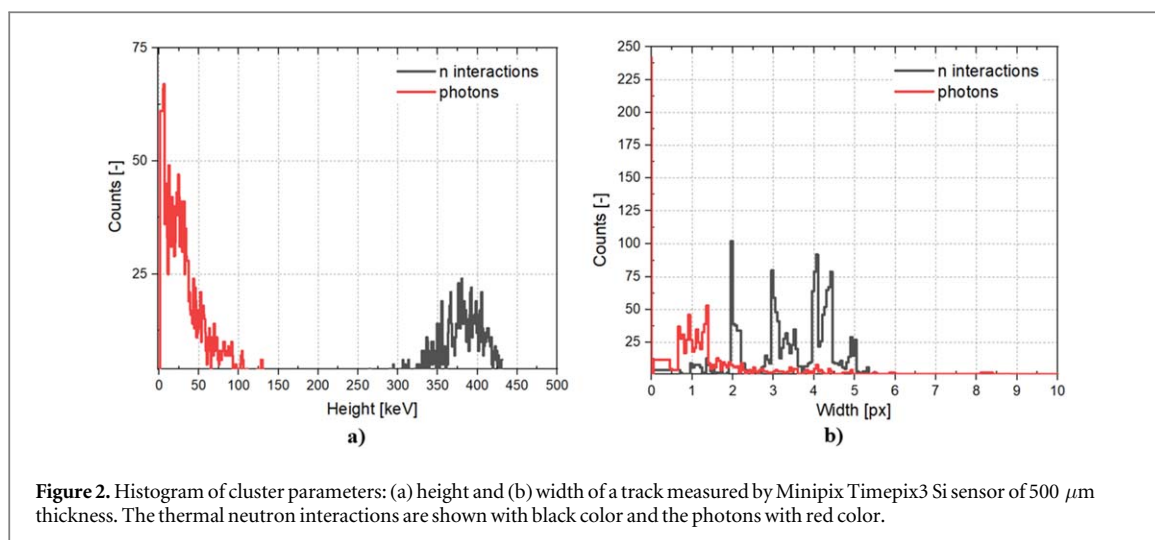


Figure 2. Histogram of cluster parameters: (a) height and (b) width of a track measured by Minipix Timepix3 Si sensor of 500 μm thickness. The thermal neutron interactions are shown with black color and the photons with red color.

Table 1. Track parameters used by the neural network for the particle classification for separation of thermal neutron-induced events and background radiation.

Parameters	Description
Size [pixel]	area of a track
Linearity [a.u]	shape of a cluster, similarity to a line
Length [pixel]	distance along the main axes of the track
Height [keV]	maximum deposited energy in one pixel by a track
Energy [keV]	deposited energy by a track
Roundness [a.u]	shape of a cluster and similarity to a circle
Border pixels [counts]	number of pixels from the vicinity of the track
Width[px]	length perpendicular the main axes of the track

is displayed the histogram of the width parameter, revealing an overlap between the two histograms representing recognized particles. By combining all seven cluster analysis parameters features is achieved the separation of thermal neutron interactions from photons. All histograms of used parameters of AI NN can be seen in as detailed in Supplementary data.

2.4.2. Particle classification with neural networks

The data processing engine is capable of particle classification by means of several algorithms: (i) heuristic decision trees, (ii) neural networks, and (iii) convolutional neural networks. This study exploits a Neural Network (NN) for the particle classification. The NN method was developed for Timepix3 detectors with Si sensors of various thicknesses. Several models with different classifications were developed for different detector setups. However, the model of interest in this work contains two classes: (i) highly ionizing heavy particles generated in the converter by thermal neutron interactions and (ii) background radiation characterized by weakly ionizing electrons created by photons.

The Python library Tensorflow (Abadi *et al* 2022) was used for the neural networks. At the input, the cluster parameters are used which represent the morphological and spectral features of the particles. These are propagated through two hidden layers, each with 20 neurons containing ReLU activations functions (Nair and Hinton 2010). The last output layer is represented by two neurons with softmax activation functions. This function was selected to calculate the probability for each class (Aggarwal 2018). The two neurons represent: (i) tracks corresponding to thermal neutron interactions and (ii) background radiation. The final predicted class is the one with the highest probability. The data sets used for the training and testing were collected in well-defined radiation fields of thermal neutrons, and electrons and photons. They were separated into one data set for training (containing 80% of the data) and the remaining data (20%) were used as a testing data set.

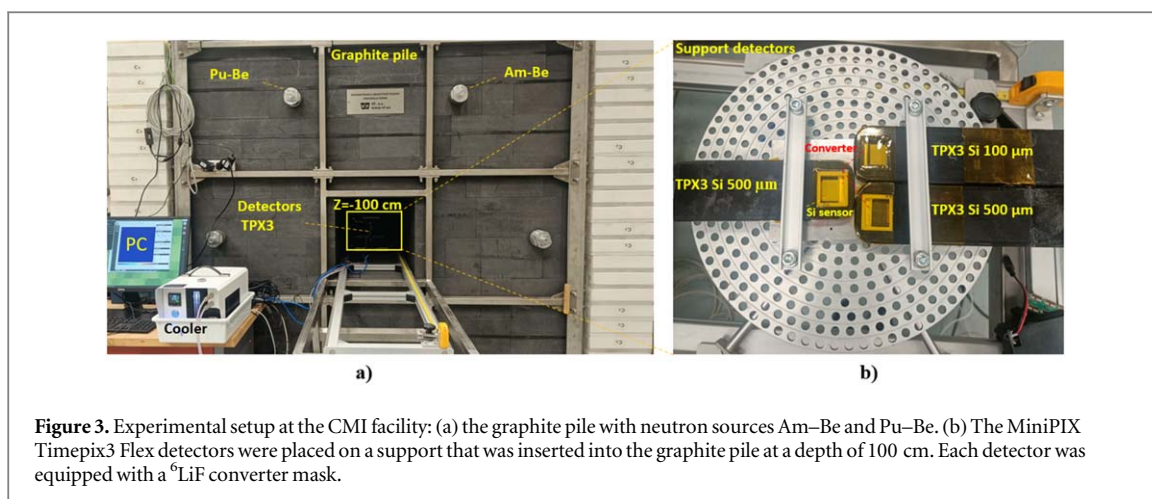


Figure 3. Experimental setup at the CMI facility: (a) the graphite pile with neutron sources Am–Be and Pu–Be. (b) The MiniPIX Timepix3 Flex detectors were placed on a support that was inserted into the graphite pile at a depth of 100 cm. Each detector was equipped with a ^6LiF converter mask.

