Measurement of the time structure of FLASH beams using prompt gamma rays and secondary neutrons as surrogates

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Abstract

Objective. The aim of this study was to investigate the feasibility of online monitoring of irradiation time (IRT) and scan time for FLASH proton radiotherapy using a pixelated semiconductor detector.

Approach. Measurements of the time structure of FLASH irradiations were performed using fast, pixelated spectral detectors based on the Timepix3 (TPX3) chips with two architectures: Advapix-TPX3 and Minipix-TPX3. The latter has a fraction of its sensor coated with a material to increase sensitivity to neutrons. With little or no dead time and an ability to resolve events that are closely spaced in time (tens of nanoseconds), both detectors can accurately determine IRTs as long as pulse pile-up is avoided. To avoid pulse pile-up, the detectors were placed well beyond the Bragg peak or at a large scattering angle. Prompt gamma rays and secondary neutrons were registered in the detectors’ sensors and IRTs were calculated based on timestamps of the first charge carriers (beam-on) and the last charge carriers (beam-off). In addition, scan times in x, y, and diagonal directions were measured. The experiment was carried out for various setups: (i) a single spot, (ii) a small animal field, (iii) a patient field, and (iv) an experiment using an anthropomorphic phantom to demonstrate in vivo online monitoring of IRT. All measurements were compared to vendor log files.

Main results. Differences between measurements and log files for a single spot, a small animal field, and a patient field were within 1%, 0.3% and 1%, respectively. In vivo monitoring of IRTs (95–270 ms) was accurate within 0.1% for Advapix-TPX3 and within 6.1% for Minipix-TPX3. The scan times in x, y, and diagonal directions were 4.0, 3.4, and 4.0 ms, respectively.

Significance. Overall, the Advapix-TPX3 can measure FLASH IRTs within 1% accuracy, indicating that prompt gamma rays are a good surrogate for primary protons. The Minipix-TPX3 showed a somewhat higher discrepancy, likely due to the late arrival of thermal neutrons to the detector sensor and lower readout speed. The scan times (3.4 ± 0.05 ms) in the 60 mm distance of y-direction were slightly less than (4.0 ± 0.06 ms) in the 24 mm distance of x-direction, confirming the much faster scanning speed of the Y magnets than that of X. Diagonal scan speed was limited by the slower X magnets.

1. Introduction

A series of studies (Favaudon et al 2014, Loo et al 2017, Montay-Gruel et al 2017, Vozenin et al 2019a) have demonstrated that irradiation delivered with ultra-high dose rate (>40 Gy s−1), also known as FLASH, has a sparing effect on normal tissue due to ‘FLASH effect’. In their groundbreaking work, Favaudon et al (2014) have demonstrated the effect in nude mice in which they used low-energy electrons to irradiate their target. The same
FLASH irradiator was used to treat the first patient with FLASH radiotherapy, a cutaneous lymphoma patient (Bourhis et al 2019). Utility of electrons is limited to the superficial targets as they are not penetrative enough for deeper tumors. There are efforts that have shown FLASH effect is possible with x-rays, both in kV (Montay-Gruel et al 2018, Smyth et al 2018, Montay-Gruel et al 2019) and MV (Kutsaev et al 2021) range. Both kV and MV x-rays are suitable for irradiation of small volumes and for in vitro studies, however, isoecentric treatments which achieve FLASH dose rates are difficult to realize.

An attractive and readily available option to deliver a FLASH beam is with cyclotron-based protons, specifically pencil beam scanning (PBS), since PBS can be better controlled in terms of position and intensity (Paganetti 2012). Moreover, protons are more penetrative, offer finite range, and are radiobiologically more effective (Paganetti et al 2019).

