

Composition and Spectral Characterization of Mixed-Radiation Fields with Enhanced Discrimination by Quantum Imaging Detection

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Abstract—Mixed radiation fields in environments such as particle radiotherapy and outer space exhibit large complexity in terms of composition and spectral distribution which are difficult to measure in detail. For this purpose, we present a high-sensitivity technique using the pixel detector Timepix3 to measure the composition and spectral-tracking characterization of secondary fields produced in proton radiotherapy. Particle-event classes are resolved into broad groups of high-energy transfer particles (HETP), such as protons, ions and neutrons, as well as low-energy transfer particles (LETP), such as electrons, X rays and, partly, low-energy gamma rays. The quantum-imaging capability of Timepix3 is exploited to enhance the resolving power for particle-type classification. The particle tracks are analyzed by spectral-sensitive pattern recognition algorithms. The response matrix for Timepix3 is newly derived and is based from experimental calibrations in well-defined radiation fields including in-beam rotational scans of protons performed at various energies and directions. Clinical proton beams of radiotherapeutic intensities and energies in the range 225 – 12 MeV were used in experimental configurations with and without a tissue-equivalent phantom. Detailed results of radiation components can be used to produce total and partial particle fluxes, dose rate, absorbed dose, deposited energy and linear-energy-transfer (LET) spectra. Dedicated Monte Carlo (MC) simulations are compared with experimental results of field composition, particle fluence, and deposited energy. The numerical information aids the interpretation of experimental data which includes also secondary neutrons. The technique and developed methodology can be applied for research and routine measurements in environments of varying complexity.

Index Terms—Particle tracking, Position sensitive particle detectors, Radiation therapy, Semiconductor radiation detectors, Radiation imaging, Monte Carlo simulations

I. INTRODUCTION

RADIATION fields produced in particle radiotherapy [1,2], high-energy particle accelerators [3] and outer space [4,5] can exhibit high complexity and wide range in terms of composition, spectral and directional distributions. Taken as degrees of freedom, these parameters determine and can

significantly complicate the various tasks of radiation transport, detection, measurement and characterization of mixed-radiation fields. Field composition is in this work understood and analyzed in terms of (i) broad-class particle species, (ii) radiation source type and (iii) radiation spatial origin. Primary particles are understood as coming from the radiation source – e.g., the particle accelerator beam either directly along the beam path or scattered e.g., in air or in a target phantom. Secondary radiation consists of different particles produced in the target phantom, surrounding material or in the air as product of interactions by the primary beam. Thus, in addition to primary beam and scattered beam particles, the radiation field contains also electrons, gamma rays, X rays and also neutrons [6,7].

In these environments the radiation fields can moreover exhibit large intensity gradients and significant variability in terms of time and position. The precise measurement of such fields is challenging especially if the use of simplified and compact instrumentation is desired. The task can be further burdened by the experimental conditions, limitations in deployment and access of the instrumentation, setup geometry as well as time and safety constraints. It should be also taken into account the specific detector limitations – such as sensitivity, dynamic range, count rate pile-up and signal amplitude saturation.

For this task and related applications are of value the hybrid semiconductor pixel detectors of the Timepix family [8,9]. The built-in per-pixel signal electronics of the ASIC chip provide dark-current free operation and wide dynamic range for precise counting, spectrometry (energy loss), tracking, imaging and timing measurements of single particles [10,11] such as X rays [12] and gamma rays (detected with limited detection efficiency) [13], charged particles [14–16] and also neutrons [17,18]. The Timepix detectors are operated at room temperature and can be controlled and readout by compact readout electronics [19,20] for online response, simplified deployment and flexible measurements.

In this work we use the Timepix3 detector [21] and develop the spectral-tracking methodology for this chip-sensor configuration (Timepix3 ASIC with a 500 μm silicon sensor). The goal is to apply these results to provide a comprehensive and precise characterization of mixed-radiation fields using compact and highly integrated instrumentation (a miniaturized radiation camera) with flexible operation and online response. The Timepix3 detector is equipped with a silicon sensor and an additional neutron converter mask [18].

Article submitted on 26th October 2023.

Work at Advacam was performed in frame of Project No. 4000130480/20/NL/GLC/hh from the European Space Agency. Measurements at the Bronowice Cyclotron Centre were carried out in frame of the EU H-2020 INSPIRE Infrastructure Research program Grant 730983 C. Granja, L. Marek and C. Oancea are with Advacam, Prague, Czech Republic (email: carlos.granja@advacam.cz).

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of a minute with selected proton beam energies up to 225 MeV.

In the selected beam-energy-phantom configuration, the proton range and Bragg peak along the beam axis are inside of the target phantom for the selected proton energies 150, 100 and 70 MeV. The range in water of 70 MeV and 225 MeV protons is 4.2 and 31.8 cm, respectively. Measurements were performed as well without the phantom in order to evaluate the beam scatter in the air and in the surrounding material including the support patient bench. This second setup was examined with proton beams of energies 225, 150, 70, 32 and 12 MeV.

The detectors were placed behind the phantom position on the forward direction and transverse plane to the beam axis as shown in Fig. 2. The detectors were placed at equidistant position to the beam axis to ensure the same radiation field conditions. Several detectors of different ASIC-sensor-chip configuration were used such as Timepix3 with 500 μm silicon sensor (analyzed in this work) and Timepix and Timepix2 detectors with Si and CdTe sensors of thickness 300 or 500 μm and 1000 μm , respectively.

