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# Imaging and tracking of clinical proton beam delivery with miniaturized stack telescope Timepix3: feasibility study of quality assurance for medical proton therapy

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ABSTRACT: We investigate the feasibility to provide a new technique for non-invasive quality assurance (QA) in clinical proton therapy using a compact stack telescope of Timepix3 (TPX3) detectors. The approach relies on detecting protons scattered at the treatment nozzle and in air downstream of the isocenter, enabling beam monitoring without interfering with patient irradiation. A dual-layer silicon TPX3 telescope was deployed in the fixed beam treatment room at the Proton Therapy Center (PTC) in Prague. Coincidence tracking of scattered protons enabled reconstruction of the therapeutic beam spot by back-plane projection. These results demonstrate the feasibility of a non-invasive QA method based on pixel detectors, highlighting its potential for integration into clinical workflows and its implications for improving proton therapy QA processes.

KEYWORDS: Hybrid detectors; Instrumentation for hadron therapy; Dosimetry concepts and apparatus

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# Contents

## 1 Introduction and motivation

Proton radiotherapy (pRT) has become an increasingly important modality in modern oncology due to its superior dose distribution compared with conventional photon therapy. The sharp distal fall-off of proton dose, the Bragg peak, enables high conformality of dose deposition while minimizing irradiation of normal tissues and critical organs. This makes pRT especially advantageous in the treatment of pediatric patients, re-irradiations, and tumors located near radiosensitive structures. As the number of clinical proton facilities grows worldwide, robust methods of quality assurance (QA) and beam monitoring are becoming ever more essential to ensure safety, precision, and reproducibility of treatments [1].

Current QA procedures in proton therapy comprise a multi-layered approach: daily, monthly, and annual machine QA, treatment plan QA, and patient-specific QA. At the Proton Therapy Center (PTC) in Prague, as in many other clinics, machine QA of the therapeutic beam relies on scintillator detectors such as the Lynx PT system (IBA). These devices provide high spatial resolution but are large, invasive, and unsuitable for use during patient irradiation. For this reason, QA is typically limited to pre-treatment verification rather than fraction-by-fraction beam monitoring. Ionization chambers, film dosimetry, and scintillator screens remain the “gold standard” of QA instrumentation, but each carries practical limitations regarding invasiveness, integration into workflow, and applicability at emerging ultra-high dose rates [2].

In recent years, a variety of novel approaches to non-invasive and real-time QA have been investigated. These include prompt-gamma detection for beam range verification [3], positron emission tomography (PET) imaging of induced activity [4], ionoacoustic measurements [5], and detection of secondary charged particles escaping the patient or beamline [6]. Each method demonstrates unique strengths but also challenges regarding sensitivity, spatial resolution, or clinical integration. Parallel to these developments, hybrid pixel detectors from the Medipix/Timepix family have emerged as powerful tools for single-particle tracking and spectroscopic imaging. They offer nanosecond timing, per-pixel energy discrimination, and the capability to reconstruct proton and ion trajectories with sub-degree angular resolution [7, 8]. Several feasibility studies have demonstrated the potential of such detectors for monitoring hadron therapy beams through detection of secondary or scattered radiation [9, 10].

Among secondary-charged-particle based techniques, an important example is the Dose Profiler (DP) detector developed within the INSIDE project and installed at the CNAO facility. The DP is a scintillating-fibre tracker placed at large angles with respect to the beam axis and designed to detect secondary protons and fragments escaping the patient during proton and carbon-ion irradiation. Its design and performance, including extensive beam-test campaigns and in-room measurements with anthropomorphic phantoms, have been reported in detail [11, 12]. More recently, the DP has been operated in a clinical trial at CNAO for $^{12}C$-ion treatments, where charged-fragment emission maps have been used to monitor the transverse beam position and to detect interfractional anatomical changes [13, 14]]. These studies demonstrate the feasibility of online, in-room monitoring in a clinical environment exploiting charged secondary fragments. The Si+Si Timepix3 telescope investigated in this work follows the same general concept, but is optimized for compact off-axis deployment in proton therapy and provides pixelated tracking with nanosecond time-stamping, which is complementary to the fibre-tracker approach.