2.5. Calibration at reference thermal neutron field at the graphite pile

The calibration of the detectors with individual converters was performed at the Czech Metrology Institute (CMI) which uses graphite pile (Vykydal and Králík 2018) to maintain reference thermal neutron field for metrology and dosimetry purposes. It consists of three Pu–Be and three Am–Be radionuclide sources positioned in a star pattern inside a $1.95 \times 1.95 \times 2.0 \text{ m}^3$ (width, length, height) graphite moderator block as illustrated in figure 3. The pile has an experimental channel in its center with dimensions of $40 \times 40 \times 135 \text{ cm}^3$ (width, length, depth). The calibration measurements were carried out at the reference point inside the pile. The reference thermal neutron fluence rate (isotropic field) was $\Phi_{\text{ref}} = 2.91(5) \times 10^4 \text{ cm}^{-2} \text{ s}^{-1}$ (Vykydal and Králík 2018), the uncertainty (number in brackets following a reported value) is given for $k = 1$ (GUM-2008 2008). The following formula was used to calculate the thermal neutron detection efficiency, η , for each pair of detector-converter:

$$\eta = \frac{N_a - N_b}{\Phi_{\text{ref}}}, \quad (1)$$

where N_a is the number of circular clusters measured under the ^6LiF converter initiated by thermal neutron interactions (clusters particles $\text{cm}^{-2} \cdot \text{s}^{-1}$), N_b is the number of the same type of clusters but measured in the area without the ^6LiF converter (background area), (clusters particles $\cdot \text{cm}^{-2} \cdot \text{s}^{-1}$).

2.6. Measurement of the stray radiation in water

The experiment to test the method for thermal neutron detection was carried out at the electron accelerator facility of the National Metrology Institute (NMI) of Germany, Physikalisch-Technische Bundesanstalt (PTB) in Braunschweig, which is described in detail in (Schüller et al 2019). The facility is equipped with a research LINAC which provides reference ultra-high pulse dose rate (UHPDR) electron beams with a dose per pulse ranging from 1.8 Gy to over 10.3 Gy (for a pulse width of $\sim 2.4 \mu\text{s}$) inside the water tank center to the beam at a depth of 4.65 cm (positions A in figure 4(c)) (Bourgouin et al 2020, Bourgouin et al 2022b, 2022a). The used values of dose per pulse correspond to a dose rate interval of 9.0 Gy s^{-1} to 51.5 Gy s^{-1} at a constant pulse rate frequency of 5 Hz.

The primary 20 MeV electron beam passed through a 0.1 mm Cu exit window before being intercepted by the water tank ($30 \times 30 \times 30 \text{ cm}^3$) positioned 50.0(3) cm downstream as illustrated in figure 3(a). The polymethylmethacrylate (PMMA) water tank front wall was 9.98 mm thick. The water tank was equipped with a remotely controlled X, Y, and Z axes positioning system. Two hybrid semiconductor Timepix3 pixel detectors were fixed to the positioning system with the help of a specifically designed plastic double holder (see figure 1(b)) and were immersed into the water tank. The whole detector holder setup was remotely moved to various lateral positions for the two water-equivalent depths used during this investigation, i.e. 12.0(3) cm and 18.5(3) cm. The measurements were performed with the detectors placed at an angle of 0° —beam perpendicular to the detector's sensor. The dose delivery to the water tank was monitored online by an in-flange integrating current transformer (ICT) (Bergoz, Saint-Genis-Pouilly, France) (Schüller et al 2017). The ICT signal has been cross calibrated against the absolute charge measurement using a Faraday cup and absolute dose to water using alanine dosimeters (Bourgouin et al 2022a). The ICT signal can measure the total charge of individual beam pulses (Schüller et al 2017), which is typically between 30 and 230 nC (Bourgouin et al Bourgouin 2022b, 2022c). In addition, a calibrated FlashDiamond detector prototype (Kranzer et al 2022, Bourgouin et al 2022a) was placed in the middle of the two Timepix3 pixel detectors, to provide in-water monitoring of the dose rate. The Timepix3

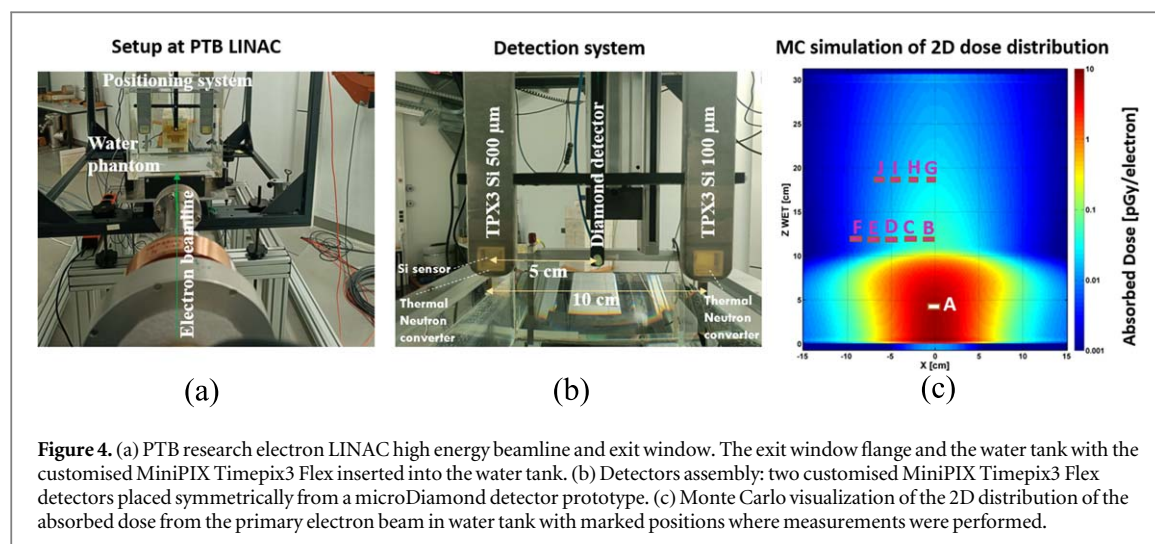


Figure 4. (a) PTB research electron LINAC high energy beamline and exit window. The exit window flange and the water tank with the customised MiniPIX Timepix3 Flex inserted into the water tank. (b) Detectors assembly: two customised MiniPIX Timepix3 Flex detectors placed symmetrically from a microDiamond detector prototype. (c) Monte Carlo visualization of the 2D distribution of the absorbed dose from the primary electron beam in water tank with marked positions where measurements were performed.