D. Detector operation settings and readout configuration

The Timepix3 detector was operated and readout in frame mode. This allows us to have a greater per-pixel spectral range (14-bit counter) than in data driven mode (10-bit counter). The frame acquisition time is ideally adjusted according to the particle event rate on the detector. The acquisition time is set sufficiently short, optimally below pixel-hit occupancy 10%, in order to avoid event pileup and ensure most events are registered as isolated tracks. This makes possible to register and analyze single tracks for maximum resolving power and high-resolution data analysis. The frame mode however brings also a detector readout dead time (29 ms for the MiniPIX-Timepix3 detector used) during which radiation is not registered. Data analyzed in this work were collected with frame acquisition frame of 4.5 ms. The resulting operation duty cycle (detector live time) is 13.4 %.

E. In-beam calibrations, low-intensity proton beams

In addition to the measurements of mixed-radiation fields, we also performed measurements in-beam with low-intensity proton beams (flux $< 10^5$ protons $\times \text{cm}^{-2} \times \text{s}^{-1}$). We used selected proton energies in wide range (225, 150, 70, 32 and 8 MeV). The detector, placed directly on the path of the proton beam, was mounted on a rotor stage in order to register particles incident at defined and different directions to the detector sensor plane. The registration of single particle tracks at selected proton energies and direction (60°) is seen in Fig. 3. The data shown are integrated offline over many individual frames in each of which single particles are registered as isolated tracks.

The in-beam measurements were performed in air, at 2 m from the beam accelerator nozzle. This work serves to test the response of the detector to well-defined radiations and to fine-tune the response matrix of particle-type discrimination.

F. Detector per-pixel energy calibration

The detector was per-pixel energy calibrated using discrete-energy X rays and low-energy gamma rays [31]. Prior to the

accelerator measurements, short tests were also performed with mono-energetic alpha particles and low-energy gamma rays from a laboratory radionuclide source (^{241}Am). This step is useful as a check of the detector configuration and calibration as well as of the resolving power of the technique.

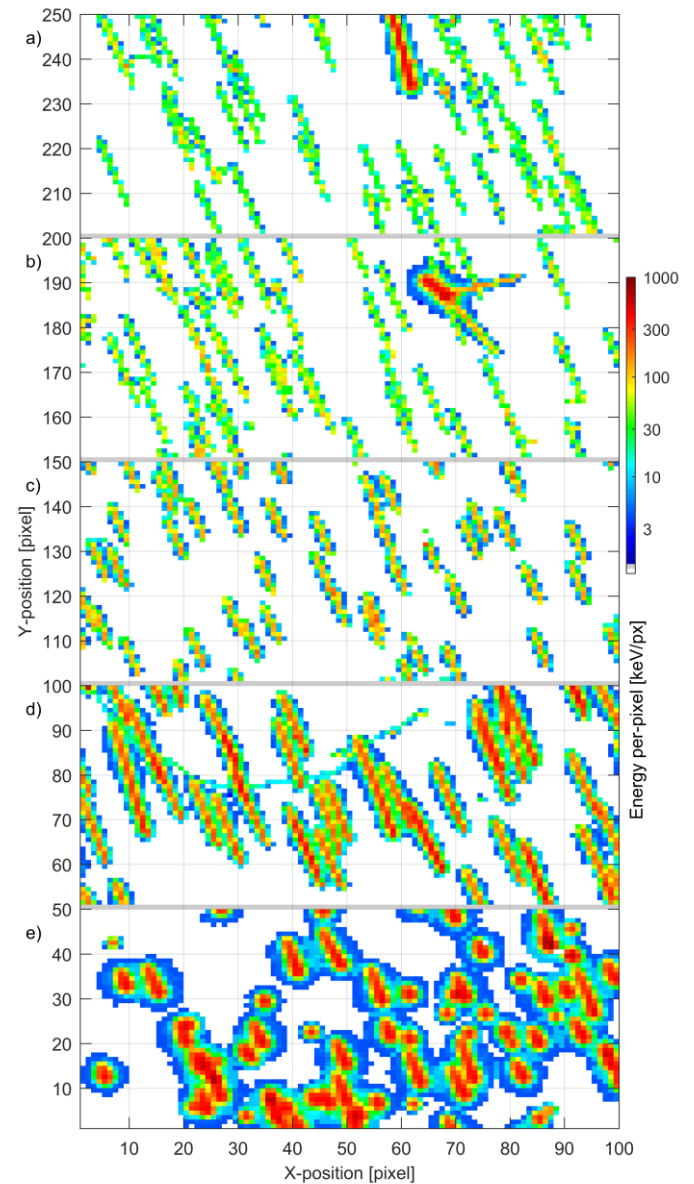


Fig. 3. Detection by Timepix3 with a 500 μm silicon sensor of protons incident at 60° to the detector sensor plane of energies: (a) 225 MeV, (b) 150 MeV, (c) 70 MeV, (d) 32 MeV and (e) 8 MeV. Only a part of the detector pixel matrix is displayed, for each data set $100 \text{ px} \times 50 \text{ px} = 5 \text{ k px} = 5.5 \text{ mm} \times 2.75 \text{ mm} = 15.1 \text{ mm}^2 = 7.6 \%$ of the detector total sensitive area (1.98 cm^2).

G. Data Acquisition and Data Processing

Raw data contain the detailed per-pixel hit registry of measured energy and event count, the frame time acquisition time (e.g., 4.5 ms) and the measurement time stamp. Data were processed offline using an integrated computing tool for pixel detectors Timepix – called Data Processing Engine (DPE) [32]. This procedure contains several consecutive stages.

(i) Preprocessing: track identification, pixel clusterization, application of the per-pixel energy calibration.

(ii) Processing: Analysis of the pixelated clusters produced by single particles with detailed pattern recognition algorithms [33]. The spectral and tracking morphology patterns are analyzed in terms of cluster analysis parameters [10]. Detailed physics data are produced for each registered particle such as deposited energy, position of interaction, trajectory across the detector sensor and the track length [16]. The particle incident direction is derived in wide field of view (FoV) with particle type resolving power [20]. The cluster parameters are used to analyze and classify the single tracks into broad particle-type classes (see Sec. III.D.). For this task, response matrices are derived based on calibrations to defined radiations.