This study further investigates the application of a compact Timepix3 (TPX3) stack telescope for non-invasive beam QA in clinical proton therapy, building on previous findings. Our approach relies on detecting protons scattered at the treatment nozzle and in air downstream of the isocenter. Previous work done on this was more aimed at reconstructing/substituting dosimetry measurements with a single-chip tracker fixed in the ceiling of the treatment room [15]. For directional mapping of the delivered beams, the single-chip configuration provides limited angular resolution (5–10°) and limited resolving power. By placing the telescope outside the beam axis, scattered protons are registered without interfering with patient delivery. Using a dual-layer silicon stack operated in coincidence mode, single proton trajectories can be reconstructed and projected back to the beam origin; enhanced by remote visualization and directional mapping of the delivered beams with high angular resolution, and the 3D trajectory of the beam can be mapped in wide field-of-view. This study reports first results from beam measurements at PTC, evaluating the potential of the method for non-invasive visualization and tracking of clinical proton pencil beams.

The present work should therefore be regarded as a feasibility study of such a concept in a clinical proton therapy environment. The measurements presented here demonstrate that a compact Si+Si Timepix3 telescope can reconstruct the direction and approximate origin of scattered protons from clinical beams in the fixed-beam room, and that the detector can be operated under high instantaneous dose-rate conditions without saturation. A clinically deployable QA system will require a larger instrumented area, systematic tests with complex pencil-beam scanning patterns and full treatment plans, and quantitative comparison with established QA tools such as scintillating screens and ionization-chamber arrays.

## 2 Materials and methods

Measurements were carried out at the Proton Therapy Center (PTC) in Prague, Czech Republic. The facility operates an IBA Proteus 235 cyclotron delivering protons in the energy range of 70–226 MeV using the pencil beam scanning (PBS) technique. The clinical program at PTC has been in operation since 2012 and treats approximately 1,500 patients annually. For this study, we used the fixed beam treatment room, which provides a stable geometry and direct access to the beam axis for detector installation.

The experimental system for this particular work consisted of a compact stack telescope based on two Timepix3 (TPX3) detectors with silicon sensors (Si+Si configuration). Each TPX3 detector is a hybrid pixelated semiconductor device composed of a silicon sensor bump-bonded to a Timepix3 application-specific integrated circuit (ASIC). The per-pixel electronics register both the time of arrival (ToA, 1.56 ns resolution) and the time over threshold (ToT, proportional to deposited energy) for each incident particle. This dual measurement enables per-pixel spectroscopic imaging and

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timing, as well as discrimination between different types of radiation. The layout of the stack detector can be seen in figure 1a.

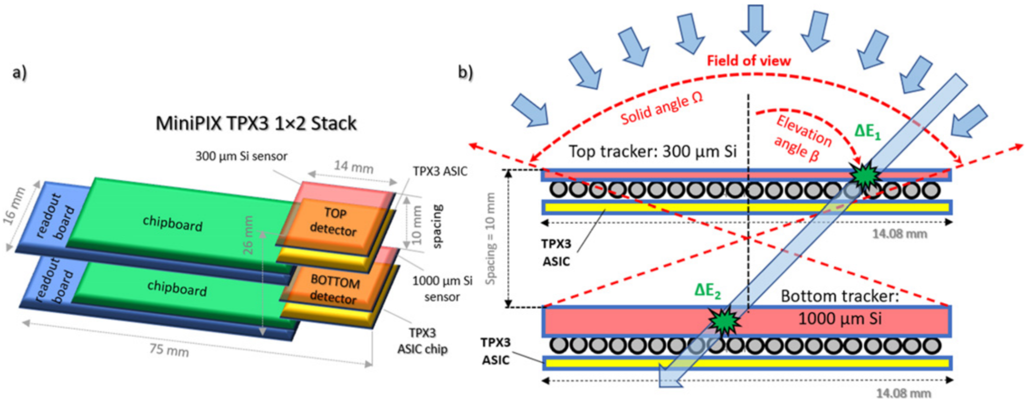
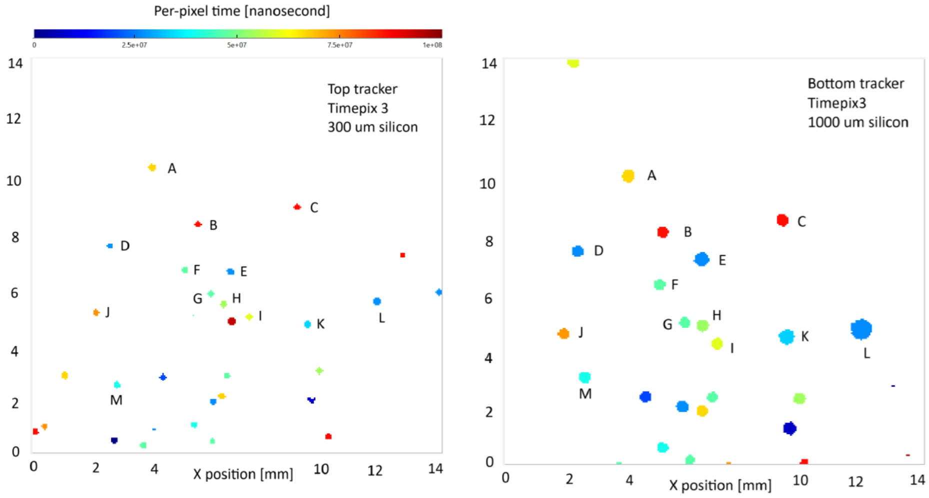


