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Spectral-tracking characterization and wide-range monitoring of scattered and secondary radiation in proton therapy

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ABSTRACT: In particle radiotherapy practice it is valuable to examine, accurately measure and monitor the secondary radiation fields produced during treatment. Measurements performed non-invasively and out-of-field avoid interfering with and modifying the delivered dose treatment. Use of a simplified and compact device is advantageous for reduced cost and effort of deployment and operation. For this purpose, we examine in detail the scattered beam particles and secondary radiation field produced well beyond even meters away from the irradiated area in proton therapy. We use the semiconductor pixel detector Timepix3 implemented as a miniaturized radiation camera which we mounted at the ceiling of the treatment room. The pixel detector provides high-resolution per-pixel spectrometry with time, position, directional and tracking response. Applying radiation imaging and particle tracking techniques together with extensive experimental calibrations in well-defined radiation fields, the single detector provides the composition and spectral-tracking characterization of the complex fields. In particular, the scattered proton field at the detector position is evaluated and unfolded into spectral-directional groups which serve to map and examine the characteristics and directional origin of the radiation out of field. Detailed particle fluxes and dose rates, total and partial, are measured out of field with sub-second time resolution. Deposited energy distributions in the detector sensor are derived in wide range. Verification and complementary information are provided by numerical Monte-Carlo (MC) simulations. The combined results and presented technique can be potentially used to inspect and systematically evaluate quality assurance irradiations and treatment plans.

KEYWORDS: Instrumentation for hadron therapy; Instrumentation for particle-beam therapy; Particle tracking detectors; dE/dx detectors

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Contents

1	Motivation, aims	1
1.1	Primary beam and dose delivery monitoring in particle therapy	2
1.2	Monitoring with secondary radiation, gamma rays	2
1.3	Secondary charged particles	2
1.4	Tracking of scattered particles, characterization of secondary radiation	3
1.5	Numerical calculations	4
2	Instrumentation, measurements	4
2.1	Proton therapy, medical IBA cyclotron, treatment room	4
2.2	Radiation camera MiniPIX-Timepix3	4
2.3	Non-invasive position, detector-sensor plane orientation	5
2.4	Measurements, therapeutic clinical beams, tissue-equivalent phantoms	5
3	Results	5
3.1	Quantum-imaging detection of single particles out-of-field	5
3.2	Decomposition of mixed-radiation field, particle-type classes	6
3.3	Time registration, detector operation duty factor, radiation field sampling	9
3.4	Particle fluxes: total, partial	9
3.5	Dose rates: total, partial	11
3.6	Deposited energy spectra	11
3.7	Directional maps, scattered protons	13
3.8	Monte-Carlo simulations: field composition, particle spectra	14
4	Conclusions	15

1 Motivation, aims

Proton therapy is characterized by enhanced relative biological effectiveness (RBE), high spatial selectivity and dose delivery depth accuracy [1–3]. It gives the ability to selectively deliver steep dose gradients, making it particularly effective for treating tumors located near critical structures. In comparison to conventional photon or electron therapy, proton beams offer the advantage of depositing the majority of their energy highly localized (at the Bragg peak), thereby minimizing radiation exposure to surrounding healthy tissues. This characteristic makes proton therapy particularly suitable for treating deep-seated tumors, pediatric cases, or tumors located near critical organs. However, this sensitivity increases risk and susceptibility to treatment uncertainties [4], with key contributors being patient setup errors, anatomical variations between treatment sessions and potential changes between the treatment plan and the actual beam-dose delivered. For these reasons characterizing the radiation fields produced and providing accurate monitoring of beam delivery and dose treatment are essential [2].

1.1 Primary beam and dose delivery monitoring in particle therapy

Various types of radiation detectors and methods are used [2, 5, 6] to verify and monitor the particle beams and doses delivered. Detectors consist of scintillating fibers, MWPC, diode detectors and segmented strip and pixel arrays. Position-sensitive devices can be placed in-beam, often inside the beam nozzle vacuum as subsystem of the accelerator beam delivery segment, to provide accurate and spatial information of the primary beam also in real time [5]. These systems can conveniently cover a relatively large sensitive area however with limited resolving power on the radiation field characteristics at the isocenter and the irradiated volume. These characteristics can be manifold in terms of composition (primary and secondary components), spectral, position and directional straggling, dose spatial and depth distribution, beam range monitoring, etc. Large area devices and assembled arrays can be costly and complex to construct and operate.

Alternative techniques of beam monitoring are also explored such as secondary electron emission on a thin foil which is placed in-beam [5]. The emitted radiation (low-energy electrons) requires high-voltage acceleration and associated detection with screens or position-sensitive semiconductor devices. The achieved spatial resolution and dynamic range are limited. Extended information on the beam intensity requires additional devices such as ionization chambers and MWPC [5].

1.2 Monitoring with secondary radiation, gamma rays

An alternative approach to mitigate the uncertainties and limitations above makes use of secondary radiation produced by interactions of the particle beam and the target/patient matter. Secondary radiation in the form of prompt gamma rays and energetic charged particles, stands as a promising probe for real-time monitoring that can be potentially exploited for tasks of beam quality assurance, dose delivery and patient treatment monitoring. This approach has also the advantage of not interfering with the primary beam and delivered dose.

Secondary gamma rays [5–7] are used via positron-emission tomography (PET) [8] and prompt-gamma imaging (PGI) [9] which provide information on the beam range and dose spatial distribution. The data, however, has limited spatial and depth (beam range) resolution with limited sensitivity (low count rate, low signal to noise ratio) [6]. These systems require large and elaborate instrumentation of complex and lengthy deployment, significant investment and high operation cost.

1.3 Secondary charged particles

Secondary charged particles can be also used as monitoring probe in ion [10–12] and proton [13] therapy. Studies make use of charged particle tracking detectors provided by segmented scintillating devices [12] such as ΔE -E and/or telescope architectures [10]. Promising results are achieved in terms of sensitivity, spectral response and radiation resolving power. Systems are, however, relatively complex and expensive to build and operate.

For beam and dose delivery monitoring, the semiconductor pixel detector Timepix in stack telescope architecture has been explored in ion therapy with detection and tracking of secondary charged fragments [14]. The proof-of-concept approach combines the high sensitivity and particle-counting response of Timepix together with high spatial and directional resolution of the stack configuration. An extension of this solution is the assembly and synchronized operation of 28 pixel detectors in stack twin-QUAD architecture [15].

1.4 Tracking of scattered particles, characterization of secondary radiation

In this work we pursue a non-invasive approach under clinical conditions in proton therapy using a single compact particle-tracking detector operated under simple as possible conditions (single USB cable for power, control and readout, room temperature, passive cooling, integrated electronics configuration, single cable readout). The detector position is well beyond ($> 5\text{m}$) from the irradiated volume — see figure 1. The sensor-plane orientation of the directional sensitive tracking detector is configured for enhanced high-resolution particle tracking of scattered beam protons (see justification below) and monitoring of secondary radiation produced in proton therapy environments at clinical conditions.