(iii) Post-processing: Detailed radiation data are evaluated, data products are generated. These include total and partial particle fluxes, dose rates [34], deposited dose and LET spectra [22]. Corresponding spatial distributions over the detector pixel matrix of these quantities are derived. Also, directional angular distributions of energetic charged particles can be produced [20,35].

III. SPECTRAL-SENSITIVE PARTICLE TRACKING

A. Quantum imaging detection of single particles

Timepix provides high granularity (spatial resolution at the pixel level 55 μm), high sensitivity (photon-counting), per-pixel spectral response and particle tracking in wide field-of-view (FoV). The detector serves as a spectral-sensitive imaging device and stands as an active nuclear emulsion [36] for quantum-imaging detection [34] and track visualization [16,37] of single particles. This ability to visualize single particles and their trajectories at the pixel and μm level can be exploited to examine in detail [34] and resolve with enhanced discrimination different particle-type events [10].

B. Spectral-sensitive particle tracking

The registered tracks consist of many pixels, called clusters [14,16], with morphology and spectral (energy loss) distribution determined by the position of interaction, particle trajectory across the sensor [10,16] and the charge sharing effect [14,38].

The characteristic spectral response, determined by the particle energy loss, is in turn related to the particle energy – see Fig. 3. Highly energetic particles, such as 225 MeV and 150 MeV protons, exhibit low energy loss (few tens of keV at the pixel level = 55 μm). Low-energy particles, such as 32 MeV and 8 MeV protons, as they approach the Bragg peak region, exhibit high energy loss (few hundred keV/px level).

The detector directional response requires no collimators and covers the entire field-of-view from the perpendicular direction (0°) to the parallel direction (90°) [20]. The trajectory and direction of incidence of the particles are registered at the pixel scale together with energy loss measurement [16,20]. It can be also seen, by evaluating the track morphology and distribution of particle incident direction, that most proton tracks correspond to the primary beam. Tracks corresponding to scattered and slowed down particles are also registered and can be resolved. For instance, see the distinct tracks of different

morphology (wider tracks of different direction) and high-energy loss in Figures 3a and 3b. Background and unwanted particles are detected and resolved as well such as electron tracks and X ray tracks registered in Fig. 3d.

C. Morphology-tracking parameters of pixelated clusters

The particle tracks in the pixelated sensor exhibit characteristic spectral and morphology pattern [10] in terms of particle type, energy and direction. These variables stand as degrees of freedom of radiation detection.

For this work we analyzed and derived the cluster parameters values for particle-type classification, previously performed for Timepix [10] and Timepix2 [39], for the chip-sensor configuration used (Timepix3 ASIC chip with a 500 μm silicon sensor). The filter values of spectral and tracking parameters are given in Table I and Table II, respectively.

TABLE I
CLUSTER SPECTRAL PARAMETERS ACCORDING PARTICLE-TYPE CLASS

#	Class	H [keV]	Epx [keV]	LET [keV/ μm]
1	A	100-1E4	20-1E3	
2	B	100-1E4	20-1E3	
3	C	100-1E4	20-1E3	
4	D	100-1E4	20-1E3	
5	E	30-300	20-80	0.5-3.0
6	F	3-180	3-80	0-1.4
7	G	3-180	3-40	0-1.1
8	H		3-100	
9	I	100-1E4		

H = cluster height, Epx = energy per px

TABLE II
CLUSTER TRACKING PARAMETERS ACCORDING PARTICLE-TYPE CLASS

Class	A [px]	LIN	Bpx/A	R
A	4-1E4	0-0.15	0-0.55	
B	4-1E4	0-0.15	0.55-1	
C	4-1E4	0.15-1	0-0.55	
D	4-1E4	0.15-1	0.55-1	
E	5-1E3	0.90-1	0.995-1.0	
F	4-1E3	0.95-1		0.80-1
G	4-1E3	0-0.95		0-0.80
H	1-3			
I	1-3			

A = cluster size (# of px), R = cluster roundness, LIN = cluster linearity, Bpx/A = ratio of # of border px to cluster size (A).

D. Particle-event type classification

Particle species are analyzed according stopping power into two broad groups: HETP and LETP [10]. HETP consist namely of heavy charged particles (HCP) i.e., protons and ions. To this group we include in this work also neutrons which can be moreover resolved into thermal and broad-energy fast components [18]. LETP consist of X rays and light charged particles (LCP) such as electrons and muons. Into this group we include the interactions in the detector sensor produced by low-energy gamma rays [13].

Using pattern recognition algorithms and the derived cluster filters, specific particle-type classes are derived. This approach is based on experimental calibrations [10], newly performed for Timepix3, on well-defined radiations of mono-energetic energy and known direction, such as radionuclide sources and low-

intensity particle beams at accelerators – see Fig. 3. The particle-type classes derived for Timepix3 are listed in Tab. III. The estimated values and range of particle energy are calculated from corresponding values of particle energy loss [40].