**Figure 1.** Illustration of architecture of the 2×TPX3 particle telescope (a) and principle of synchronized detection and directional tracking of energetic charged particles in wide field-of-view (b). Reproduced from [7]. © 2022 IOP Publishing Ltd and Sissa Medialab. All rights reserved.

Operating two TPX3 detectors in coincidence allows reconstruction of the trajectories of individual protons. A particle traversing both sensors is detected as a correlated hit pair, from which a directional vector can be determined (see figure 1b). This tracking approach forms the basis of the stack telescope principle, providing angular resolution below one degree and enabling back-projection of detected particles to their origin within the beamline. The compact Si+Si telescope used in this work had a footprint of approximately 10 cm, making it suitable for integration into clinical environments.



(A). Top tracker Timepix3 300 µm Si sensor.

(B). Bottom tracker Timepix3 1 000 µm Si sensor.

**Figure 2.** Coincidence imaging detection of 30 MeV calibration proton beam at UJF Řež by the 2×TPX3 stack. The full sensor pixel matrix is shown for the top TPX3 tracker with 300 µm Si sensor (left) and bottom TPX3 tracker with 1000 µm Si sensor (right). Time registration is displayed by the color scale in ns. The colour scale encodes the time-of-arrival (ToA) in nanoseconds, while the circle is in fact a particle, in this case a proton. That's the morphology/shape of the protons of 30 MeV nominal energy.

The telescope was positioned at PTC downstream of the isocenter at a distance of approximately 2 m, off the primary beam axis, as can be seen in figure 3. This placement ensured that the detector registered only protons scattered at the nozzle window, in the intervening air path, or in an optional thin scattering foil placed along the beam axis. The off-axis geometry is inherently non-invasive, as the primary therapeutic beam remains unaffected. The telescope employs an asymmetric sensor configuration, with a 300 µm thick silicon sensor in the upstream Timepix3 plane and a 1000 µm thick sensor in the downstream plane. The thinner upstream sensor is used as the entrance tracking plane, where a reduced material budget limits multiple scattering and charge sharing and thus preserves spatial and angular resolution. The thicker downstream sensor provides increased stopping power and higher energy deposition for forward-scattered protons, resulting in larger time-over-threshold values and improved detection efficiency and cluster reconstruction, and helping to discriminate these protons from minimum-ionising backgrounds.

During treatment delivery, the primary proton beam and its interactions in the exit window, the polyamide (PA) foil and air generate a mixed radiation field composed of scattered protons, heavier charged fragments, electrons and prompt gamma rays. The Si+Si Timepix3 telescope is operated in two-plane coincidence, and the track reconstruction relies on straight clusters traversing both silicon sensors. This selection strongly favours charged secondaries, predominantly scattered protons, and suppresses most of the background from prompt gamma interactions, which mainly produce short, low-dE/dx electron tracks with different cluster morphology. Prompt gammas therefore influence the measurement only indirectly via their contribution to the charged-secondary background that is largely removed by the applied filters of track parameters.