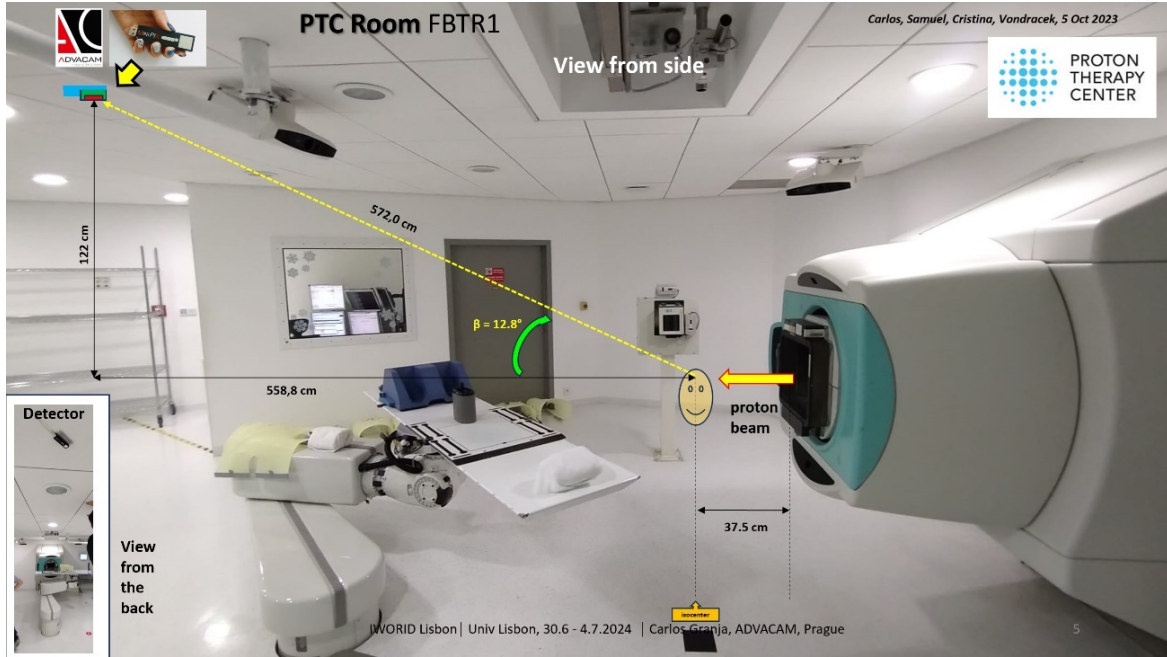


Figure 1. The fixed-beam patient treatment room at the Proton Therapy Center, Prague. The stray radiation field 5.7 m behind the patient position is measured non-invasively by the MiniPIX-Timepix camera (shown on top left) attached to the room ceiling at large distance (5.7 m) from the isocenter. The view from the back of the room is given in the inset (bottom left).

The subject of this work is to experimentally examine in detail the out-of-field environment at the selected position (far from the isocenter) for independent evaluation and potential exploitation for monitoring of delivered dose fields and treatment plans in particle therapy. The desired approach would be based on a simple high-resolution tool without interference with the primary delivered beam nor with the targeted or surrounding irradiated volume in or around the isocenter. This setup also enables to operate the sensitive detector in a reasonable radiation field of limited i.e., low intensity for long-term operation and optimal detector performance in radiation-tolerant conditions.

For this purpose, we use the Timepix3 ASIC chip [16] implemented as a compact radiation camera [17]. The detector operates at room temperature including a simplified passive cooling holder for maximal ease of deployment. Timepix3 provides detailed and wide-range information on the mixed-radiation field [18] which can be potentially analyzed and correlated to the delivered beam-target configurations and dose-field treatment plans.

In particle therapy environments the Timepix detector has been used for detection and characterization of scattered and secondary radiation and out-of-field measurements [18–20], delivered beam monitoring [15, 21–23], proton treatment planning [24] and FLASH therapy research [25, 26].

1.5 Numerical calculations

We complement and expand the experimental approach with numerical Monte-Carlo (MC) calculations of the radiation fields produced at the detector position. The purpose is to verify and compare the results produced by the detector in terms of radiation field relative composition and spectral distribution. The energy loss information by the detector can be related to the total (kinetic) energy of the particles provided by the numerical calculations.

2 Instrumentation, measurements

2.1 Proton therapy, medical IBA cyclotron, treatment room

This research is conducted at the Proton Therapy Center (PTC) in Prague. The medical IBA cyclotron provides proton beams in the range 230–70 MeV including modulated and pencil beam scanning [27]. Measurements are performed at a patient treatment room with fixed beam.

2.2 Radiation camera MiniPIX-Timepix3

The radiation camera MiniPIX [17] with the Timepix3 and a 300 μm thick silicon sensor has also a fast and thermal neutron converter mask [28] — figure 2(a). The detector is readout by single USB 2.0 cable and operates at room temperature. The holder for the camera serves also as passive heat dissipator for thermal stability and optimal operation.

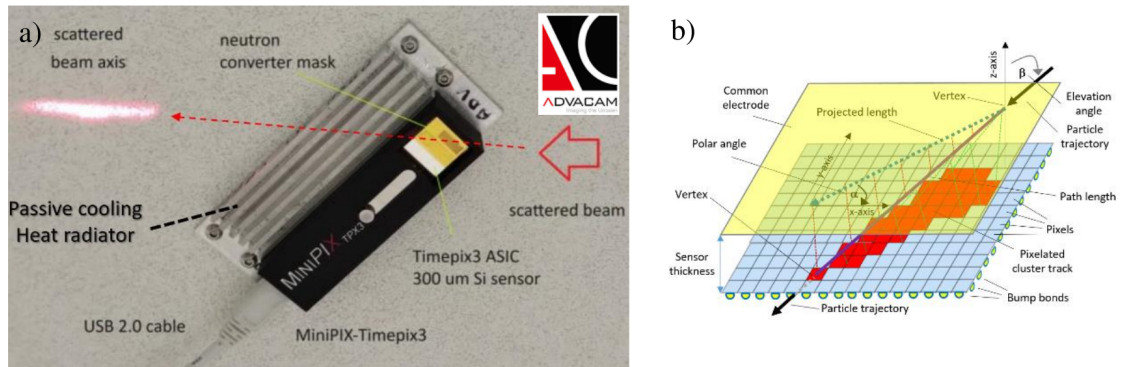


Figure 2. (a) The MiniPIX TPX3 Si radiation camera mounted on the ceiling of the treatment room. A thermal conductive (Al) backing holder serves for passive cooling and temperature stabilization. The field-of-view and directional axis of incidence of detected scattered particles and secondary radiation is indicated (red arrow/dash line). (b) Illustration of spectral-tracking analysis of single particle tracks [29].