TABLE III
DERIVED PARTICLE-TYPE CLASSES: TIMEPIX3 500 μM SILICON

Class	Type	Particle	Energy	Direction
A [⊠]		protons	4-50 MeV	$< 5^\circ$
		protons	1-4 MeV	OD
		ions	$> 10 \text{ MeV/u}$	$< 5^\circ$
		ions	$< 10 \text{ MeV/u}$	OD
B	HETP	neutrons	$\geq \text{MeV}$	OD
		protons	100 keV-1 MeV	OD
		protons	$> 50 \text{ MeV}$	$< 5^\circ$
		neutrons	$\approx \text{MeV}$	OD
C		protons	4-50 MeV	$> 5^\circ$
		ions	$> 10 \text{ MeV/u}$	$> 5^\circ$
		neutrons	$\geq 10 \text{ MeV}$	OD
D		protons	50-150 MeV	$> 5^\circ$
E		protons	$> 150 \text{ MeV}$	$> 5^\circ$
F ^{&}	LETP	electrons	$< 3 \text{ MeV}$	OD
G ^{#%}		electrons	$> 3 \text{ MeV}$	OD
H [*]		X rays	3-30 keV	OD
I [@]	noisy px ----			

HETP = high-energy transfer particle, LETP = low-energy transfer particle, np = noisy px, OD = omnidirectional, [⊠] admixture of thermal neutrons (using the converter mask) [&] admixture of gamma rays ($< 1 \text{ MeV}$), [#] admixture of gamma rays ($\approx \text{MeV}$), [%] admixture of muons, MIP protons ($> 200 \text{ MeV}$) $> 5^\circ$, ^{*} muons, MIP protons $< 5^\circ$ ($> 200 \text{ MeV}$), [@] admixture of fast neutrons.

The HETP group is further classified according spectral-tracking pattern into classes A and B, which correspond to tracks of round morphology and distinct energy loss, and classes C, D, and E, which correspond to track of elongated morphology and distinct energy loss.

The particle-type class assignments and corresponding values of particle energy for the various radiations are approximate and can exhibit partial overlap between different particle species. For very high energy loss particles, such as heavy ions and also low-energy light ions approaching the Bragg peak region, a saturation of the per-pixel spectral response distorts and can saturate the energy registration [41].

IV. DECOMPOSITION OF MIXED-RADIATION FIELDS

A. Mixed-radiation fields: all particles

The radiation field at the detector position registered by Timepix3 is shown in Fig. 4. The data shown were measured without (top) and with (bottom) the PMMA phantom (Fig. 2). All particles are displayed, i.e., no event filters are applied. The data are summed over many raw frames for an integrated detector live time of 711 ms and 94.5 ms, respectively. A large number of particles is displayed in order to provide an overall idea and greater visual inspection of the radiation field. The apparent pile-ups, i.e., joint tracks connecting two and more single particle tracks, consist of isolated events registered separately i.e., as single tracks and are thus processed separately. Registering isolated tracks allows us to apply the quantum-imaging visualization [17] and high-resolution spectral-sensitive tracking technique [16] of single particles for

detailed analysis and high-resolution results (Sec. III).

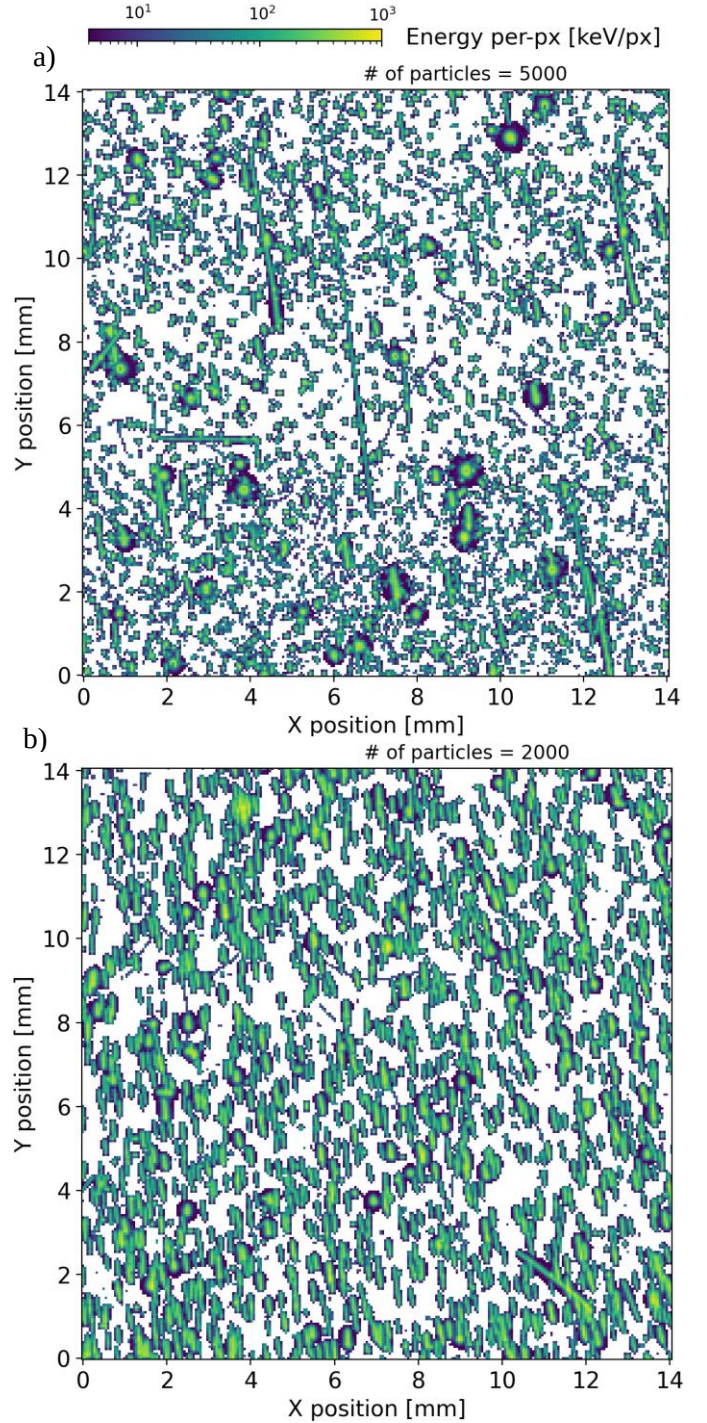


Fig. 4. Detection and track visualization of the radiation field at the detector position as measured by the Timepix3 detector. Data shown for a 150 MeV proton primary beam (a) without and (b) with the PMMA phantom. All registered particles are displayed: 5 k particles collected in 711 ms (top) and 2 k particles in 94.5 ms (bottom). The entire detector sensor area is displayed: $256 \text{ px} \times 256 \text{ px} = 65 \text{ k px} = 14.1 \text{ mm} \times 14.1 \text{ mm} = 1.98 \text{ cm}^2$. The per-pixel energy response is displayed by the color bar in log scale.