With FLASH gaining a lot of momentum, determination of dose rate is a key factor in such a delivery. Average dose rate for FLASH studies is defined as the ratio of delivered dose to the irradiation time (IRT) and requires accurate measurement of both the dose and the IRT. IRT, in this definition, includes the sum of individual spot durations plus the time it takes for the beam to move between spots (scan time). Cyclotron-based proton systems have pulse repetition and duration rates in the order of nanoseconds and can be considered as continuous wave sources (Ashraf et al 2020) for the context of this study. IRT (in the order of ms, if not μs) is usually obtained from log files (Diffenderfer et al 2021) and needs to be verified with measurements.

Commercially available detectors and quality assurance devices do not offer a temporal resolution in such granularity. Hence, the dosimetry for FLASH must rely on detectors with poor or no time resolution. Clearly, there is a need to know and monitor the IRT for FLASH. One way to measure IRT is to use prompt gamma rays (PG) or secondary neutrons (SN) which are emitted within nanoseconds after proton interactions, which can be considered ‘real-time’ (Golnik et al 2014, Diffenderfer et al 2020, Haertter et al 2021). Consequently, they are good surrogates for primary proton IRT. Haertter et al investigated the feasibility of real-time dose rate monitoring via PG timing using NaI(Tl) crystal coupled to a photomultiplier tube. They placed the NaI(Tl) detector along the beamline at a distance of 73 cm from the first scatterer (the source of PGs) where the gamma count rate was ∼7 × 10⁵ counts s⁻¹ at the detector saturation. They have concluded that due to scintillation afterglow, real-time dose monitoring is possible for irradiations less than 36 Gy s⁻¹. For real-time monitoring with higher dose rates, NaI is susceptible to PG count saturation (Haertter et al 2021). More recently, strip ionization chambers are becoming popular for real-time monitoring (Zhou et al 2022, Yang et al 2022). Yang et al successfully demonstrated the feasibility of FLASH beam monitoring up to a 20 kHz sampling rate using a 2D strip ionization chamber.

As an alternative and potentially 100–1000 times faster, a semiconductor detector based on the Timepix3 (TPX3) chips developed at CERN (Poikela et al 2014) can be used for the better IRT monitoring purposes, especially in a radiofrequency modulated beams with ∼10 ns pulses. The TPX3 instrumentation and methodology were used in conventional and FLASH proton beams due to their high spatial resolution (sub-pixel level) for linear energy transfer (LET) measurements (Charyyev et al 2021, Granja et al 2021, Harrison et al 2022), for dose measurements inside water (Oancea et al 2023), for monitoring and identifying the secondary particles created in proton and carbon ion therapy (Jakubek et al 2011, Martisikova et al 2011), for range monitoring (Martisikova et al 2012), for ion detection and charged particle tracking (Granja et al 2013, Bergmann et al 2017), and for proton radiography (Biegun et al 2016, Wurl et al 2020, Charyyev et al 2021).

In this work, we aim to investigate the feasibility of online monitoring of IRT and scan time for FLASH proton radiotherapy using a pixelated semiconductor detector. Because of the complexity and speed of FLASH delivery, and because clinical interpretation of outcomes relies on spot-by-spot dose rates, it is important to know the IRT instantaneously. It is anticipated that methods like we developed in this work are implemented for a real-time patient in vivo FLASH monitoring.