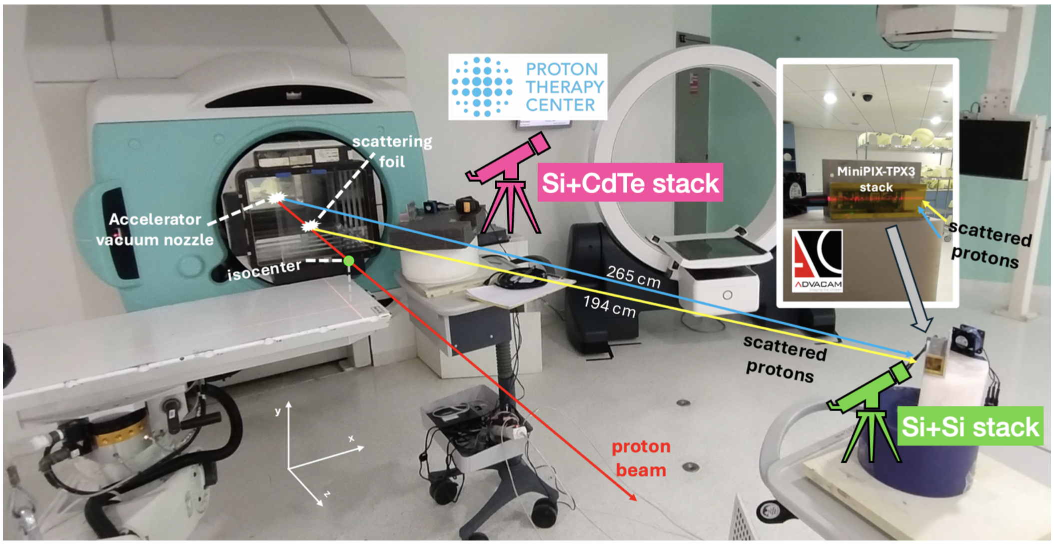


**Figure 3.** Experimental setup in the fixed beam treatment room.

During measurements, therapeutic proton pencil beams of different nominal energies were delivered under clinical conditions. The telescope operated in data-driven acquisition mode, where each pixel asynchronously reports hits with corresponding ToA and ToT values. Data from both layers were synchronized offline to identify coincidence events corresponding to single protons traversing the stack.

Acquisition intervals were typically on the order of 100 ms, balancing sufficient event statistics with manageable data volumes. The raw pixel data were first processed by an offline clustering and event-selection step that removes hot/nosy pixels, background radiation, and selects hits that can be associated into geometrically consistent coincidences between the two detector planes. Coincidence matching between the two silicon layers was then applied to reconstruct proton trajectories. From these directional vectors, a back-plane projection was performed to estimate the spatial distribution of the beam at the isocenter plane. This analysis provided 2D images of the reconstructed beam spot derived solely from scattered proton tracks. An illustration of the reconstruction results can be seen in figure 4 [9].

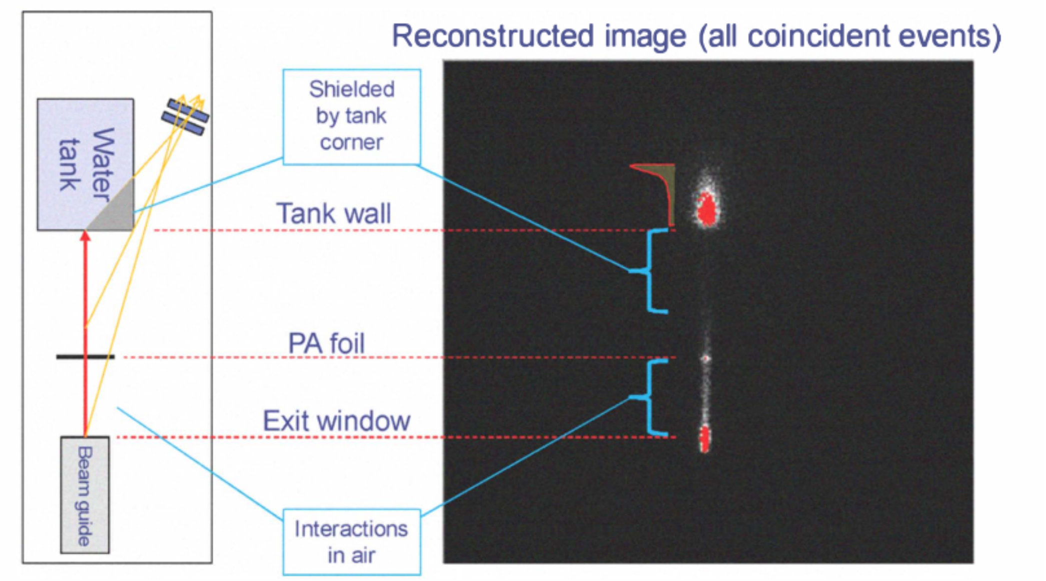


**Figure 4.** Illustration of the reconstruction of the beam from scattered coincident events viewed from the top horizontal plane. The back-plane-projection (BPP) shown on the right visualizes the trajectory and interaction vertices of the beam. Reprinted from [9], Copyright (2011), with permission from Elsevier.

