In-water fast-time-sensitive measurements with Timepix3 detector for dosimetry and tracking characterization of stray radiation fields produced by FLASH proton beams

Cristina Oancea[1], Lukas Marek[1], Jiri Pivec[1], Stepan Polansky[1], Carlos Granja[1], Jan Jakubek[1]
Elisabeth Bodenstein[2], Jörg Pawelke[2,3]
Jaroslav Solc[4]

[1]ADVACAM, U Pergamenky 12, 170 00 Prague 7, Czech Republic
[2] OncoRay - National Center for Radiation Research in Oncology, Faculty of Medicine and University Hospital Carl Gustav Carus, Technische Universität Dresden, Helmholtz-Zentrum Dresden-Rossendorf, Dresden, Germany
[3] Helmholtz-Zentrum Dresden-Rossendorf, Institute of Radiooncology - OncoRay, Dresden, Germany
[4]Czech Metrology Institute, Radiová 1136, 102 00 Prague 15, Czech Republic

Introduction and Purpose

Emerging technologies such as FLASH radiotherapy require the development of new detectors to be able to cope with ultra-high-pulse-dose-rates (UHPDR) beams. The purpose of this work is to characterize the stray radiation produced in a water-phantom irradiated with so-called "FLASH" proton beams using an optimized Timepix-3 detector. The data are valuable to develop traceable and validated methods for the characterization of stray radiation outside the UHPDR primary proton beam.

Materials and Methods

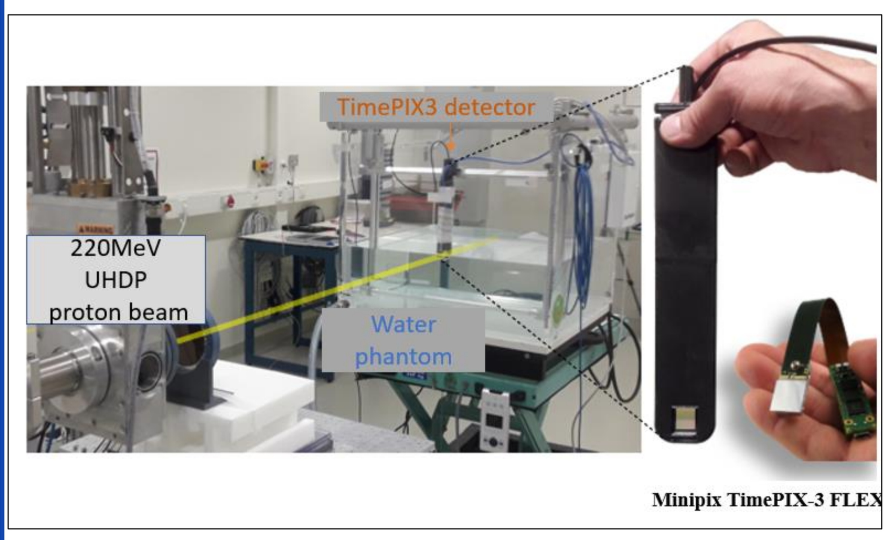

Figure 1. Experimental setup at the University Proton Therapy Dresden, with Minipix-Timepix3-Flex detector placed in a waterproof cadge. The detector chip-sensor assembly (shown on the bottom right) is detached from the readout electronics board.

The beam, provided at the University Proton Therapy Dresden (UPTD), OncoRay – National Center for Radiation Research in Oncology, Dresden, Germany, was fixed to irradiate the water phantom. The measurements were performed in FLASH mode, with dose rates (DR) exceeding 160 Gy/s delivered by a pencil proton beam (PB) of 220 MeV energy. Scattered radiation was registered at different positions lateral to the beam direction and behind the Bragg peak. A schematic representation of the measured positions inside the water phantom can be seen in Fig. 2. Two customized detectors based on Timepix3 ASIC [1] chip with Silicon (Si) sensors of 100 and 650 μm thickness were immersed inside the IBA Blue water-phantom and inclined 45º towards the beam core. For data acquisition, the detectors were moved, in turns, laterally at different depths during irradiation to measure the scattered particles. Using a compact semiconductor pixel detector, equipped with a 5 cm flexible cable extension, separating the sensor from vulnerable electronic (Fig. 1), we measured the composition, spatial, time and spectral characteristics of mixed radiation fields.