detectors were operated in frame mode (Event+iToT) with an acquisition time of 0.1 s in order to image individual pulses of $2.4 \mu\text{s}$ duration and a frequency of 5 Hz.

2.7. Monte Carlo simulations

All Monte Carlo simulations were performed in the general-purpose MC code MCNP6.2[®] (Werner 2017) with neutron cross section library ENDF/B-VIII.0 at 293.6 K (Conlin et al 2018), photonuclear reaction library ENDF/B-VII.0 (Chadwick et al 2006), and electron-photon relaxation library EPRDATA14 (Werner et al 2018).

2.7.1. Thermal neutron equivalent dose

One of the aims of this investigation was to quantify the out-of-field dose from thermal neutron in the stray radiation field. To do so, the radiological protection quantity equivalent dose in tissue, H_T was used (ICRP 2010). Tabulated conversion factor from fluence (ICRP 2010) was not applied since the neutrons are thermalized inside the water and the original neutron spectrum entering the water tank (if originated outside) or generated inside is unknown and the tabulated values were determined for external exposure only. Therefore, the conversion factor from thermal neutron fluence to equivalent dose, k_H , was determined by means of Monte Carlo (MC) method. The following assumptions were made: (i) the tissue for which the H_T is determined is the ICRU 4-component tissue (ICRP 2010); (ii) for simplification, the geometry for which the H_T is determined is the ICRU sphere (ICRP 2010), although equivalent doses are otherwise calculated using anthropomorphic phantoms (ICRP 2010) and (iii) H_T includes both direct contributions from thermal neutrons as well as the contribution from secondary photons generated by neutron interactions. Points of origin of thermal neutrons were homogeneously sampled within the water tank volume and the neutrons were emitted isotropically with energy distribution following the thermal neutron peak and with the maximum neutron energy limited to 0.25 eV. The scored quantity was the equivalent dose which was divided into neutron and photon components. The neutron component of H_T was obtained using the energy heating tally F6 modified with a constant equal to 2.5 which is the radiation weighting factor for thermal neutrons (ICRP 2007). The F6 tally was scored using energy losses (kerma factors) available in the neutron cross section tables. The photon H_T was obtained using the same tally type, but without the multiplication constant since w_R is unity for photons (ICRP 2007). The final H_T was obtained as the sum of the results for neutrons and photons. To obtain k_H , the H_T was divided by the average thermal neutron fluence in the ICRU sphere which was scored using the F4-type tally (average fluence in volume).

2.7.2. Electron accelerator model

The modelled geometry consisted of 200 cm long final part of the beamline, the exit window embedded in the stainless-steel flange, and the realistic water tank with PMMA walls. The point source was positioned at 118 cm from the exit window with a monoenergetic spectrum of 20 MeV. The electrons generated were isotropically distributed into a cone with the vertex angle of 2° . Such definition is a simplification of the real beam which has the Gaussian profile with a sigma of 0.047 MeV (Bourgouin et al 2022a). However, the defined beam source was sufficient for simulations related to neutrons which originate primarily in the metal components of the beamline by interactions of bremsstrahlung photons. The spatial distribution of thermal neutron fluence in the water tank was scored using a cylindrical mesh tally with mesh bin width and depth of 5 mm. The neutron was scored if its energy was below 1 eV.