In Fig. 4 it can be observed that the radiation field exhibits a wide collection of distinct tracks with observable changes in terms of yield, composition, spectral and directional distribution. The total and partial number of particles registered varies. For the data shown in Fig. 4, the total particle flux is

2×10^4 particles $\times$ cm $^2 \times$ s $^{-1}$ (with) and 8×10^3 particles $\times$ cm $^2 \times$ s $^{-1}$ (without) the phantom. The various pattern groups of tracks are analyzed and described in terms of spectral-tracking classes (Tab. III) as follows below.

B. Scattered and secondary high-energy protons

Events of classes C and D are observed in the measured data. The corresponding events resolved in the data with the PMMA phantom given in Fig. 4b, are shown in Fig. 5.

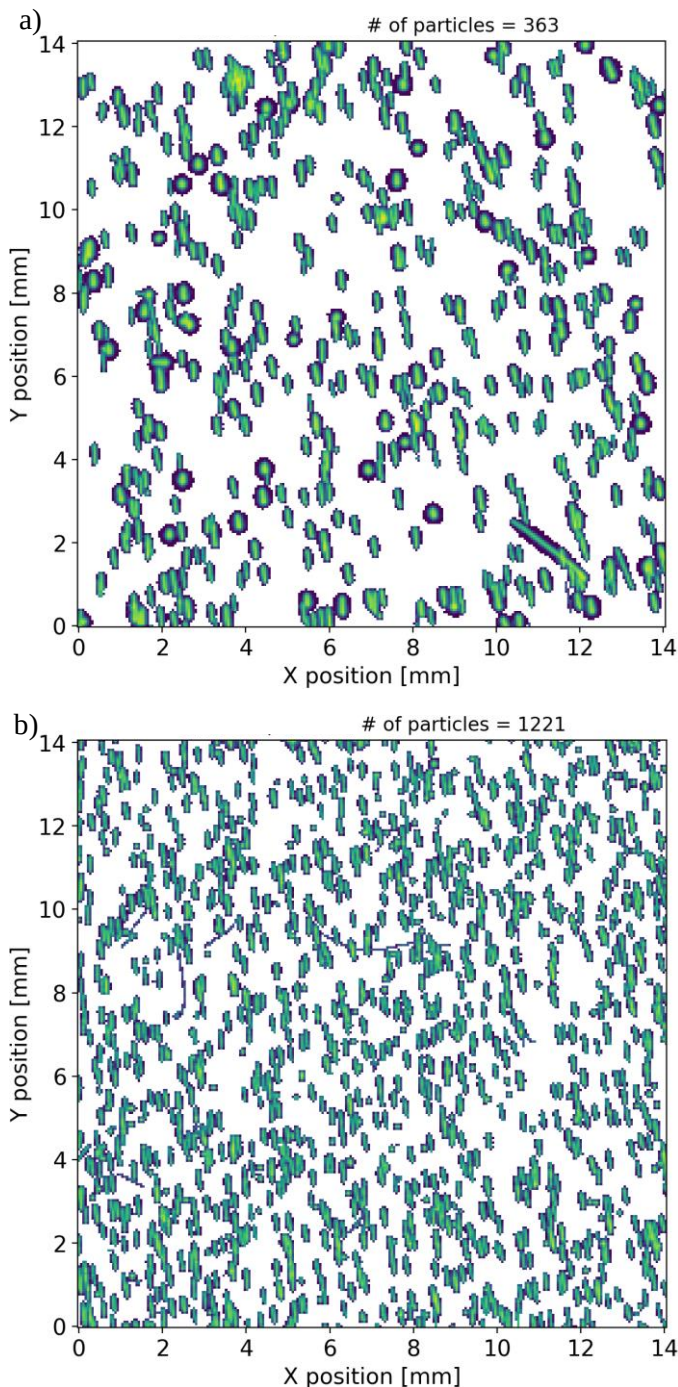


Fig. 5. Similar to Fig. 4 showing the particle-type events of (a) class C and (b) class D found in the data given in Fig. 4b (150 MeV proton beam with the PMMA phantom). The number of events is included in the headings of the plots.

Taking into account the directionality of the registered tracks

for these classes, and the beam-target-detector geometry used (Fig 2), these events correspond to scattered and secondary protons of high energy in the range 4-50 MeV and > 50 MeV, respectively (Tab. III).

These event classes C and D are also observed in the data without the phantom (not shown). Similar but also specific patterns are observed with measurable differences between both sets of data in terms of event count rate and in the respective spectral and also directional distributions.

C. Scattered and secondary low-energy protons

Events of classes A and B are also registered in the data. The corresponding events in the data without the PMMA phantom given in Fig. 4a are shown in Fig. 6.

These events should correspond to scattered and secondary protons of low energy in the range 1-4 MeV and 0.1-1 MeV, respectively (Tab. III). However, given the beam-target-detector geometry, this type of tracks is produced instead by fast neutron interactions in the silicon sensor (Tab. III), see Sec. IV.E below.