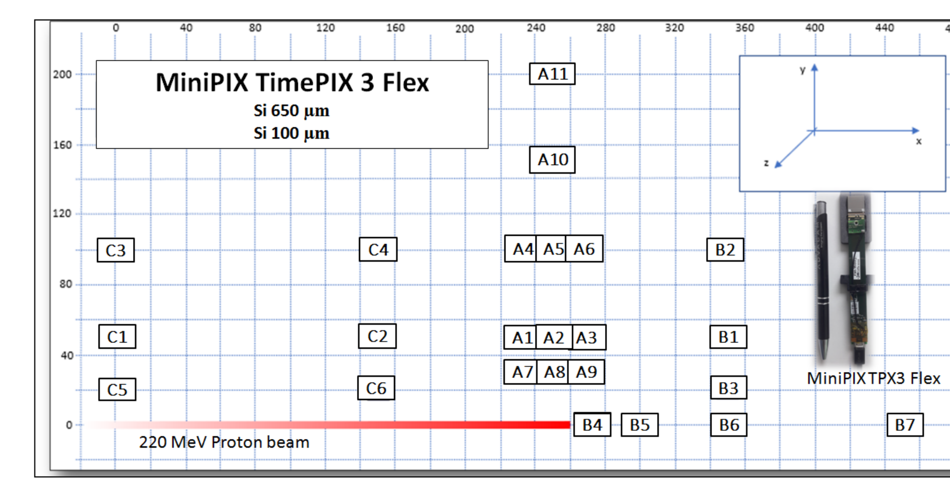

Figure 2. Experimental setup at the University Proton Therapy Dresden with identification of the positions where the detector was placed inside the water-phantom.

Timepix3 Detectors

The detector module for FLASH radiotherapy is based on the "MiniPIX-Timepix3-Flex" device produced by ADVACAM (see Fig. 1 right). It is adapted for operation immersed in a water phantom. Its material composition is made tissue equivalent to minimize disturbances of the measured radiation field (Fig. 3). The novel Timepix3 detector can improve the current dosimetry and metrology to cope with mixed radiation fields especially under conditions of Ultra-High Pulse Dose Rate [2]. The sensitive area of its semiconductor sensor is segmented to 256x256 very small pixels (55 μm each). Moreover, the pixelated detector provides the image of track for each detected particle. This imaging capability allows for distinguishing the particle types and their directions (see Fig. 4 left). The neutron sensitivity can be provided by a suitable convertor layer (e.g. 6LiF). Therefore, not only the total energy and intensity are recorded but the composition of the radiation field can be extracted as well analyzing the shapes of the particle tracks. The additional value for flash beam comes from Timepix3 ability to record the arrival time for each particle with a precision of 1.6 ns which allows Time-of-Flight (ToF) spectrometry. The specialized software tool evaluates the shape parameters for each particle track recorded by the Timepix3 detector e.g. deposited energy, time of flight, track area, track length, roundness, flatness, linearity, polar angle. Such characterization is possible for scattered particles with a flux of about 10E5 particles/cm²/s. For higher fluxes, the detector can be operated in frame mode (Event +iToT) and measure the total per-pixel deposited energy (iToT, which provides spectral/dosimetry information) and the number of hits in each pixel (counts, intensity information). In this study, both detectors were operated in frame mode (Event +iToT) with a 5 keV threshold.

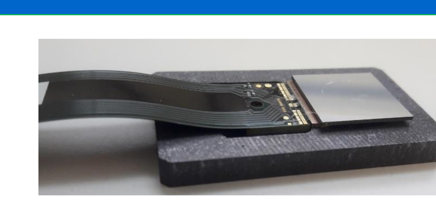

Figure 3. Customized Minipix-Timepix3-Flex detector with the sensor placed on a graphite material.