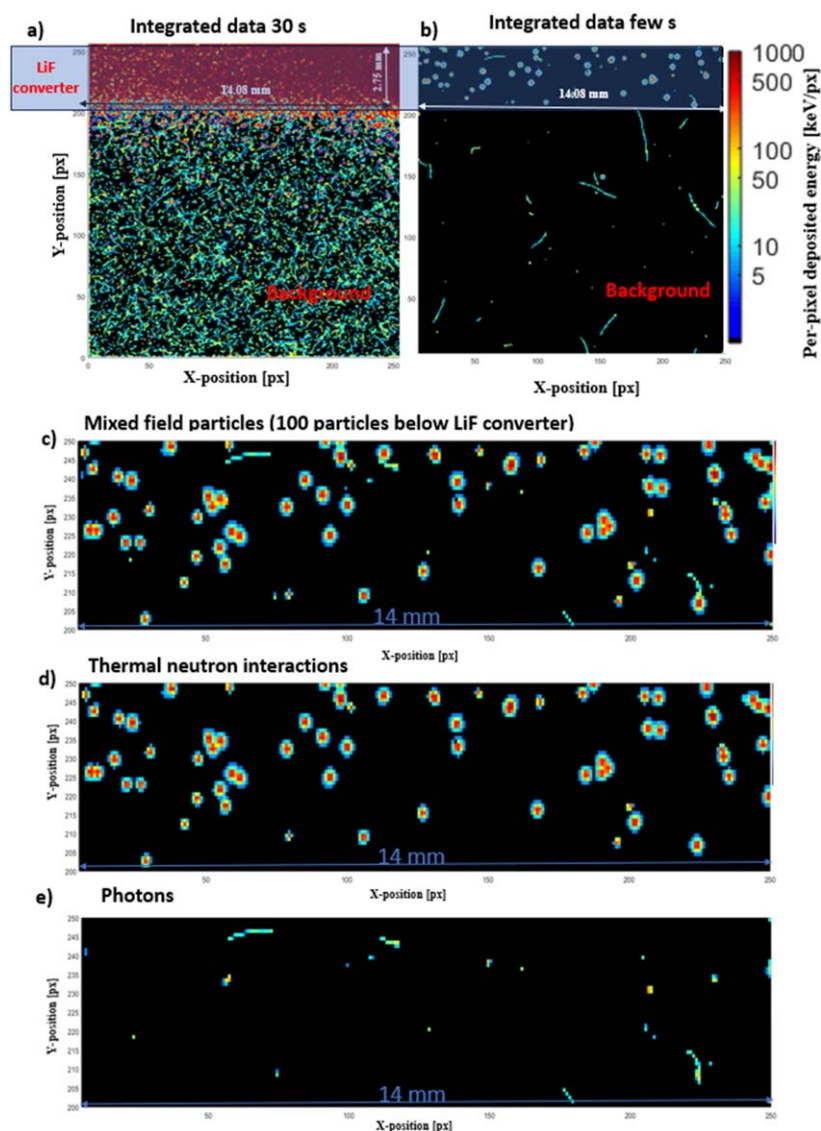


Figure 5. (a) Integrated detection and 2D map of deposited energy in the Timepix3 detector with thermal neutron converter on the top area. Data collected at the thermal neutron graphite pile integrated over a long acquisition time (30 s). (b) Single particle detection in the thermal neutron field showing the map of deposited energy (shown in color scale) for a short acquisition time (few s) in the MiniPIX Timepix3-Flex 500 μm Si detector with thermal neutron converter (top region). The whole sensor pixel matrix is shown (256×256 pixels) in (a)–(c) Integrated data showing single particle track resolving power displaying 100 particles created by the interaction of thermal neutrons in the ^6LiF converter for a selected area of the detector sensor with the thermal neutron converter (50×250 pixels corresponding to $2.75 \times 13.75 \text{ mm}^2$). The large high-LET circular tracks correspond to alpha and tritium particles from thermal neutron interaction in the converter. (d) AI NN identified thermal neutron events. (e) AI NN identified photons created directly in the Si sensor.

3. Results and discussion

3.1. Testing and calibration with thermal neutrons

The data acquired during the calibration of the Timepix3 detector in the thermal neutron pile using the ^6LiF converter are displayed in figure 5(b). The per-pixel deposited energy displayed in color logarithmic scale with an illustration of the region where the ^6LiF converter was placed on the top region can be seen in figure 5(b), whereas on the bottom of the figure, the background selected area of $2.75 \times 14.08 \text{ mm}^2$, having the same dimensions as the converter, is emphasized. The entire surface of the sensor is displayed (256×256 pixels, equivalent to an area of $14.08 \times 14.08 \text{ mm}^2 \simeq 2 \text{ cm}^2$) with an emphasis on the top region where the thermal neutron converter was placed. In this area, specific circular tracks are seen which are created by the interaction of neutrons with ^6LiF and emission of alpha and tritium particles. Enhanced visualisation of those tracks imaged under the converter area is displayed in figure 5(c). Separated tracks, as in figure 5(c), were individually imaged and selected for testing data utilized in the confusion matrix evaluation (see table 2).

Table 2. Evaluation of the method for particle recognition on the data set measured in the thermal neutron reference field. A confusion matrix was created and its result is given for the method based on AI NN. The predicted class is expressed in percentages and represents the total predicted class from an input class of 100% radiation.

AI NN method	Input class	Predicted class [%]	
		Thermal neutrons	Background
	Thermal neutrons	99.51	0.49
	Background	1.78	98.22

Table 3. Thermal neutron detection efficiency, η , for Timepix3 detectors with thermal neutron converters. Values given for each calibrated detector. Presented uncertainties include statistical uncertainty of the number of detected neutron-induced tracks and the uncertainty of the reference thermal neutron flux.

Detector TPX3	Sensor thickness & bias [μm , V]	η [%]
1.I10 ^b	500 μm , 200 V	1.45 ± 0.04
2.F07 ^b	650 μm , 100 V	1.36 ± 0.05
3.K03 ^b	100 μm , 50 V	1.18 ± 0.04
4.H02 ^b	500 μm , 200 V	1.08 ± 0.04
5.J05 ^c	500 μm , 200 V	0.46 ± 0.03

^a Obtained from circular tracks.

^b MiniPIX Timepix3 Flex detector.

^c AdvaPIX Timepix3 Flex detector.

3.2. Identification of thermal neutrons using AI NN

The integrated data measured in the reference thermal neutron field by Timepix3 below the ^6LiF thermal neutron converter (with an area of 50×250 pixels corresponding to $2.75 \times 13.75 \text{ mm}^2$) can be seen in figure 5(c). In this case, the AI NN was used to distinguish the high-energy tracks created by products of thermal neutron interactions in the converter and to calculate the detection efficiency of each detector-converter pair. In figure 5(c) is displayed a fraction of the measured data containing 100 particles. As can be seen, there are mostly two species of particles identified in the mixed field: mainly alpha and tritium particles from thermal neutron interaction in the converter (figure 5(d)) and photons which are predominantly detected also in the area without the neutron converter by direct interactions in the Si sensor (figure 5(e)). The percentage of detected circular tracks was 70.35(65) %. The rest is assigned to tracks generated by photons. The per-pixel deposited energy is displayed in color in logarithmic scale.

3.3. Evaluation of the method using a confusion matrix

A confusion matrix (a statistical method) created to evaluate the methods for particle classification is displayed in table 2. The confusion matrix was created with visually selected tracks assigned to thermal neutron interaction products only and background radiation. Over 500 tracks were manually selected to create the test data set containing only circular tracks as seen in figure 5(d). The results are reported in table 2. A very good result was obtained with a positive-positive probability of 99.51%.

3.4. Detection efficiency

Thermal neutron detection efficiencies obtained for five detectors are summarized in table 3. The detection efficiency for the MiniPIX Timepix3 Flex detectors equipped with thermal neutron converter ranges from 1.08% to 1.45%. On the other hand, for the Advapix Timepix3 Flex with the converter, the detection efficiency was lower, 0.46%. For the later, the neutron converter was manufactured in another batch where the ^6LiF converter thickness was below 2 μm , significantly thinner than the converters used for MiniPIX Timepix3 Flex.