2. Materials and methods

2.1. Detectors and experimental setup
PG and SNs were tracked using fast, hybrid semiconductor pixelated spectral detectors (ADVACAM s.r.o., Czech Republic), AdvPiX-TPX3 and Minipix-TPX3 with different readout speeds: 4 × 10⁶ hits s⁻¹ and 2.35 × 10⁶ hits s⁻¹, respectively. A detailed description of each detector and their capabilities is explained elsewhere (Granja et al 2018, Charyyev et al 2021, Granja et al 2021). Briefly, each comes with an advanced semiconductor pixel ASIC readout chip, TPX3, bonded to either 500 μm (for AdvPiX-TPX3) or 650 μm (for Minipix-TPX3) thick silicon sensor (Oancea et al 2022). The TPX3, developed within the Medipix collaboration at CERN, is position, energy and time sensitive. For each ionizing particle, it digitally registers its position, energy loss, time of arrival and track shape. These data about each detected particle are either read-out immediately (in
pixel mode) at a maximal rate of $2.35 \times 10^6$ hits s$^{-1}$ for Minipix-TPX3 and $4 \times 10^7$ hits s$^{-1}$ for AdvaPIX-TPX3 or accumulated in images (frame mode) and read out later at a maximal speed of 16 frames s$^{-1}$. Total sensitive area of the detector is $14.08 \text{ mm} \times 14.08 \text{ mm}$ divided into a matrix of $256 \times 256$ energy sensitive pixels with a pixel pitch of $55 \mu\text{m}$. Each ionizing particle generates a signal that involves multiple pixels forming a cluster of pixels which will have unique characteristic patterns, i.e. morphology, in the pixelated semiconductor sensor. These clusters are a result of the convolution of the deposited charge along the particle’s path, which spreads the deposited charge into adjacent pixels. The extent of this spread depends on the applied bias and the distance to the pixelated electrode. The detectors were operated at the lowest bias recommended during calibration (80 V for the 500 $\mu\text{m}$ thick Si sensor). The detectors are controlled via USB2.0 interface with standard $\mu\text{USB}$ connector and via the satellite port. Data acquisition is done via a complex software PIXET PRO (ADVACAM s.r.o 2022).

The AdvaPIX-TPX3 is a high-performance, fast readout, rigid detector (Poikela et al 2014). The Minipix-TPX3, is a miniaturized version of the AdvaPIX-TPX3 and it has a fraction of its sensor coated with a material (made out of $^6\text{LiF}$) to increase sensitivity to thermal neutrons. Thermal neutrons interact with $^6\text{Li}$ creating triton and alpha particle ions, which generate easily recognizable, thick, circular clusters in the detector sensor. Thermal neutron detection efficiency for Minipix-TPX3 with the converter is 1$\%$–2$\%$ (Solc et al 2022).

To avoid pulse pile-up, we placed the AdvaPIX-TPX3 well beyond Bragg peak, where gamma fluence is low, figure 1(A). We placed Minipix-TPX3 at a large scattering angle to minimize the flux even further, as Minipix-TPX3’s readout speed is much lower than that of AdvaPIX-TPX3’s. In figure 1(B), one can see the simulated particle hits mm$^{-2}$ that can be detected for each detector at their corresponding locations, as shown in figure 1(A), when $5 \times 10^6$ primary protons are simulated. Neutron, proton, and gamma hits mm$^{-2}$ are indicated with green, blue, and red colors, respectively. The predicted particle hits mm$^{-2}$ at detector’s sensor was obtained using a well-established Monte Carlo code, Tool for Particle Simulation (TOPAS) (Perl et al 2012), version 3.1. p2. Modeling of PBS characteristics in TOPAS is done based on methods described elsewhere (Charyyev et al 2020). The choice of $5 \times 10^6$ is not random but corresponds to approximately 1 monitor unit (MU) of 250 MeV protons, roughly the minimal number of protons that can be delivered. The number of particles that interact with the detector and deposit energy above the threshold is $13 \pm 4$ particles. At 150 nA nozzle current, the
detected fluence rate at the detector surface at a depth of 56 cm is $3 \times 10^5$ hits s$^{-1}$ for AdvaPIX-TPX3 and $2 \times 10^5$ hits s$^{-1}$ for Minipix-TPX3. These are well within readout speed ($4 \times 10^7$ hits s$^{-1}$) of AdvaPIX-TPX3 and Minipix-TPX3 ($2.35 \times 10^6$ hits s$^{-1}$). Figure 1(C) shows the setup of anthropomorphic phantom to demonstrate the feasibility of in vivo online monitoring.