The detector is operated and readout in data driven mode with per-pixel settings in energy and time. The camera is controlled by the PIXET software [30] with online detector response of visualization of the radiation field. Data are stored to standard windows/linux running miniPC. Data is processed offline in two stages: preprocessing and processing of the pixel detector data, using the integrated data processing tool DPE/TraX engine [31] followed by customized physics-dosimetry level data postprocessing (Python scripting).

2.3 Non-invasive position, detector-sensor plane orientation

The detector is positioned out-of-field away from the irradiated volume and is fixed on the room ceiling with direct field of view to the phantom-patient position. The distance and elevation direction to the isocenter vertex are 572 cm and angle 12.8° — figure 1.

The detector-sensor plane is set parallel to the floor and beam horizontal plane. Furthermore, along this plane, the detector orientation is rotated (at nearly 45°) to the trajectory vector of the scattered beam from the isocenter (see figure 2a). This configuration geometry enhances the spectral-tracking resolving power of the detector [29, 32] to the radiation emerging from the isocenter and irradiated volume — see also figure 2b.

2.4 Measurements, therapeutic clinical beams, tissue-equivalent phantoms

We worked with therapeutic irradiations of clinical beam-energy and dose-intensities delivered in standard treatment conditions. We measured the out-of-field stray radiation field beyond the irradiation-patient volume at the detector fixed position (figure 1). Various irradiations and beam-target setups were investigated and measured:

- (1) Irradiations without target (no phantom, no patient)
- (2) Beam-target-detector calibrations with fixed beam (size, energy, position) and simplified tissue-equivalent target-phantoms
- (3) Quality assurance (QA) irradiations with water-equivalent phantoms
- (4) Patient treatment irradiations

In this work we analyze and present the preliminary results of measurements (1) and (3).

3 Results

3.1 Quantum-imaging detection of single particles out-of-field

The detection and particle track visualization of the stray radiation field [19, 20] registered at the detector position are shown in figure 3. Raw data with all detected particles are given. The per-pixel energy calibration is applied. The figure is integrated offline, acquired in a total interval of 1.03 seconds. The resulting particle count rate on the detector is at the $\approx 10^{-3}$ level per second during QA and therapy treatment sessions with the proton beam of clinical intensities.

Thanks to the Timepix3 detector and the MiniPIX-TPX3 camera ability to operate in continuous data-driven mode, single particles are registered separately in large gradients of radiation field intensity. This makes possible to perform continuous measurements (high duty cycle) and high-resolution spectral-tracking analysis of the radiation components resolved [29, 33] in order to analyze and characterize in detail the complex mixed-radiation field [18].

In the geometry and detector orientation setup used, the detected particles enter in figure 3 from the top right corner of the detector pixel-matrix — see also figure 2(a). Even by visual inspection, it can be readily observed that the radiation field consists of groups of events of distinct spectral-tracking morphology [33]. Scattered primary beam particles (protons) produce the large tracks of varying morphology ranging from thin straight tracks of small per-pixel energy to broad and round tracks of large per-pixel energy. These events originate from the primary beam and immediate irradiated

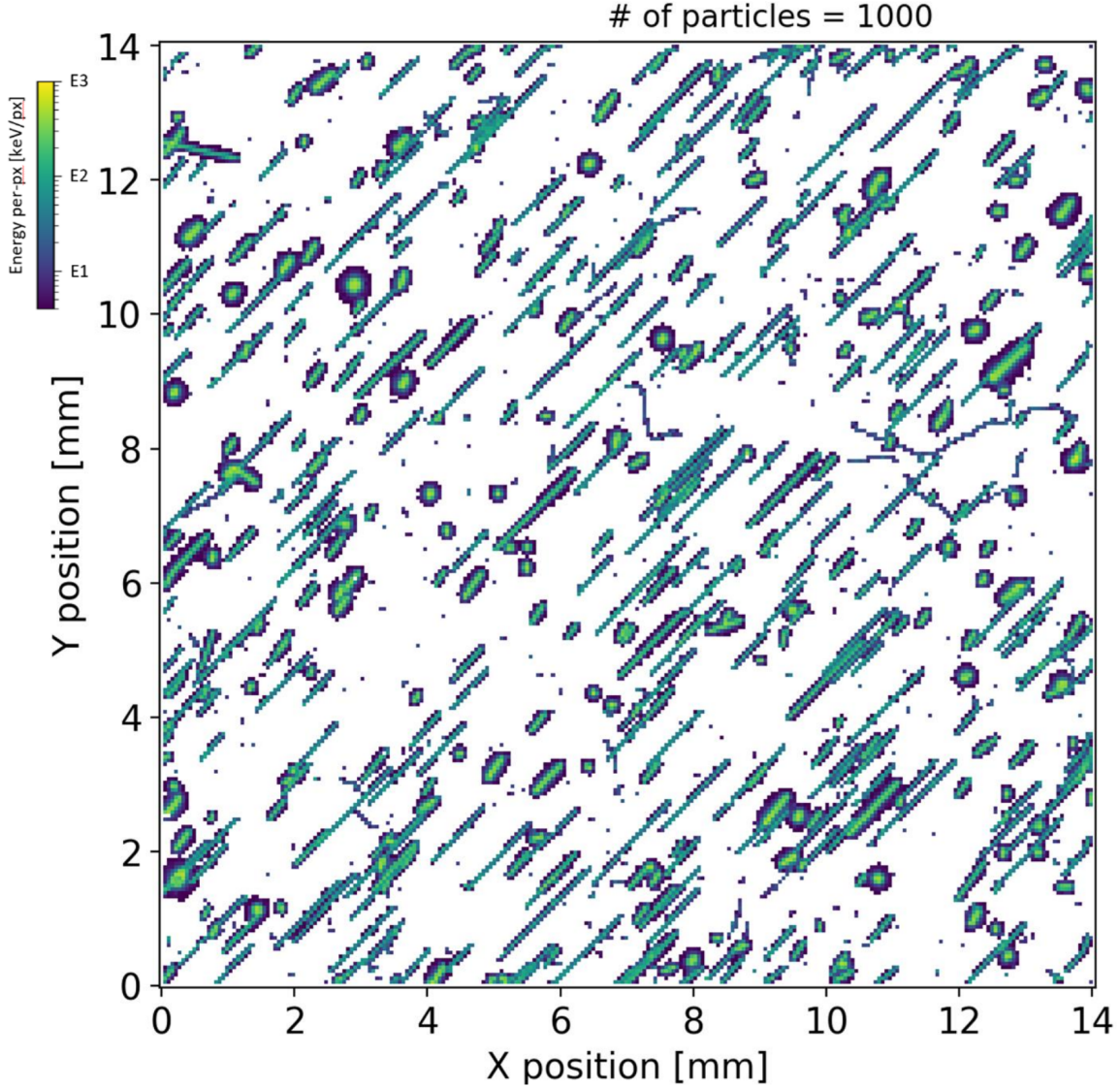


Figure 3. Imaging detection and particle track visualization of the stray radiation field produced by a 100 MeV proton beam at the PTC treatment room with no phantom. Measured at the detector position (see figure 1) by Timepix3 with a 300 μm thick silicon sensor. Data shown integrated for a 1.03 s irradiation interval. All detected particles are shown. The full detector pixel matrix is displayed ($256 \text{ px} \times 256 \text{ px} = 14.08 \text{ mm} \times 14.08 \text{ mm} = 1.98 \text{ cm}^2$). The per-pixel registered energy is shown by the color scale.

volume carrying spectral and directional information. Secondary particles — thin narrow curly tracks (electrons) and small few-pixel tracks (X rays), originate along a wider volume in and around the beam isocenter and irradiated volume.