These event groups A and B are also observed in the data with the phantom (not shown) exhibiting overall similarities but also specific differences. They exhibit an increased event yield relative to all particles registered. This supports the assignment of these event classes as fast neutron interactions (see below). Quantification and more detailed interpretation can be aided by MC simulations (Sec. V) and further analysis beyond the scope and extent of this article.

D. Electrons, X rays, low-energy gamma rays

Low-energy transfer particles are detected in all the data. Few events corresponding to this group (narrow curly tracks) can be seen in Fig. 3d. These particles are produced as secondary radiation and consist of light charged particles, namely electrons which are resolved into two classes of broad energy: below about 3 MeV (class F) and above about 3 MeV (class G).

To this broad group belong also X rays (class H) and low-energy gamma rays (admixture in classes F and G). The gamma rays are detected with decreasing detection efficiency for increasing energy. The tracks produced by electrons and gamma rays are narrow (1 to 2 pixels wide) and mostly elongated. Tracks by X rays are small (track area ≤ 3 pixels) and low per-pixel energy distribution.

E. Neutrons

In the data measured in this work, taking into account the beam-target-detector geometry, events of type A and B (Sec. IV.C and Fig. 6) are assigned to interactions produced by fast neutrons in the silicon sensor. No thermal neutrons are registered. Quantification and confirmation of these assignments can be aided by the MC simulations (Sec. VII) and extended data analysis which are beyond the extent of this paper.

V. DEPOSITED ENERGY

The deposited energy spectra measured in the 500 μ m silicon sensor for the experiments with and without the phantom are

given in Fig. 7. The data span a wide range of energy and counts, each over $4\times$ orders of magnitude.

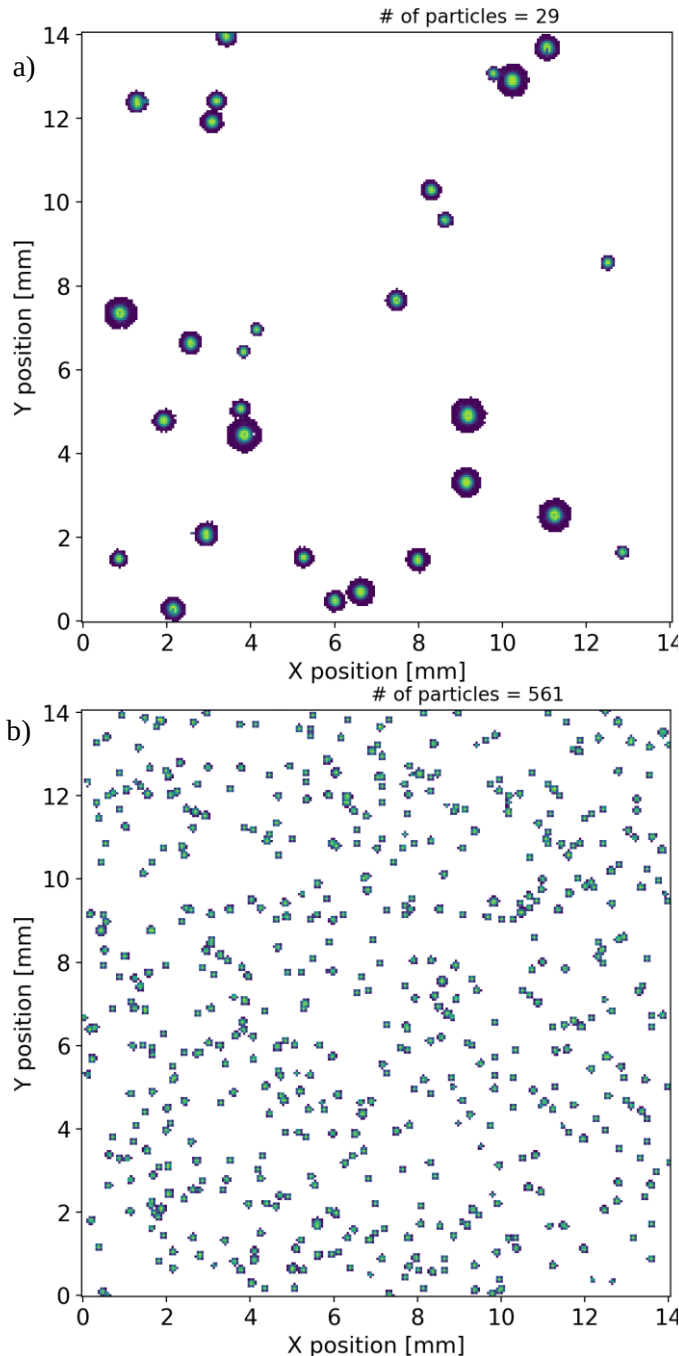


Fig. 6. Similar to Fig. 5 showing the particle-type events of (a) class A and (b) class B found in the data without the phantom given in Fig. 4a.

Results are given for all particles (black) and for the dominant particle-type classes: HETP of round tracks and mid energy loss (class B – red curve), HETP of elongated tracks and high energy loss (class C – green curve) and mid energy loss (class D – light blue curve), all LETP together i.e., classes F+G+H (purple curve). These classes exhibit in the data large yields. Class A events (HETP of round tracks and high energy loss) exhibit a low count rate and are assigned to fast neutron interactions in the silicon sensor. Class E events correspond to

highly energetic/MIP protons of energy above 150 MeV (see Tab. III) and are not registered in the data evaluated in this work.