## 3 Results

In the fixed beam room setup, the Si+Si TPX3 telescope successfully registered scattered protons from therapeutic pencil beams under clinical operating conditions. Individual detector planes recorded characteristic pixel clusters corresponding to charged particle tracks. After coincidence filtering between the two silicon layers, clean sets of correlated events were obtained, confirming that the system was able to resolve single protons traversing the telescope. These coincidence events provided the basis for trajectory reconstruction.

Using reconstructed proton trajectories, back-plane projection images of the beam were generated at the isocenter plane. Figure 5 shows the reconstructed image. The distribution clearly reproduced the position and shape of the primary beam, despite the telescope being placed off-axis and outside the treatment field. The method thereby demonstrates that the scattered proton signal carries sufficient information to non-invasively visualize the therapeutic beam.

The angular resolution achieved with the Si+Si telescope was consistent with expectations from the detector geometry, remaining below one degree. This level of directional sensitivity was sufficient to

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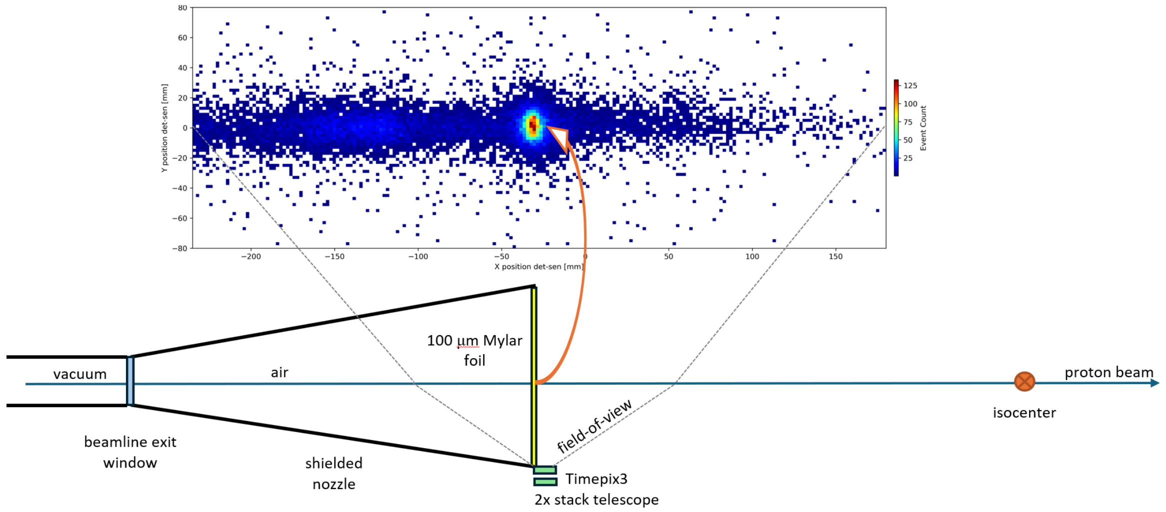

**Figure 5.** Back plane projection of 115 MeV central spot continuous beam; beam-on time approximately 1 minute.

distinguish individual beam spots delivered in isolation. The measurements also confirmed the ability of the system to operate at therapeutic beam intensities without saturation or loss of tracking performance.

While the feasibility of the approach was demonstrated, several limitations were identified. The relatively small sensitive area of the telescope restricts the number of detected scattered protons, which in turn limits statistical precision, particularly for complex spot patterns or short acquisition times. In addition, reconstruction of extended scanning fields will require more sophisticated analysis to separate overlapping trajectories. Finally, the present study relied on offline data processing; real-time reconstruction and integration with the clinical workflow remain to be developed.