3.2 Decomposition of mixed-radiation field, particle-type classes

The registered mixed-radiation field (figure 3) can be analyzed and decomposed into particle spectral tracking components (figure 4). Particle-event type sensitivity is provided by the detector spectral-tracking response [33, 34] together with pattern recognition analysis of the single particle tracks [35]

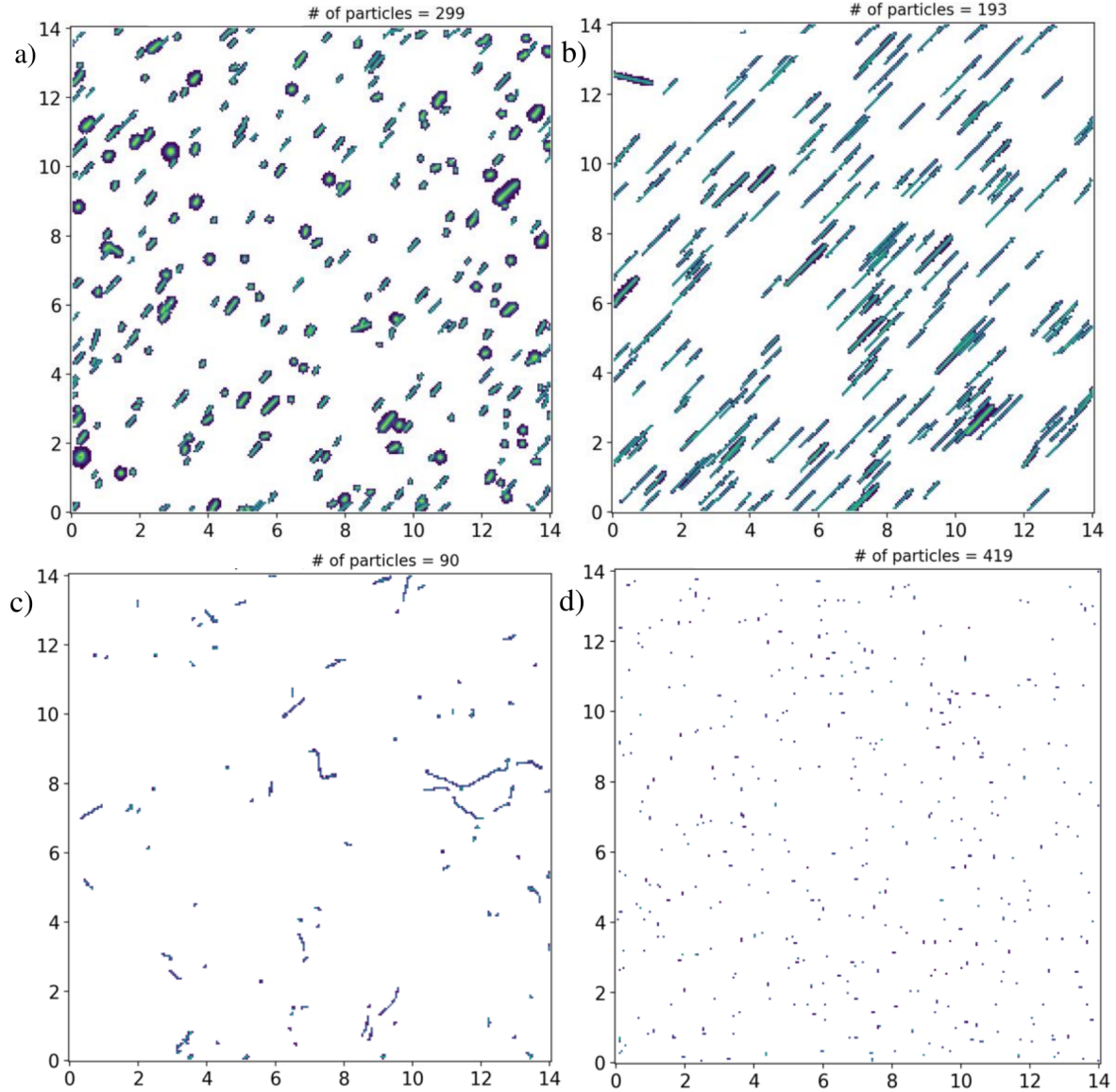


Figure 4. Decomposition of the mixed-radiation field in figure 3 according to particle-type classes: (a) low-energy protons (includes partial admixture of fast neutrons), (b) high energy protons, (c) high-energy electrons and low-energy gamma rays, and (d) X rays and low-energy electrons. See table 1. The number of particles in each class is included — see plot headers. The same set of data, per-pixel energy scale and displayed detector sensor area apply as in figure 3.

and experimental calibrations at well-defined and reference radiation fields [31, 33]. Resolved event classes (table 1) are associated with distinct particle-radiation groups: scattered primary beam particles (protons) of low energy — figure 4(a) — and high energy — figure 4(b), secondary/background particles consisting of secondary electrons and low-energy gamma rays — figure 4(c) and X rays — figure 4(d).

Charged particles, both light e.g. electrons and heavy e.g. protons, are registered with essentially $\approx 100\%$ efficiency provided they reach the detector sensor [33]. The track spectral morphology is determined by the particle type, stopping power (energy loss) and direction relative to the detector sensor plane [22, 33].

X rays and gamma rays (up to few tens of keV) are detected with sizeable detection efficiency in the detector thin silicon sensor [36]. For higher photon energies, the detection efficiency is exponentially reduced.

Neutrons, thermal and fast, are detected with low detection efficiency ($\leq 1\%$) and limited discrimination [28]. Response and detection channels proceed [28] via (i) neutron converter mask — e.g., for thermal neutron detection with ^6Li or ^{10}B converters, and (ii) direct interactions in the detector silicon sensor — through nuclear reactions such as (n,p) and (n, α) by fast neutrons on ^{28}Si . In proton therapy, neutrons have been detected in secondary fields by the detector placed in different geometry and with a different beam-phantom setup [37]. In the radiation environments investigated with targets (WE phantom, patients), a neutron component can be also partially registered [37]. Broad-energy neutrons are produced from high-energy proton interactions in the phantom-patient material and in the surrounding room walls and floor [27, 37].