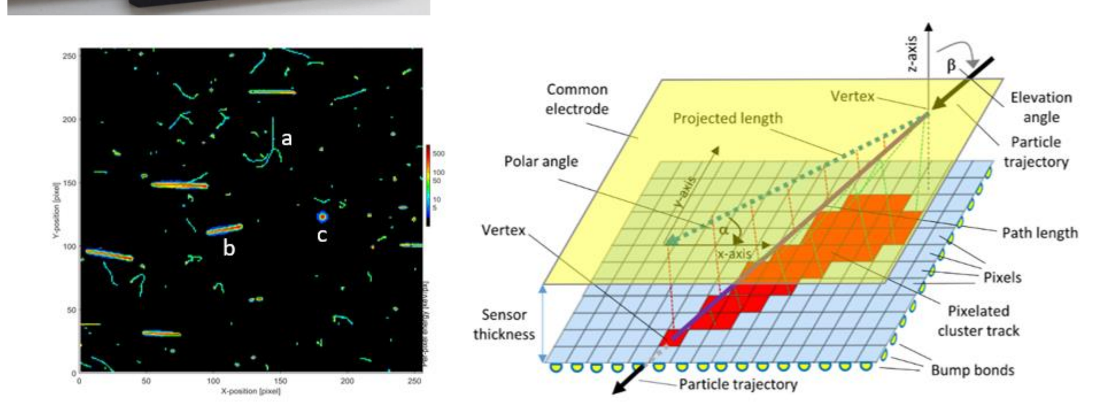

Figure 4. Left: The snapshot of particle tracks recorded by the Timepix3 detector with 650 μm thick Si sensor inside the water-phantom in a lateral distance of 5 cm from the therapeutic proton beam of 220 MeV in the middle of their range. Low-energy, narrow, curly tracks are typical for electrons (a), high-energy, wide, straight tracks for energetic heavy charged particles such as protons (b). The track length often indicates the impact angle (see perpendicular case c). **Right**: The charged particle flies through the thick sensor causing an ionization which is projected to a pixelated electrode and its image is recorded by the Timepix3 chip (See more in P. Stasica's presentation).

Results and Conclusion

Spectral- and intensity- sensitive characterization of UHPDR proton beams were done using the customized Minipix-Timepix3-Flex Si. Two sensors were tested to identify the most suitable detectors and settings to be used for the characterization of scattered particles inside a water phantom. In Fig. 5 can be seen the spatial distribution of integrated deposited energy at position B5, 50 mm and position B6, 100 mm behind BP for a 2 ms proton pulse measured with both detectors Minipix-Timepix3 tested. Results showed a detector equipped with a thin silicon sensor, 100 μm, is more suitable for UHPDR PB measurements.

A thinner Si sensor, 100 μm, provides a radiation-sensitive volume of smaller dimensions which thus:

- ❖Reduces the detection efficiency for high energy X-rays and gamma rays
- ❖Reduces the event count rate, see Fig. 7
- ❖Reduces the amplitude* (charge created per px) of the detected signals
- ❖Reduces the pixel size of the signal, allowing to register higher event count rate

*signals of smaller amplitude are collected faster and allows to register more particles.

In Fig. 6 can be seen measurements of lateral penumbra from 50 mm up to 200 mm distance from the BP. The detector's per-pixel saturation level was tested and in this set-up, they were not achieved. The overall sum of per-pixel hits is below 6.7E7, which could allow for measurements at positions closer to the primary beam (Fig. 7).

Our preliminary measurements showed the customized version of Minipix Timepix3-Flex with a silicon sensor of 100 μm thick is the most suitable detector tested to be used for characterizing high fluxes of stray radiation produced in UHPDR proton pencil beams. Further work includes testing other detectors for both primary and stray radiation in proton and electron beams.