2.2. Principle of IRT determination

Each incident particle generates a charge signal that is detected in the sensor and identified as a cluster (or a particle) track with a timestamp. IRT can be calculated based on timestamps of the first detected cluster (beam-on) and the last cluster (beam-off) arriving on the sensor. IRT includes the sum of individual spot durations plus the time it takes for the beam to move between spots (scan time). In other words, $IRT = \{t(\text{spot1}) + t(\text{spot1} \rightarrow \text{spot2}) + t(\text{spot2}) + t(\text{spot2} \rightarrow \text{spot3}) + t(\text{spot3}) + \ldots\}$. In continuous line scanning delivery method (our PBS system’s delivery), beam remains on between spots, i.e. there is no scan time when distances between spots are below the customizable threshold (10 mm for our PBS system) (Li et al. 2022). To introduce the scan time, distance between two spots was set as 24 mm in the $x$-direction and 60 mm in the $y$-direction. Figure 2 and table 1 show the principle of IRT determination on a sample measured FLASH field, with an average dose rate (Folkerts et al. 2020) of $\sim$50 Gy s$^{-1}$ delivered over 270 ms. Panel (A) illustrates particle detection behind the Bragg curve and track visualization for a photon, an electron, a proton and a heavy charged particle with each of them having a distinct morphology. As seen in figure 2(A), several morphologies are possible: (i) due to photons, small blobs occupying 1–2 pixels, (ii) due to electrons, long, narrow and usually not straight tracks occupying multiple pixels, (iii) due to protons, straighter and wider clusters (with length to width ratio of above 1.3) occupying more than 5 pixels, (iv) due to heavy charged particles, large and circular blobs that occupy more than 5 pixels. Table 1 lists the first 20 of 150 000 total clusters (particles) registered by the detector for this sample measurement. Panel (B) of figure 2 shows a plot of the time structure of this sample FLASH field. The beam is on during the steep portion of the curve. Panel (C) shows time structure on an expanded scale, corresponding to 1.5 $\mu$s of the 270 ms irradiation. With little or no dead time and an ability to resolve events that are closely spaced in time (tens of nanoseconds), both detectors can accurately determine IRTs as long as pulse pile-up is avoided (Usman and Patil 2018).

2.3. Proton beam accelerator and workflow

The experiments were carried out using a Varian ProBeam PBS system capable of delivering 250 MeV (the highest energy) at various beam currents in its special ‘Racehorse’ mode. We followed the steps as outlined in figure 3 to demonstrate accurate IRT and scan time measurements and the feasibility of online time monitoring. Firstly, a single spot IRT at clinical beam current, $\sim$5 nA was experimentally investigated. Afterwards, beam current was gradually increased to test if and when the IRT measurement becomes inaccurate, thereby exposing the detector sensor to a gradual step up of the flux and testing its limits at FLASH dose rates. This step was followed by a measurement of IRT of a small animal field, a $30 \times 30$ mm$^2$ field at isocenter created using scanned spots with 5 mm spot spacing (i.e. 7 spots in both $x$- and $y$-direction, with a total of 49 spots). This is a typical irradiation map used for irradiating mice as part of an ongoing small animal studies in this center. Measurement for the small animal field was repeated five times to check reproducibility and to quantify the uncertainty. Furthermore, scan times and speeds in $x$, $y$, and diagonal directions were measured. To achieve this, two spots separated by 24 mm in the $x$-direction or 60 mm in the $y$-direction were delivered. For the diagonal scan, two spots separated by 24 mm in both $x$- and $y$-directions were delivered. Moreover, the capability of the detector to measure the beam-off by triggering a beam fault when trying to scan in $x$-direction with a very large interspot
distance of 60 mm was demonstrated. Afterwards, the IRT of a patient field with spots of irregular spacings to mimic realistic fields that could be delivered in clinical scenarios was measured. Lastly, we delivered a ridge filter optimized field and measured IRT for it, first with AdvapIX-TPX3 followed by a measurement with Minipix-TPX3. We performed these measurements using anthropomorphic phantom to demonstrate the feasibility of \textit{in vivo} online monitoring. The ridge filter optimized field has irregular spot spacings and irregular monitor units.