The detector particle-type resolving power is derived from the spectral signature (energy loss) together with event-by-event spectral-tracking and cluster morphology pattern recognition analysis of the pixelated tracks [18, 33, 35]. Assignments are made in terms of particle type, energy and direction of incidence to the detector sensor plane. These parameters stand as degrees of freedom of the detector-particle response [33]. For simplicity and robustness, the decomposition is simplified, from more elaborate detailed classifications [18, 33], to four broad particle classes (table 1). A given class can have more than one particle type determined also by the particle energy and direction — the values and ranges of which are indicated approximately, see labels in the table footnote.

Table 1. Particle-type classification by Timepix3 with silicon sensor. The dominant radiation in the radiation fields in this work are highlighted (bold letters). See text, see footnote labels.

<i>Class</i>	<i>Track morphology</i>	<i>Interaction</i>	<i>Radiations</i>	<i>Energy (direction)</i>
a	large tracks (≥ 4 px) broad, elongated	HETP	LE protons ions neutrons*	< 70 MeV (OD) > 1 MeV/u (OD) thermal [#] , fast (OD)
b	large tracks (≥ 4 px) narrow, straight		HE protons electrons, muons	> 70 MeV (NPP) MIP
c	large tracks (≥ 3 px) narrow long	LETP	HE electrons	> 300 keV (OD)
			gamma rays**	> 30 keV–100's keV (OD)
d	small tracks (≤ 4 px) round		X rays** LE electrons protons neutrons*	5–30 keV (OD) < 300 keV (OD), > 10 MeV (PP) MIP, > 150 MeV (PP) fast, IE

* = limited detection efficiency (DE) $\leq 1\%$

** = limited DE, limited energy range < 100 keV

[#] = in the thermal neutron converter mask (Lithium or Boron converter) [28]

HETP = high-energy transfer particles, LETP = low-energy transfer particles, OD = omnidirectional

PP = perpendicular, NPP = non-perpendicular, px = pixel (55 μm), MIP = minimum ionizing particle

IE = intermediate energy, HE = high energy, LE = low energy

3.3 Time registration, detector operation duty factor, radiation field sampling

Together with the spectral (energy loss) registration, the time of interaction of single particles is also recorded. The time stamp of particle registration has a timing resolution of ≈ 50 ns. The detector data readout time, which depends on data packet size and thus on the particle count rate on the detector, amounts at most to few minutes per hour. The measured radiation field is evaluated (or sampled) in arbitrary intervals of time down to subsec level.

3.4 Particle fluxes: total, partial

The particle flux of the data in figure 3 is $490.3 \text{ particles} \times \text{cm}^{-2} \times \text{s}^{-1}$. Detailed time distributions are produced for all particles (total flux) and particle-event classes, described in table 1, (partial fluxes) as shown in figure 5.

Measured particle flux data vary over four orders of magnitude and are evaluated in subsecond sampling time (100 ms). The results are time-stamped according to the real elapsed time (about 48 minutes in the data shown). The detector readout deadtime is included which for this data interval amounts to over 3 minutes. The particle fluxes at the detector position are measured in high-resolution and in wide range from few and even single particles up to $10^6 \text{ particles} \times \text{cm}^{-2} \times \text{s}^{-1}$ [18]. In the presented data, the flux varies up to four orders of magnitude. The lower range, has a flux value of $5 \text{ particles} \times \text{cm}^{-2} \times \text{s}^{-1}$, corresponds to a single particle registered in the evaluated time bin (100 ms). The mean flux and integrated fluence of particles were evaluated in the intervals of beam irradiation and are indicated (see subplot legend labels).

The evaluated number of particles (integrated fluence and mean particle flux in the detector) given in figure 5 (values in the plot legends) are produced for the irradiation intervals, i.e., the time periods when the beam was on. The effect and correction for the detector readout deadtime, estimated at few percent, is not taken into account in the values presented.

The QA data contains three beam-phantom fields (at around 4:52–53, 5:11–18 and 5:32–34) and one diagnostic X ray radiography (at around 5:03). The different QA intervals exhibit different patterns of selective population according to particle classes and varying intensity.

Beyond the irradiated periods, the particle flux registers the background and cosmic ray flux levels [29]. Following the beam irradiations, a short interval of few minutes of limited increased intensity readily observed in the last QA field can be assigned to residual activation in the surrounding material — namely by Aluminum.

The particle identification of each class exhibits a dominant component highlighted in table 1 (3^{rd} column from left, text in bold). The non-proton admixture of class 2, resulting from overlapping tracks produced by electrons and muons, has limited extend (few events from over 20 k particles registered in nearly 1 h of detector operation) as noted in the data intervals without irradiation.

The proton components (classes a and b — figures 5a,b) closely correlate with the primary beam irradiations exhibiting overall pattern similarities. Sizable and relative differences are also noted between their relative yields at specific irradiation sub-fractions — e.g., at times 4:52 h, 5:11 h and 5:17 h. The non-proton admixture in class b is revealed in the intervals without irradiation where namely cosmic rays and short-live activation radiation are registered.

The X-ray, and low-energy electron, component (class d — figure 5d) correlates with the diagnostic-positioning X-ray interval at 5:03 h. This component appears also in the irradiation periods (as secondary radiation) and in the non-irradiation periods (as background and secondary cosmic