3.5. Particle flux of thermal neutrons in the graphite pile

To verify the presented method for particle identification, calculation of the detection efficiency, and testing of fluctuations of the detector, the thermal neutron flux measured by 3 detectors at the thermal neutron pile is presented in figure 6. The selected detectors have a thickness of 500 μm and two architectures (MiniPIX and AdvaPIX). The average value of the thermal neutron flux registered in the sensor area with the neutron converter ($2.75 \times 13.75 \text{ mm}^2$) is presented in measured intervals of 100 s (figure 6 top). Fluctuations in the registered

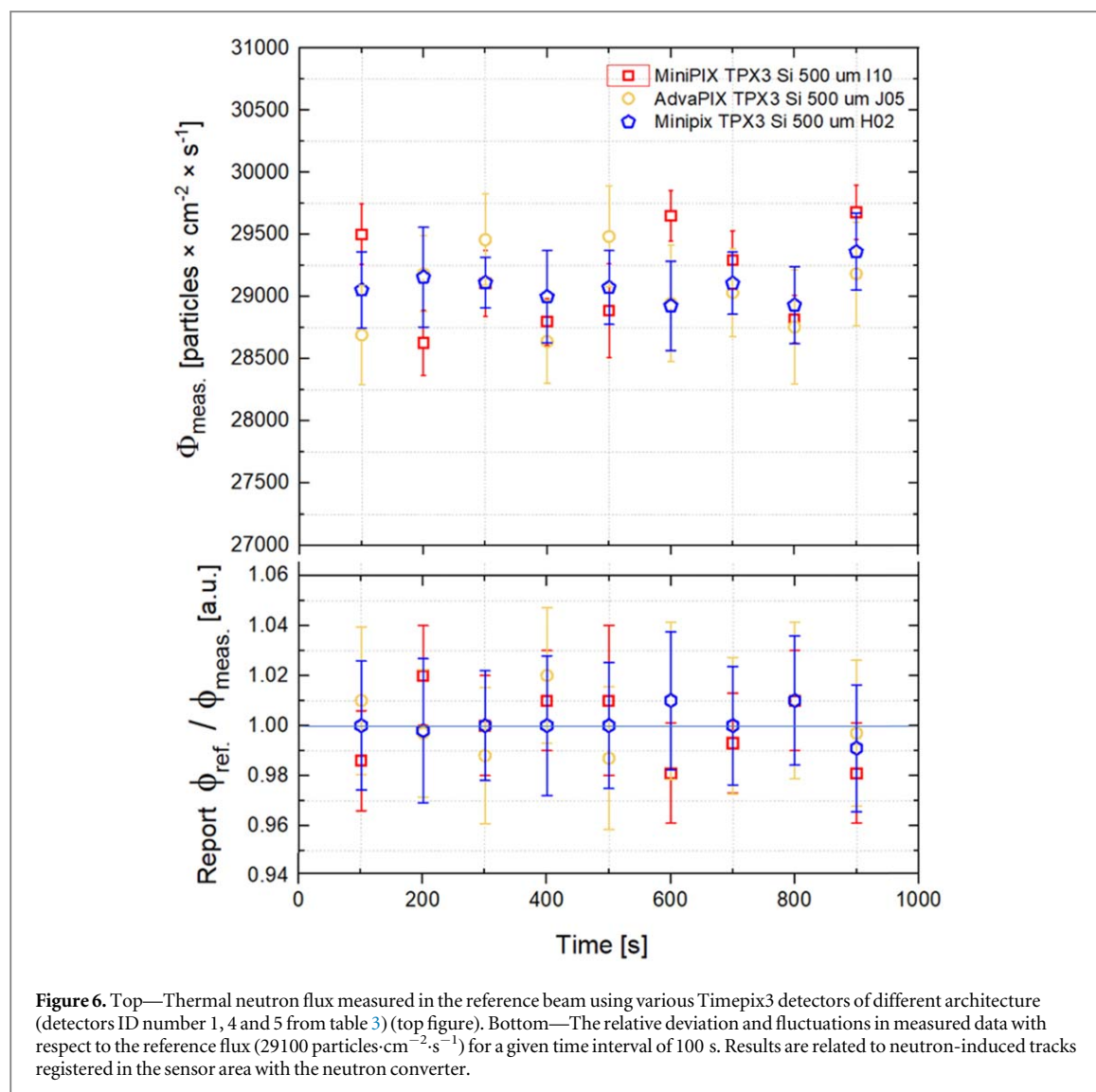


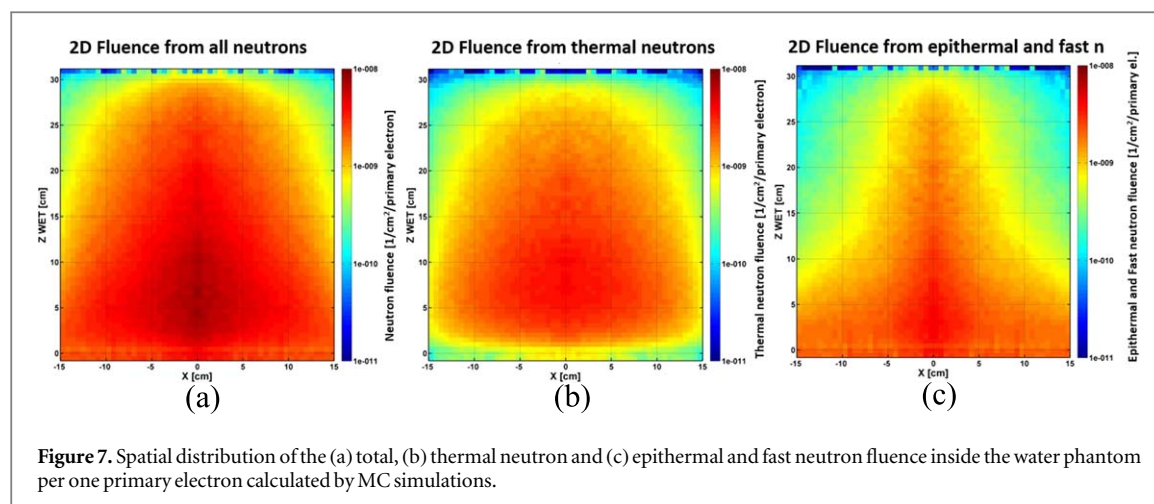
Table 4. The conversion from the thermal neutron fluence to the thermal neutron equivalent dose obtained from MC simulations.

k_H	$2.13(10) \text{ pSv}\cdot\text{cm}^2$
Neutron only contribution	21.7(9) %
Photon only contribution	78.3(9) %

tracks during 100 s long acquisitions are presented in figure 6 (bottom). Absolute flux derivation is possible by applying the presented method for calibration and using the detector-converter pair with its corresponding neutron detection efficiency constants.