Table 1. Particles as registered by the detector from the sample (from figure 2). FLASH field measurement (only the first 30 registrations are shown) and individual cluster parameters determined for each particle (coincidence ID, timestamp, size, deposited energy, position in x and y direction, maximum deposited energy in a pixel, etc) are listed.

| Coincidence ID | Time (ns) | Size (px) | Energy (keV) | Center X (px) | Center Y (px) | Height (keV) | Max time (ns) |
|----------------|-----------|-----------|--------------|---------------|---------------|--------------|---------------|
| 1              | 189 900 388.00 | 2         | 236.671      | 191.862       | 129           | 204.096      | 1.90E+08      |
| 2              | 189 900 455.00 | 2         | 19.7586      | 192.399       | 204           | 27.4716      | 4.57E+08      |
| 3              | 316 722 486.00 | 7         | 367.474      | 69.9589       | 241.325       | 109.549      | 3.17E+08      |
| 4              | 456 853 917.00 | 1         | 27.4716      | 233           | 204           | 27.4716      | 4.57E+08      |
| 5              | 1426 229 392.00 | 4         | 203.204      | 241.141       | 206.526       | 93.2913      | 1.43E+09      |
| 6              | 1426 231 015.00 | 6         | 239.202      | 245.317       | 241.882       | 74.2992      | 1.43E+09      |
| 7              | 1426 234 897.00 | 7         | 178.814      | 202.797       | 139.146       | 42.5198      | 1.43E+09      |
| 8              | 1426 236 291.00 | 5         | 220.058      | 47.06         | 152.764       | 103.888      | 1.43E+09      |
| 9              | 1426 236 443.00 | 14        | 1582.15      | 169.61        | 26.0931       | 433.818      | 1.43E+09      |
| 10             | 1426 236 890.00 | 106       | 1290         | 225.948       | 162.974       | 715.864      | 1.43E+09      |
| 11             | 1426 237 343.00 | 24        | 445.866      | 149.867       | 235.583       | 84.1307      | 1.43E+09      |
| 12             | 1426 238 729.00 | 1         | 20.8524      | 117           | 14           | 20.8524      | 1.43E+09      |
| 13             | 1426 244 675.00 | 3         | 150.541      | 218.948       | 106.846       | 119.468      | 1.43E+09      |
| 14             | 1426 245 573.00 | 15        | 1859.98      | 1.35216       | 89.8298       | 502.356      | 1.43E+09      |
| 15             | 1426 250 231.00 | 28        | 3057.79      | 4.67326       | 236.416       | 366.721      | 1.43E+09      |
| 16             | 1426 250 522.00 | 5         | 633.519      | 28.9697       | 170.996       | 459.519      | 1.43E+09      |
| 17             | 1426 250 589.00 | 1         | 7.14286      | 28            | 170           | 7.14286      | 1.43E+09      |
| 18             | 1426 251 098.00 | 25        | 2469.93      | 115.03        | 244.717       | 296.79       | 1.43E+09      |
| 19             | 1426 251 608.00 | 7         | 250.511      | 191.879       | 33.4576       | 110.966      | 1.43E+09      |
| 20             | 1426 251 811.00 | 13        | 1455.24      | 245.207       | 129.946       | 340.315      | 1.43E+09      |
| 21             | 1426 255 674.00 | 13        | 1757.79      | 67.1128       | 51.3912       | 648.022      | 1.43E+09      |
| 22             | 1426 255 725.00 | 1         | 5.92878      | 69            | 51           | 5.92878      | 1.43E+09      |
| 23             | 1426 256 289.00 | 22        | 3058.32      | 178.17        | 14.8776       | 633.026      | 1.43E+09      |
| 24             | 1426 256 403.00 | 19        | 2546.21      | 67.3151       | 172.607       | 715.864      | 1.43E+09      |
| 25             | 1426 264 798.00 | 42        | 5984.93      | 185.708       | 91.4449       | 715.864      | 1.43E+09      |
| 26             | 1426 264 868.00 | 1         | 6.29798      | 188           | 94           | 6.29798      | 1.43E+09      |
| 27             | 1426 266 481.00 | 48        | 1214.48      | 11.6258       | 117.371       | 154.977      | 1.43E+09      |
| 28             | 1426 267 565.00 | 1         | 8.71817      | 126           | 221          | 8.71817      | 1.43E+09      |
| 29             | 1426 272 079.00 | 31        | 3142.86      | 132.702       | 27.0052       | 303.924      | 1.43E+09      |
| 30             | 1426 272 348.00 | 1         | 9.33486      | 131           | 104          | 9.33486      | 1.43E+09      |
for each spot and was designed based on a real patient’s tumor target and anatomy information. It is optimized to cover 3 cm diameter tumor volume using 250 MeV proton beam (Liu et al 2021, Liu et al 2023).