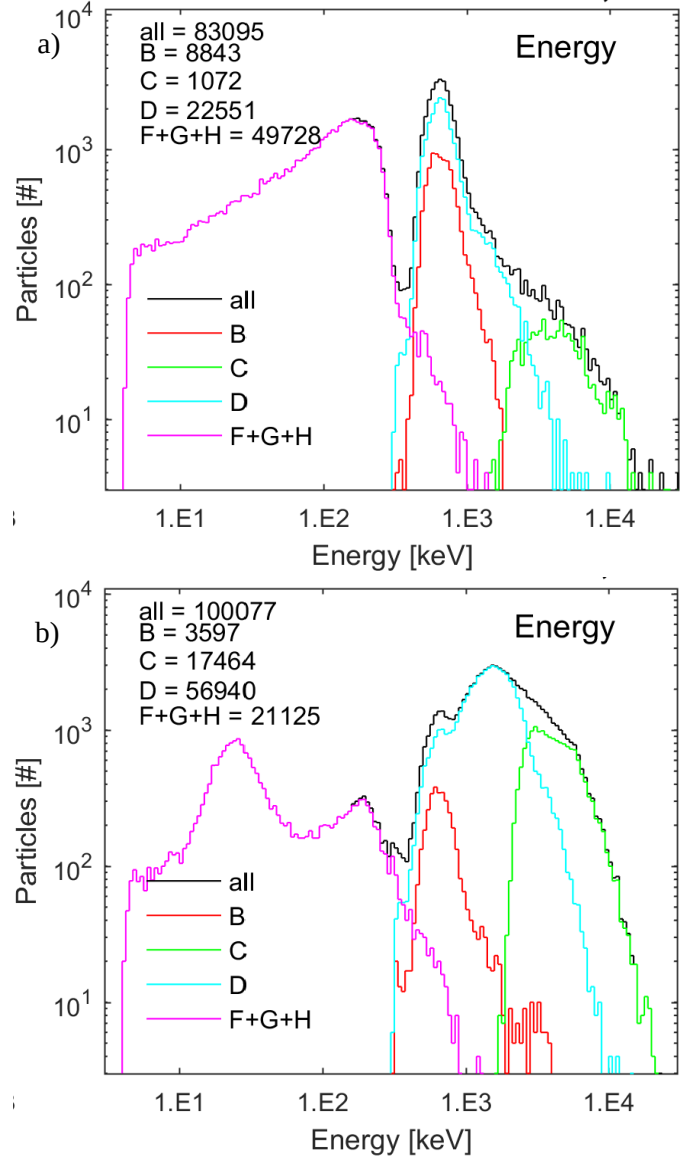


Fig. 7. Deposited energy spectra for the 150 MeV proton (a) without and (b) with the PMMA phantom. Results are produced for a larger data set than shown in Fig. 4. Data shown for all particles (black curve) and selected particle-type classes (color curves) – see inset labels. The number of events according particle-event classes is included. Plot axis displayed in log scale.

In the data without the phantom, the proton component is dominated by classes D, B and partly also C. The energy loss is dominated by a low-energy narrow component (at ≈ 800 keV) resulting from high-energy primary beam protons (class D) which underwent limited scattering (namely in air). The next component (class B) points to the presence of low-energy protons (≤ 1 MeV) with admixture of fast neutrons [9,26]. The higher-energy loss component (class C) is produced by energetic protons of mid-energy (≈ 4 -50 MeV) which underwent more extended scattering and loss of kinetic energy. The LETP part has a dominant single component of high energy (≈ 150 keV) produced namely by secondary electrons.

In the data with the phantom, the HETP part of the deposited energy spectrum shifts towards higher energy also with significant broadening of the distribution. The spectrum is dominated, in order of significance, by classes D, C and B. This results from increased scattering and greater slowing down of the primary proton component together with increased production of secondary protons. A partial admixture is due to fast neutron induced events of rather high-energy spectrum ($\geq$ MeV). The LETP part is shifted to lower energies with a dominant component at ≈ 20 keV which is produced mainly by X rays. The observed characterization corresponds to the expected greater production of secondary radiation.

VI. DOSE RATE, LET SPECTRA, DIRECTIONAL FLUX

The results produced can be further evaluated into additional physical quantities such as dose rates, deposited dose, LET spectra and directional distributions. These quantities can be produced as detailed time-dependent distributions of total and partial components which are subject of extended and future work.

VII. MONTE-CARLO SIMULATIONS

Numerical simulations can provide valuable and detailed information of the mixed-radiation field produced in the environments studied. They complement the experimental results and can significantly aid the analysis and interpretation of the obtained results. Of particular value in this work is the information on the composition of the radiation field at the detector position in terms of secondary radiation and scattered primary beam particles. Similarly of high value is knowledge of the particle energy spectrum and particle deposited energy at the detector position. For this purpose, dedicated Monte-Carlo simulations were performed at the CMI by means of the general-purpose MC code MCNP[®] version 6.2 [42].

A. Geometry

The modelled geometry was kept simple. It consisted of the air path from the accelerator beam nozzle, the rectangular PMMA phantom and the wooden bench of position, size and configuration as in the experimental setup (Fig. 2). A simplified model of surrounding environment was included which consisted of the floor and walls of the experimental hall made of barite concrete. The surrounding material can serve for assessment of the potential influence of secondary radiation, in particular neutron interactions in nearby material, especially via backscatter, thermalization as well as photon generation. The accelerator gantry head with beam nozzle, beamline, and exit window, as well as the Timepix detectors including the detector semiconductor sensor, power adapters and nearby computers, were not taken into account. The particle source was defined as a monoenergetic parallel pencil proton beam with full-width at half maximum of 1.3 cm and centered on the PMMA phantom axis. The proton beam travelled through a distance of 50 cm in air to the upper side of the phantom (Fig. 2).