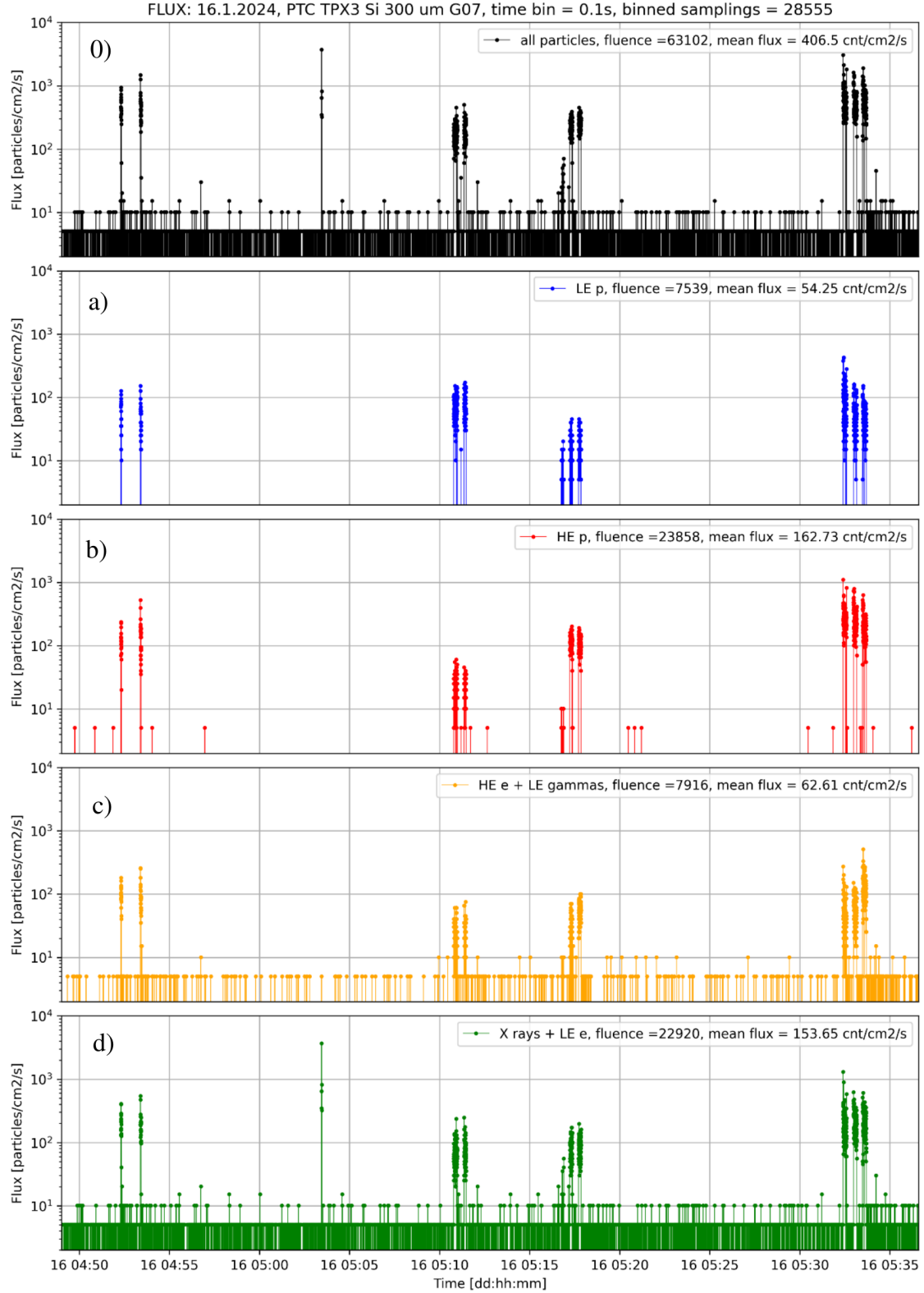


Figure 5. Particle flux at the detector position during a QA irradiation session (48 min). Values derived in time bins of 100 ms for (0) all particles — black, (a) low-energy protons — blue, (b) high-energy protons — red, (c) high-energy electrons and low-energy gamma rays, and (d) X rays and low-energy electrons — green. The number of particles (integrated fluence in the detector) and mean particle flux, derived when the beam was on, are included — see plot legends. See text, see also table 1 and figures 3, 4.

ray radiation). In the irradiation periods, the X rays appear correlated with the high-energy protons (class a) and partly anticorrelated with the low-energy protons (class b).

The last component, high-energy electrons and low-energy gamma rays, appear in all irradiations, and in the non-irradiation periods, namely as secondary radiation. Like the other components, the time-stamped characteristics and gradients in flux, direction, deposited energy (see below) carry information on the beam-target irradiation configuration.

3.5 Dose rates: total, partial

Detailed particle dose rates are measured at the detector position for all particles and the resolved particle-event types. The corresponding results for the QA irradiation session presented are given in figure 6.

The dose rate exhibits a variability of up to six orders of magnitude. The lower end, at $\approx 0.1 \mu\text{Gy/h}$, corresponds to the cosmic ray background level. The mean values and the integrated particle dose were evaluated also in the intervals of beam irradiation and are similarly indicated (see subplot legend labels).

3.6 Deposited energy spectra

The spectral and composition characterization out-of-field (at the detector position) is suitably expressed by the deposited energy of the registered particles in the detector silicon sensor which is measured in high resolution and wide range for all particles and the resolved particle-event classes as shown in figure 7.

The spectral distribution of energy loss of the radiation out-of-field, measured in the detector silicon sensor, covers nearly four orders of magnitude. The low energy range is given by the detector spectral threshold at the level of $\approx 4 \text{ keV}$ per pixel [33]. The high energy range is given by low-energy HETP particles ($\approx \text{MeV}$ protons, light ion reaction products of fast neutron direct interactions in silicon [28]) registered in the detector [38].

The high-energy loss component, above few hundred keV per particle, is produced by the HETP particles (namely protons — classes *a* and *b*) in the measured data. The low-energy loss component, down to few keV per particle, is produced by X rays and low-energy electrons (class *d*). The component in between of low-yield corresponds to high-energy electrons, and partly low-energy gamma rays (class *c*).

Comparing the data of the two setups it can be observed a hardening of the distributions of the charged particles, namely the protons. In the QA data, the beam particles have a broad distribution including lower energies and the scattered protons, which lose energy in the phantom, reach the detector with lower energy. Similarly, the yield of secondary radiation increases in the QA data. This can be noted by the relative yield of the electron component, compared to the low-energy proton component.

Together with information on the particle track length in the detector sensor, measured accurately for energetic charged particles [29], detailed LET spectra can be derived too [38].

The characteristics of the spectral distributions and measured particle fluence with particle class resolving power can be analyzed and potentially exploited for evaluation and monitoring of quality and stability of QA (and also patient) irradiations.