3. Results

Figure 4(A) illustrates the measured single spot IRTs as a function of beam current. IRT decreases as the beam current is increased for the first three increments and then stabilizes at 20 nA beam current. We measured IRT around constant 48 ms for the beam currents 20–150 nA. Our detector accurately measured IRT for beam current of 150 nA, highest our machine can achieve, without further modifications. Figure 4(B) illustrates the IRT reproducibility for a small animal field, a 30 × 30 mm² at isocenter created using scanned spots with 5 mm spot spacing. The timing resolution of the detector is in the ns level and measured standard deviations for 4A and 4B are 0.6 ms and 0.7 ms, respectively. For both of these, error bars are shorter than the marker itself.

Table 2. Comparison of measurements performed with the pixel detectors with log files obtained from the vendor for different FLASH irradiations scenarios investigated in this work. Reported values are average values of repeated measurements.

| Description                          | Measurement time (ms) | Log file time (ms) | % (min, max) difference |
|--------------------------------------|-----------------------|--------------------|-------------------------|
| Single spot                          | 47.788                | 47.786             | (–0.970, 0.820)         |
| Small animal field (3 × 3 cm²)       | 288.16                | 288.28             | (–0.34, 0.19)          |
| Patient field                        | 1920.7                | 1902.5             | (0.4, 0.9)             |
| In vivo, AdvaPIX-TPX3, PGs as surrogate | 764.74               | 764.75             | (<–0.01, 0.04)         |
| In vivo, Minipix-TPX3, SNs as surrogate | 808.5                | 764.7              | (5.6, 6.1)             |

Table 2 shows for each spot and was designed based on a real patient’s tumor target and anatomy information. It is optimized to cover 3 cm diameter tumor volume using 250 MeV proton beam (Liu et al 2021, Liu et al 2023).

Figure 5 shows scan times in x, y, and diagonal directions, as reflected by the plateau region of the time structure for each irradiation. These scan times are measured by AdvaPIX-TPX3. Each plot encompasses the irradiation of two spots, separated by 24 mm in the x-direction (figure 5(A)), 60 mm in the y-direction (figure 5(B)), or 24 mm in both the x- and y-directions (figure 5(C), diagonal scan). The scan time in the x-direction, 4 ± 0.06 ms, resulted in scan speed of 6 mm ms⁻¹ and the scan time in the y-direction, 3.37 ± 0.05 ms, resulted in scan speed of 17.8 mm ms⁻¹, confirming the faster scanning speed of the Y magnets. Diagonal scan speed was limited by the slower X magnets. Figure 5(D) shows the time structure of the beam fault that was triggered when two spots were separated by 60 mm and scanned in x-direction.