3.6. Fluence to equivalent dose conversion factor

The value of the conversion factor from the thermal neutron fluence to the thermal neutron equivalent dose decomposed into the neutron and photon contributions are presented in table 4. The final total value for the given phantom geometry and tissue definition is $k_H = 2.13(10) \text{ pSv}\cdot\text{cm}^2$. This value is comparable to the tabulated conversion coefficient from fluence to ambient dose from external irradiation by neutrons, h^* , defined by (ICRU 2020). For 25 MeV thermal neutrons, $h^* = 4.0 \text{ pSv}\cdot\text{cm}^2$. The ICRU95 defines the quantity h^* as the maximum ratio of effective dose and external fluence for various irradiation conditions as calculated for the whole-body ICRP/ICRU adult reference phantoms (ICRP 2009). This quantity (h^*) does not correspond exactly to the equivalent dose, nevertheless in this case it serves to confirm that the calculated value of k_H is realistic.



It should be noted that k_H depends on the tissue definition and the size of the phantom. In addition, the resulting value describes the equivalent dose at the measurement point as if the measured thermal neutron fluence occurs in the ICRU 4-element tissue.

The total equivalent dose should take into account, besides the equivalent dose from thermal neutrons, the contribution of the non-thermal neutron component (above 1 eV). The described Timepix3 detectors are not neutron spectrometers, therefore it is not possible to determine the flux and equivalent dose of fast neutrons and neutrons of intermediate energies. Fast neutrons could be detected via (n, p) interactions in a suitable (e.g. polyethylene) converter layer placed above a part of the sensor (Campbell *et al* 2013). The reliability of the use of such a converter depends on the type and energy of the primary particles.

3.7. Thermal neutrons in a water tank at LINAC facility at PTB

This study is focused on the dosimetry of thermal neutrons thermalized inside the target volume by neutrons generated primarily outside of the water tank. The water tank setup was chosen as a substitute for tissue and behaved as a moderator as well. The neutrons produced by the 20 MeV UHPDR electron beam originate mainly from the interaction of bremsstrahlung photons generated by high energy electrons interacting with the beam line and the apparatus. The thermalization of neutrons takes place in the water tank. Such a thermal neutron field is relatively low-intensity embedded in a high-intensity primary and secondary electron and photon environment; therefore, limited studies exist in the literature regarding the thermal neutron contribution to the out-of-field dose in conventional electron radiotherapy. Likewise, with advances in the modality of treatment delivery, such as UHDR electron radiotherapy, the characterization of out-of-field radiation becomes more difficult due to short duration pulses of high dose. Especially when active detectors are used, the time resolution should be high-enough to image individual pulses of μ s-level together with selectivity and detection resolving power for different types of particles (electrons, gamma, neutrons, protons and ions).

The simulated 2D distribution of the total neutron fluence inside the water tank is shown in figure 8(a), whereas in figure 8(b) only the distribution of the thermal neutron fluence is presented and in figure 7(c) only the 2D distribution of the epithermal and fast neutrons is shown. Data are normalized per one primary electron. Although the primary electron beam has a range of about 10 cm (see figure 4(b)), the neutron fluence is distributed throughout the whole water volume in the tank. This is due to the mean free path, representing the average distance between two successive collisions, being of the order of several cm in water for neutrons with the energy of a few MeV (Shahmohammadi Beni *et al* 2017).

Visualization of the radiation field measured by the MiniPIX Timepix3 detector (H02) with a Si sensor of 500 μ m which was located at a depth of 18.5 cm and lateral position of 5 cm in the water tank irradiated with 20 MeV electron beam at 2.87 Gy doses per pulse with a pulse length of 2.4 μ s is displayed in figure 8. When a particle interacts with the detector, it transfers energy, which is then recorded and displayed using a color scale (see figure 5 for an illustration of single particle tracks). Figure 8 illustrates an integrated measurement where the energies from multiple particles are summed. In this particular measurement, the significant presence of background tracks originating from electrons and x-rays, causes the color to transition to orange. On the other hand, in the thermal neutron reference field measurements (figure 5(b)) one can observe numerous neutron interactions without many other particles, resulting in a predominantly black background. The ability to selectively identify neutrons within such a high flux field is particularly valuable. Energy deposition inside the Timepix3 sensor caused by alpha and tritium particles from ^6Li disintegrations were recognized and discriminated against other detected particles such as electrons and x-rays events in the high-intensity