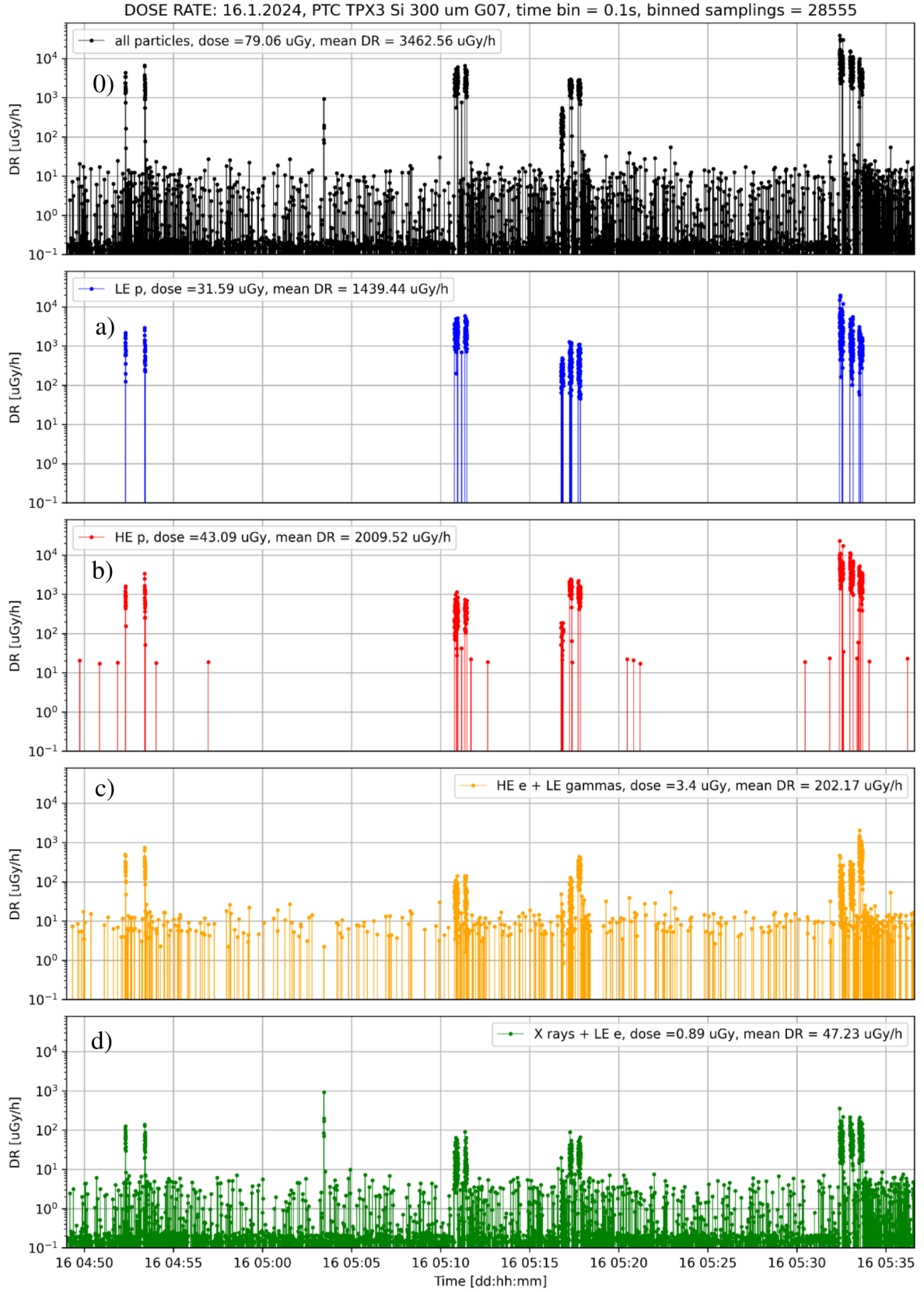


Figure 6. Corresponding dose rate, measured at the detector position, for the data in figure 5. Values of integrated dose and mean dose rate, derived during the beam irradiation intervals, are included (see plot legends).

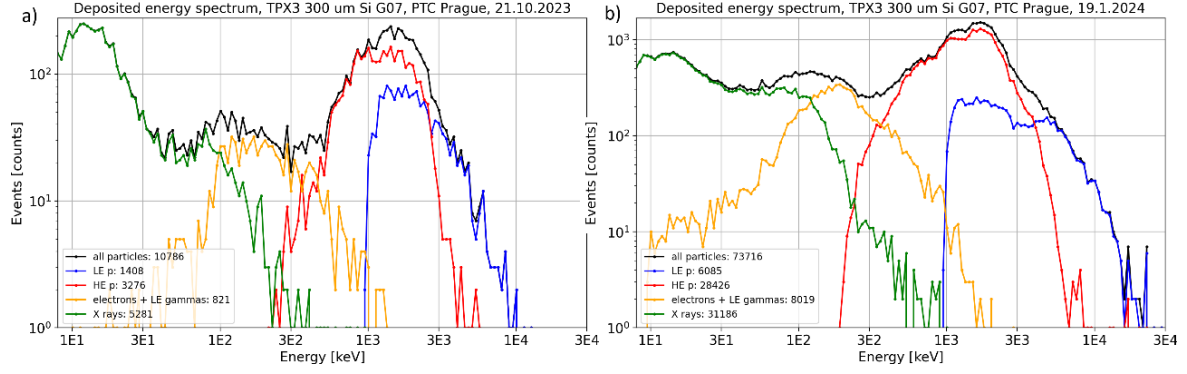


Figure 7. Deposited energy spectra in the detector silicon sensor for (a) the 100 MeV proton no phantom measurement, and (b) the QA irradiation session (see figures 5 and 6). The data in (a) corresponds to figures 3 and 4 acquired in 20 sec. Distributions are given for all particles (black curve) and the customized particle-event classes (table 1). The numbers of particles for the data subsets are included (see legend inset).

3.7 Directional maps, scattered protons

The particle fluxes registered by the detector planar sensor (section 3.4) are omnidirectional. Taking into account the detector field-of-view and geometric factor [29], directional information can be derived and analyzed in the form of angular fluxes for scattered protons — see figure 8.

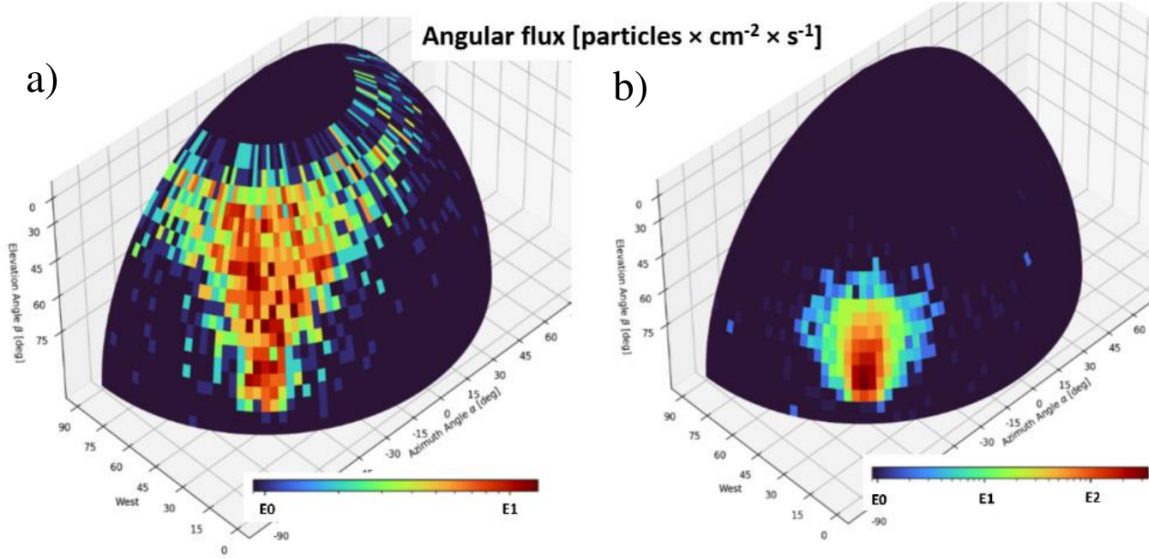


Figure 8. Angular flux at the detector position for (a) low-energy and (b) high-energy protons. Results for the data with 100 MeV protons, no phantom — see figure 4a and figure 4b, respectively. The angular resolution (map bin) is 2° along both the elevation (vertical axis) and azimuth (XY plane) directions.