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4. Discussion

Among the results presented in section 3, several observations are noted and discussed in this section. First, one would expect IRT to get shorter and be linear, in theory, as beam current is increased. Looking at figure 4(A), we can see that it is getting shorter (though not perfectly linear) up to 15 nA beam current and then stays constant up to 150 nA beam current. We have observed that beyond 15 nA, monitoring ionization chamber saturates (probably due to ion recombination issues) and does not shut off beam on time. We have shown that independent raw charge measurements increase as a function of increasing beam current beyond 15 nA (Charyyev et al 2023).

There are other definitions of dose rate beyond average dose rate that are relevant for FLASH effect (Wilson et al 2019, Vozenin et al 2019b, Petersson et al 2020), for proton PBS, dose rate can be defined, at each point in the field, as the sum of contributions from multiple spots (Folkerts et al 2020, Zou et al 2021). In that sense, considering the subset of voxels in a field, the dose rate can be higher than the dose rate reported in the section 3 of this work. It is relevant to study dose rate in the context of sub-voxels, because the processes that are believed to be responsible for the FLASH effect happen at the cellular level.

In addition to being a much faster way of online monitoring of IRT, the proposed method offers the advantage of measuring LET over other existing methods (Charyyev et al 2021). Delivering the same LET radiation at FLASH dose rates will reduce oxygen enhancement ratio and increase relative biological effectiveness (RBE) (Jones 2022). With this dependence of RBE/LET on LET, integrated biological optimizations frameworks are proposed (Liu et al 2023) where dose, dose rate and LET are optimized simultaneously to deliver a more effective FLASH irradiation. It is conceivable that there will be a need for a methodology to measure dose, dose rate, and LET simultaneously. The extreme timing resolution (ns scale) would potentially be useful to characterize the timing structures of pulsed proton cyclotron and electron linear accelerators in the future, besides the fine spatial resolution for LET measurements.
We can see that repeated measurements reveal delivery is reproducible within 1%. Because of instabilities of monitoring ionization chamber to control the beam, secondary and possibly tertiary confirmation measurements of dose rate have to be performed. Also, this uncertainty needs to be taken into account when interpreting outcomes of studies with the current clinical system.

IRT was overestimated in measurements using SNs as a surrogate (with Minipix-TPX3). \( ^{6} \text{LiF} \) will increase the detection efficiency for thermal neutrons, which arrive to the detector much later (few hundred \( \mu \)s to few ms) than fast neutrons (few ns). A potentially more accurate way to measure SNs would be to enhance the Minipix-TPX3 with a hydrogen rich plastic scintillator placed above the sensor. The signal from the plastic scintillator (together with photomultipliers) would be used as a trigger to open the TPX3 shutter to record coincident signals. This way, protons from the plastic scintillator recoiled by fast neutrons can be detected in TPX3 sensor. Detection of fast neutrons with TPX3 is an ongoing investigation by Granja et al. (2023).

Future work involves developing a dual detector method, a primary detector to measure the absolute dose at a high dose rate but periodically and a secondary detector to collect the whole acquisition time, as illustrated in this work. Such dual detector method can potentially explore the time resolution in nanosecond scale and other operation modes of the detectors, which would allow a larger particle flux rate and pile-up in the sensor area. These are typical conditions under which pulsed accelerators are operated for FLASH applications. We will propose a framework which enables IRT monitoring even when there is pulse pile-up by essentially saving the time-of-arrival until the end of the acquisition and not overriding it.

5. Conclusions

In this study, we have shown that IRT ranging from a few ms to hundreds of ms can be measured accurately with the proposed detection system and method. A very good agreement was found when using the pixeled detector AdvaPIX-TPX3 (within 0.1%). The IRT measurements with Minipix-TPX3 showed a discrepancy (within 6.1%) —likely due to late arrival of thermal neutrons to the detector sensor and lower readout speed— between the log files and results measured by the AdvaPIX-TPX3. Moreover, we were able to show scan time and differences between x-scan and y-scan speed in order of ms.

Data availability statement

All data that support the findings of this study are included within the article (and any supplementary information files). Data will be available from 27 March 2023.

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