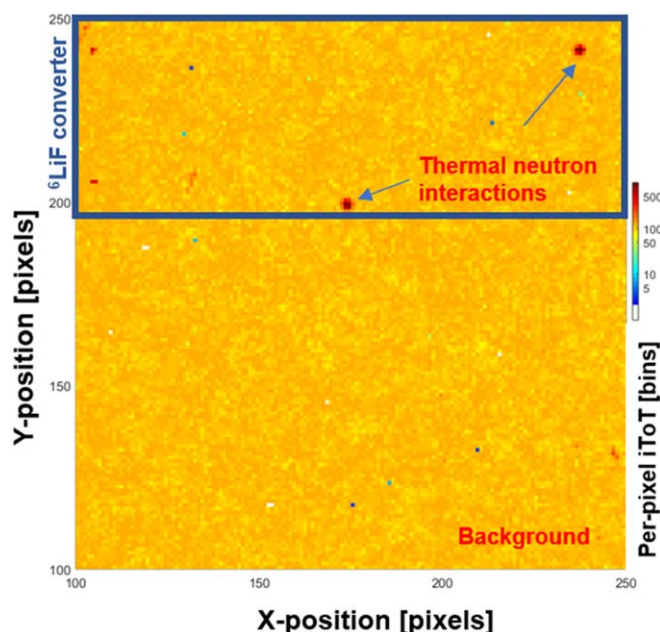


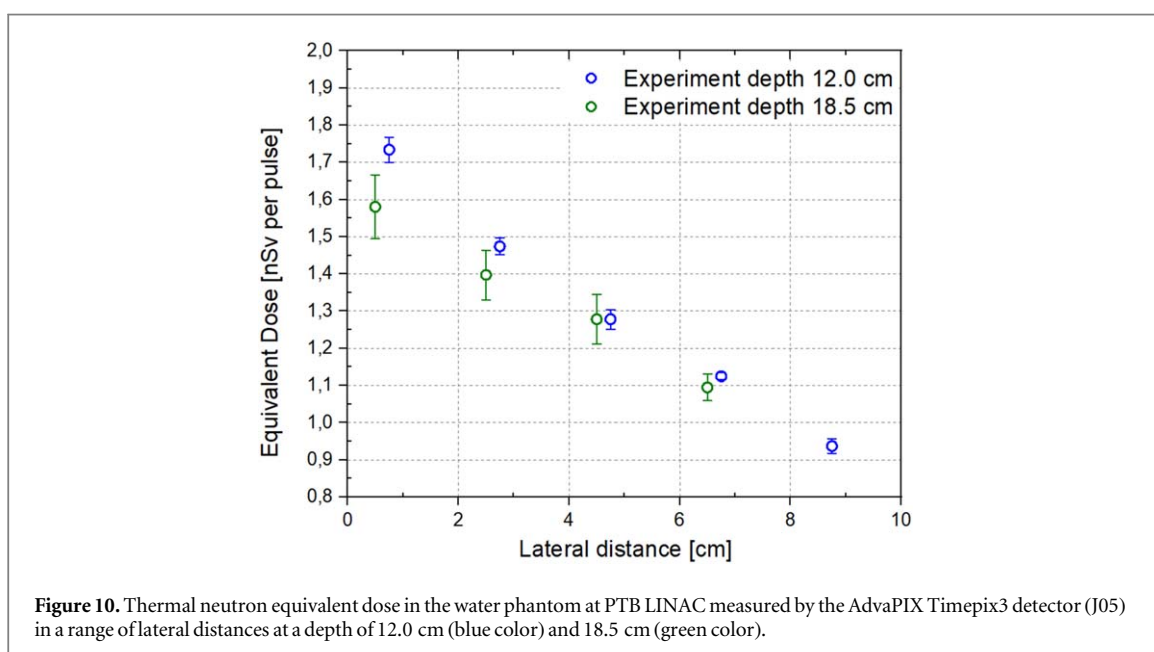
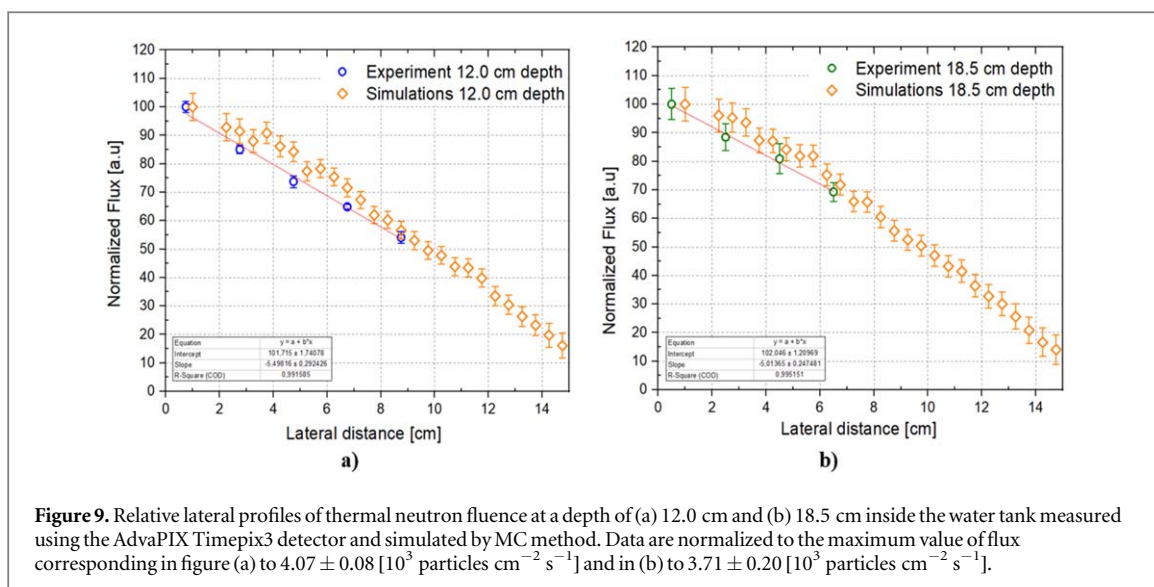
Figure 8. Spatial map of deposited energy per-pixel in Timepix3 at the depth of 18.5 cm and lateral 5 cm distance in the water tank irradiated with 20 MeV electron beam at 2.87 Gy doses per pulse with a pulse length of 2.4 μ s at the reference point on beam axis. The high-LET (red color) circular tracks were created by thermal neutron interactions in the neutron converter region (upper region). Data shown for single pulses. The remaining area of the sensor contains homogeneously distributed scattered and stray radiation created by electrons and x-rays (orange color).

Table 5. Thermal neutron flux and equivalent dose measured at selected positions inside the water tank illustrated in figure 4(c). The delivered dose per pulse corresponds to 1.85 Gy (pulse length of 2.4 μ s) at the reference depth (position A).