The beam-phantom configurations measured exhibit differences in the distributions in terms of angular spread, contour pattern and intensity gradients between the proton components. The high-energy protons exhibit a narrow directional spread — pointing to the primary beam path up to the isocenter region. Low-energy protons undergo many interactions and originate from a larger spread-out region. Information on the particle source vertex-location can be extracted [29].

3.8 Monte-Carlo simulations: field composition, particle spectra

Numerical simulations were performed by means of the general-purpose Monte Carlo (MC) code MCNP® version 6.2 [39] for the coupled transport of ionizing radiation particles. The simulations used the same cross-section tables as in the previous studies [20, 40], i.e, electron-photon relaxation library EPRDATA14, electron library MCNP4B, proton library ENDF/B-VII.0, photonuclear reaction library ENDF/B-VII.0 and neutron library ENDF/B-VIII.0. Delayed particles from non-fission nuclear interactions were also considered.

The MC model includes: a) the gantry head with a glass entrance window; b) all walls, ceiling and floor of the irradiation room re-used from a previous study [41]; c) the MiniPIX detector with 500 μm Si sensor [42] adjusted to match the detector used in this study. The detector was positioned and oriented in the irradiation room as in the experimental setup. A monoenergetic parallel proton source with realistic Gaussian distribution in lateral directions is set before hitting the entrance window. The radiation field at the detector position is calculated in terms of composition (radiation species) and (total or kinetic) energy spectra. Results for one of the studied beam-target configurations (100 MeV proton beam, no target/no phantom — presented in this work) are given in figure 9.

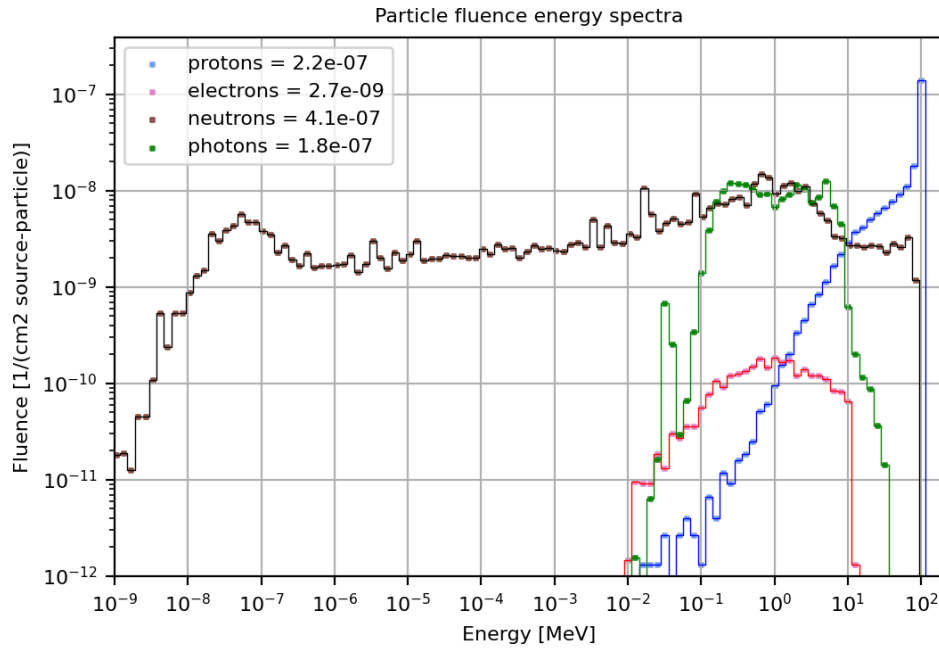


Figure 9. Particle fluence energy spectra of radiation components at the detector position for: scattered protons (light blue), electrons (pink), neutrons (brown), and photons i.e., X rays and gamma rays (dark green). Data calculated for a 100 MeV primary proton beam and no target (no phantom). The total number of events according radiation component are included (see inset). Values given per one primary beam proton.

The proton component, for this particular beam-target configuration, largely maintains the mono-energy distribution of the delivered (100 MeV) primary beam. This corresponds to the high-energy proton component observed (figures 4b, 5a, 6a, 8b) of the scattered beam particles (protons) reaching the detector. The associated experimental data on energy loss (figure 7a) is measured however with broadened energy resolution (due to the fluctuations of energy loss and the detector limited spectral resolution) [33, 38]. The tail of low-energy protons (figure 9) can be associated below ≈ 70 MeV

(see table 1) to the high-energy loss proton component resolved in the detector (figures 4, 5, 6, 8). The yield (relative ratio) of the two spectral proton components resolved (low-energy protons below 70 MeV and high-energy protons above 70 MeV) is about 32:68 in the simulations (figure 9) and, only approximately, 61:39 in the experiment (figure 4). The discrepancy can be in a small extent (due to the limited neutron detection efficiency [37]) accounted for by admixture of the fast neutron component which above ≈ 1 MeV produces tracks in the detector [28] undistinguishable from low-energy proton tracks (see event class a in table 1). However, the main reason remains the uncertainty and limitation in the estimation of the particle (proton) kinetic energy from the energy loss data [43] which moreover exhibit large fluctuations.

The neutron component [37] exhibits a wide energy range of non-negligible yield. The electron and photon (X rays, gamma rays) components observed in the detector and in the numerical calculations, can be in principle also (partially) exploited for the purpose of beam and dose delivery monitoring.

4 Conclusions

The stray field, at a distant non-invasive position well beyond the isocenter and irradiated volume in proton therapy, has been measured and characterized with a compact single-chip detector. Two beam-target configurations were examined and compared. Detailed experimental information is obtained in terms of field decomposition of radiation spectral-tracking classes with selective spectral (energy loss), directional and time distributions. Particle fluxes and dose rates of high sensitivity and large dynamic range are produced with subsecond (e.g. 100 ms) timing resolution. Integrated particle fluences and absorbed doses are selectively measured in high resolution at the detector position. These results can serve to inspect and compare treatment plans and models from numerical simulations. For potential clinical application, a complete model (future work) is required to quantitatively correlate and extrapolate the detector out-of-field data with the targeted irradiated isocenter position. The patterns and measurable differences in the experimental observables can be exploited to systematically examine and indirectly monitor the quality and stability of QA irradiations which however requires further elaboration and detailed model.

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