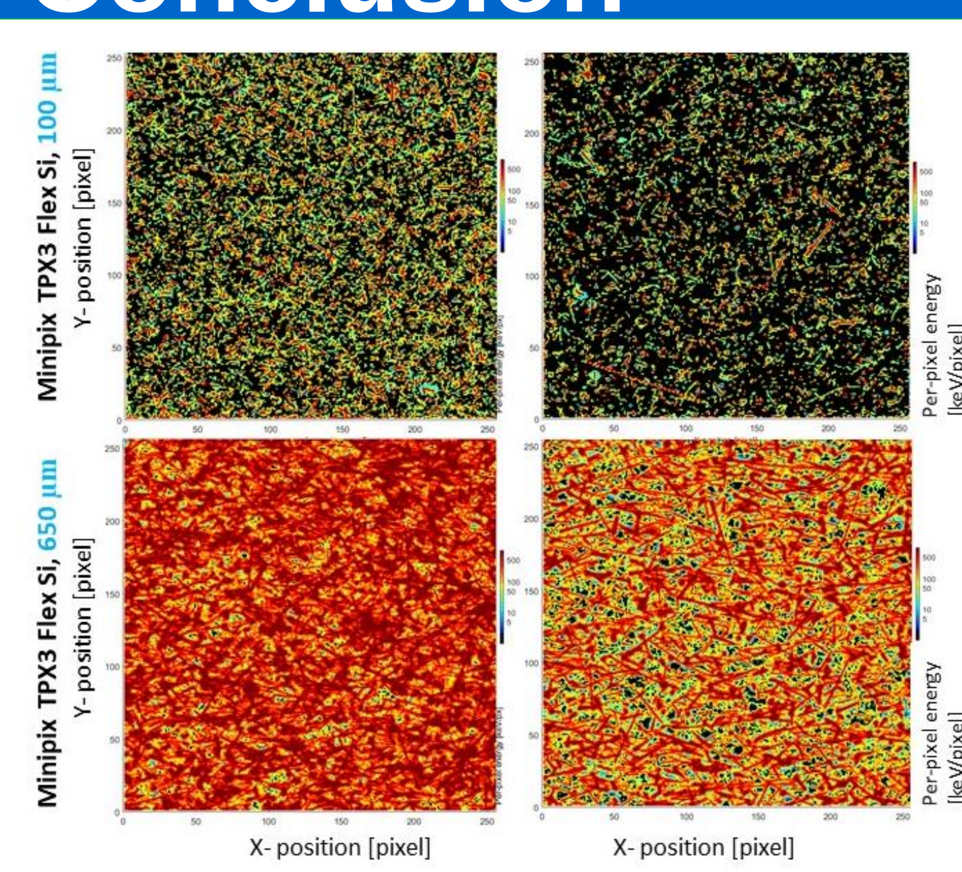

Figure 5. Spectral- and intensity-sensitive characterization of high-flux radiation fields by Minipix-Timepix3-Flex. The plots show the spatial distribution of integrated deposited energy at 50 mm (left column) and 100 mm (right column) behind BP for a 2 ms proton pulse measured with Minipix-Timepix3 with 100 μm (top row) and 650 μm (bottom row) thick Si sensor.