In the UHDR-like configuration shown in figure 6 we focused on verifying stable operation of the Si+Si telescope and the absence of saturation in the raw hit and coincidence rates at the highest intensities used, rather than on obtaining a back-plane reconstruction analogous to figure 5. A detailed study of reconstruction performance for clinically realistic UHDR fields will require dedicated measurements and is beyond the scope of the present work. These preliminary measurements indicate that the telescope can be operated without saturation in UHDR/FLASH-like proton beams, supporting its potential applicability to future high-dose-rate treatments, although a full reconstruction and monitoring of clinically complex UHDR fields remains a subject for future studies.

In the present configuration the hit rate in each sensor and the coincidence rate between the two planes remained well within the nominal data-throughput capability of Timepix3. For the clinical fields studied in this work, the telescope was exposed to scattered-proton fluxes of the order of $10^4$ particles $\mathrm{cm}^2\,\mathrm{s}^{-1}$ while the highest-intensity configuration used for the UHDR/FLASH-like measurements in figure 6 reached fluxes of the order of $10^5$ particles $\mathrm{cm}^2\,\mathrm{s}^{-1}$ at the telescope position. These values are below the Timepix3 design limit of 40 million hits per s, and no saturation of the time-of-arrival or time-over-threshold encoding, nor any loss of tracking efficiency, was observed within these measurements. It should be stressed that these fluxes refer to the scattered field at the off-axis telescope and not to the primary beam fluence at isocenter.

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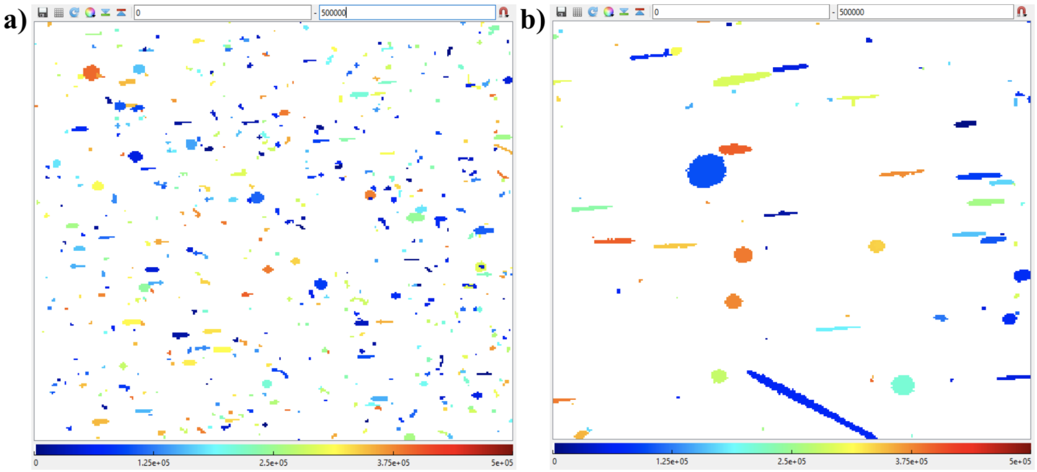

**Figure 6.** Raw data acquired of the ultra high dose rate proton beam. Both top (a) and bottom (b) TPX3 detectors are shown. Similar to figure 2, showing the synchronized registration of energetic charged particles at PTC. The proton beam energy was 226 MeV. The data shown corresponds to an interval of 500 ms. The top tracker (TPX3 300 µm Si) is on the left, the bottom tracker (TPX3 1000 µm Si) is on the right. Per-pixel time registration is shown in color by the scale bar [ns].

## 4 Conclusions and outlook

This feasibility study has demonstrated that a compact Si+Si Timepix3 stack telescope can be used for non-invasive visualization and tracking of clinical proton beams. By registering scattered protons outside the beam axis, the system enabled back-projection of the beam spot at the isocenter without perturbing the therapeutic delivery. The results show that the method provides sufficient angular resolution and sensitivity to reconstruct individual pencil beams in a clinical setting.

At present, the implementation relies on offline analysis and a relatively small sensitive area, and the statistical precision achievable for complex scanning patterns within short acquisition times is limited. Future work will therefore need to address both hardware scaling, for example by increasing the instrumented area or deploying multiple telescopes, and algorithmic development towards fast and eventually real-time reconstruction, in order to integrate this type of detector into clinical quality-assurance workflows.

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