Position Label	Lateral distance [cm]	Thermal neutron flux [$10^3 \text{ cm}^{-2} \text{ s}^{-1}$]	Thermal neutron equivalent dose [nSv per pulse of 1.84 Gy]
Depth 12.0 cm			
B	0–1.5	4.07 ± 0.08	1.73 ± 0.03
C	2–3.5	3.46 ± 0.05	1.47 ± 0.02
D	4–5.5	3.00 ± 0.06	1.28 ± 0.03
E	6–7.5	2.64 ± 0.02	1.12 ± 0.01
F	8–9.5	2.20 ± 0.05	0.94 ± 0.02
Depth 18.5 cm			
G	0–1	3.71 ± 0.20	1.58 ± 0.09
H	2–3	3.28 ± 0.16	1.40 ± 0.07
I	4–5	3.00 ± 0.16	1.28 ± 0.07
J	6–7	2.57 ± 0.84	1.09 ± 0.04

mixed-field. As can be seen in figure 8, below the ^6LiF thermal neutron converter region, the TPX3 detector can register and distinguish particles identified as circular tracks (see highly energetic red circular tracks). The remaining area of the sensor contains electron energy depositions (orange color). Furthermore, by selecting and identifying the number of tracks created by thermal neutron interactions in the given area and time interval, the thermal neutron flux was obtained.

The thermal neutron flux was measured and converted to the equivalent dose at various positions inside the water tank as illustrated in figure 4(c) using the AdvanPIX TPX3 detector with a Si sensor of 500 μm which was placed to a water-equivalent depth of 12.0 cm and 18.5 cm. The results are summarized in table 5. The first two columns give the position identified with letters as labeled in figure 4 and the central position of the detector sensor in the lateral distance, respectively. The statistics contain over 75 pulses (15 s measurement time).



The relative lateral profiles of thermal neutron fluence measured with Timepix3 detectors with 500 μm thick Si sensor and simulated by Monte Carlo method are compared and can be visualised in figure 9. The measured profiles at depth of 12.0 cm (figures 9(a) and 18.5 cm (figure 9(b)) are in a good agreement with the MC predictions for both depths.

By applying the k_H conversion factor, the particle flux profile visualised in figure 9 was converted into thermal neutron equivalent dose. For the given experimental setup of the LINAC and the water tank, the H_T at a depth of 12.0 cm and 18.5 cm was found to be at order of a few nSv with the maximum H_T on the beam axis reaching 1.73 nSv for a single pulse delivery (figure 10). The secondary thermal neutron equivalent dose at this position is lower by 9 orders of magnitude than the therapy dose delivered at the reference point (position A in figure 4). At a depth of 12.0 cm, where the maximum measured H_T from thermal neutrons was 1.73 nSv, the total measured dose corresponded to 12.24 mGy. The decrease of H_T with the lateral distance from the beam axis follows a linear trend with a slope of about 50% decrease per 10 cm.

4. Conclusions

The purpose of this work was to provide a method for enhanced detection, imaging, and measurement of the thermal neutron flux. The method was tested in the thermal neutron reference field and applied to characterize

the thermal neutron flux and equivalent dose in high-intensity FLASH electron beams generated by a research LINAC at PTB.

Measurement of out-of-field thermal neutron equivalent dose in well-defined conditions presented in this study provides appropriate methodology and is significant for the estimation of secondary cancer risk, as well as input to analytical models for eventual clinical implementation.

Absolute thermal neutron flux derivation was possible because of the calibration of the measurement device in the reference thermal neutron field. Data processing based on detector response matrices, pattern recognition and artificial neural networks, enables the separation and discrimination of the high-LET circular tracks specific for thermal neutron interactions in the ^6LiF converter. Thermal neutron detection efficiency was measured in absolute for specific pairs of detectors-converter in well-defined thermal neutron reference field. In addition, the conversion factor from the thermal neutron fluence to the thermal neutron equivalent dose was derived from Monte Carlo simulations. The conversion factor obtained for a reference geometry has the value $2.13 \text{ pSv}\cdot\text{cm}^2$. Detector-converter pairs were used in an experiment performed in UHPDR electron beam in a water phantom to measure the thermal neutron flux and equivalent dose rate. For the reference UHPDR primary electron dose of 1.85 Gy per pulse with a pulse length of $2.4 \mu\text{s}$, the thermal neutron fluence reached $814(16) \text{ neutrons}\cdot\text{cm}^{-2}$ per pulse giving the thermal neutron equivalent dose of $1.70(3) \text{ nSv}$ per pulse on the beam axis at the water-equivalent depth of 12.0 cm . The thermal neutron fluence and equivalent dose decreased to $440(10) \text{ neutrons}\cdot\text{cm}^{-2}$ per pulse and $0.90(2) \text{ nSv}$ per pulse, respectively, at the lateral distance of 8.75 cm at the same depth. The thermal neutron H_T is small resulting in low associated risks and secondary effects of the treatment at these further depths inside water. The shape of the particle flux normalized to maximum roughly follows a linear trend being in agreement with the Monte Carlo simulations.

In this investigation, it has been shown that the Timepix3 detector with thermal neutron converter is suitable to detect and measure the thermal neutron flux and derive the equivalent dose. Future work involves applying the developed method to characterize the out-of-field thermal neutron contribution created in heavy charged particle therapy (proton, carbon, and helium radiation therapy). In these radiation fields, the discrimination of thermal neutron interactions in the pixel detector will be hindered by the presence of high-LET scattered and secondary particles. On the contrary, conventional electron and photon radiation therapy primarily produces low-LET particles such as x rays, gamma rays and electrons which deposit less energy per pixel and create tracks which can be well distinguished from neutron tracks. The tracks in the detector produced by thermal neutrons will partly overlap with those created by e.g. low-energy protons thus limiting the discrimination. For this purpose, the method will be further developed by more elaborate pattern recognition analysis and extensive data processing as well as by evaluation of different regions of the detector with and without a neutron converter. This involves further training of artificial neural networks and selection of additional filter parameters for pattern recognition of the single particle tracks. Furthermore, the method for thermal neutron flux measurement can be exploited to estimate the flux in particle therapy to explore new methods of treatment such as neutron capture enhanced particle therapy. This method serves to benchmark Monte Carlo simulations in mixed particle fields.

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Data availability statement

The data cannot be made publicly available upon publication because no suitable repository exists for hosting data in this field of study. The data that support the findings of this study are available upon reasonable request from the authors.

Conflict of interest

CO, CG, JJ, LM, JP are working for ADVACAM and they are involved in the manufacture of Timepix3 detectors.

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