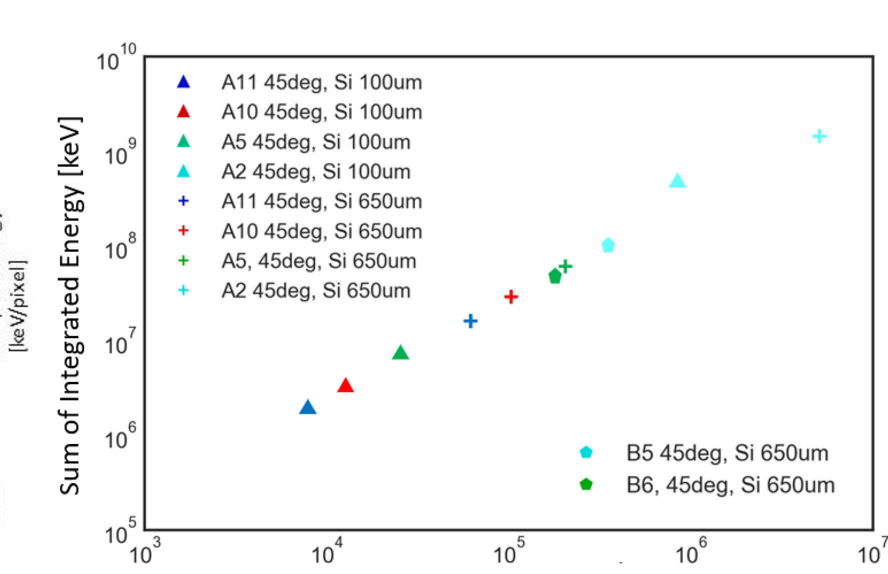

Figure 7. Sum of integrated energy deposited vs the sum of hit pixels (pixel counts) measured in one frame for a single pulse of UHPDR proton beam using Minipix Timepix3-Flex Si sensors of 100 and 650 μm at various positions around the BP.

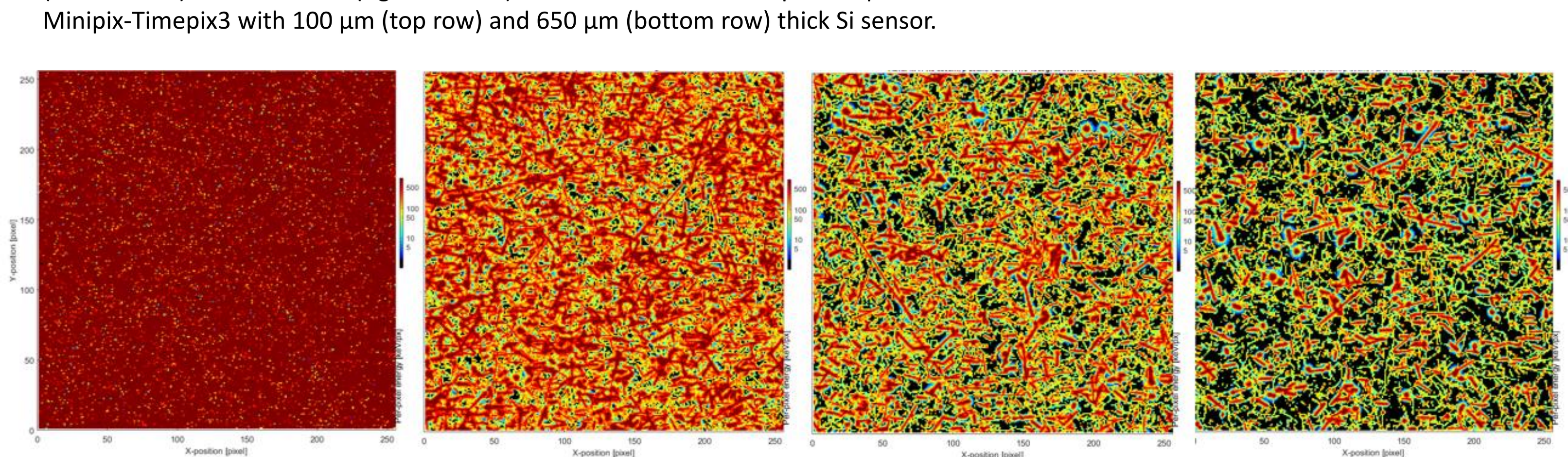

Figure 6. Spectral visualization of FLASH fields of deposited energy integrated per-pixel at various depths lateral to the BP (50, 100, 150 and 200 mm) for a 2 ms pulse measured with Minipix Timepix-Flex with a 650 μm thick Si sensor.

Acknowledgment

This work was supported by the project 18HLT04 UHDpulse. This project has received funding from the EMPIR programme co-financed by the Participating States and from the European Union's Horizon 2020 research and innovation programme. We acknowledge the beam time received through the EU INSPIRE project (730983) .

The EMPIR initiative is co-funded by the European Union's Horizon 2020 research and innovation programme and the EMPIR Participating States

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