B. Setup, radiations, energy range

The following particles were tracked in the simulations: protons, neutrons, photons (consisting of X rays and gamma rays), electrons, deuterons, tritons, ³He ions, ⁴He ions, and

heavy ions. Ion recoils were set on. All other settings were kept default. Elastic and inelastic scatterings, and photonuclear interactions were considered.

The cut-off energy was set to 1 MeV for ions, 0.1 MeV for protons, and 0.01 MeV for photons and electrons. Delayed particles from non-fission nuclear interactions were also considered. The Bertini intra-nuclear cascade model [43] with the Dresner evaporation model [44] was used when nuclear cross-section tables were not available. Otherwise, the incident neutron cross section library ENDF/B-VIII.0 at 293.6 K [45], and proton cross-section library ENDF/B-VII.0 [46] were used. Photons and electrons were generated and transported according to the electron-photon relaxation library EPRDATA14 [47] and the photonuclear reaction library ENDF/B-VII.0 [48].

No variance reduction method was used. However, the advantage of cylindrical symmetry of the geometry (neglecting possible small difference due to the rectangular phantom) was exploited in such a way that the azimuthal angle (angle of rotation around the proton beam axis) was irrelevant.

Each simulation run for about 7 hours (Intel Core i9 13900K, 20 CPU @ ~ 4.7 GHz) reaching about 1.5×10^9 and 2×10^{10} primary protons of 150 MeV for geometries with and without the PMMA phantom, respectively.

C. Calculated quantities

The quantities were scored in an annulus of the inner and outer radii of 19.2 and 22.6 cm, respectively, and thickness of 500 μm . The annulus axis was the same as the proton beam axis. The parameters correspond to the position of the Timepix detector with respect to the phantom, and to the thickness of the detector sensor (500 μm silicon).

The composition of the radiation field was calculated in terms of protons, electrons, photons (X rays and gamma rays), neutrons and ions. The following physical quantities were produced: particle current, particle fluence, detector count spectrum and LET spectra in silicon at the detector position. The particle current was obtained by means of F1-type tally scoring particles crossing the front surface of the annulus. The result was divided into 91 angular bins with respect to the surface normal. The particle fluence was obtained by means of the F4-type tally scoring the average track length in the annulus volume. The current and fluence was calculated in void annulus. On the contrary, the LET and detector spectrum were obtained for annulus filled with Si. LET was calculated by using the F4-type tally modified by the LET keyword, and the detector spectrum was determined by using the F8-type tally, which scores the deposited energy and converts it into counts.

D. Particle fluence, particle energy spectra

The calculated energy distribution of particle fluence is given in Fig. 8. Data are shown for a 150 MeV proton beam in both setup configurations, with and without the PMMA phantom. Results are produced for all particles including neutrons and for the main field components. This information serves to verify the experimental assignments of particle components (Tab. III).

E. Particle deposited energy

Deposited energy spectra were calculated at the detector position in the detector sensor material (500 μm silicon).

Results for the same data evaluated – 150 MeV proton beam with and without the PMMA phantom – are given in Fig. 9. Data are given for protons, electrons (which include the photon interactions in the detector sensor) and ions (mostly light ions including ^2H particles). Data from neutron interactions in the silicon sensor were not calculated as the model and library of reaction mechanisms were not considered complete (subject for future work).

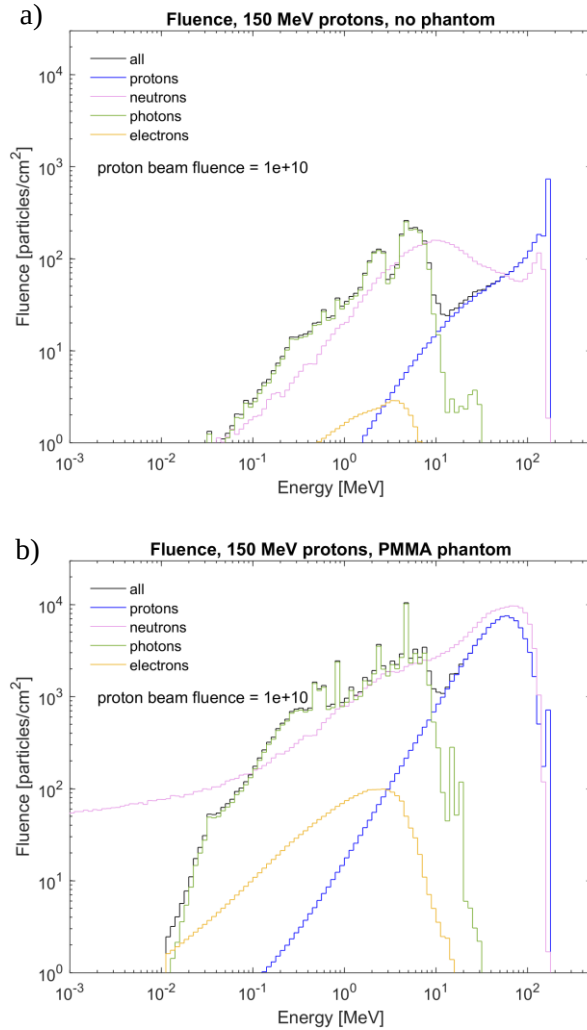


Fig. 8. Monte-Carlo calculation of particle fluence at the detector position for the experiments performed with 150 MeV protons (a) without and (b) with the PMMA phantom. Results are given for all particles including neutrons and the main particle components – listed in inset. Values are given per cm^2 normalized relative to 1×10^{10} primary beam protons. Plot axes are displayed in log scale.

The numerical results can be compared with the experimental energy spectra measured by the detector (Sec. V, see Fig. 7). The broad radiation components are qualitatively reproduced for both setups. The HETP component in the simulations consists namely of protons and light ions. It does not include the partial contribution by fast neutrons from interactions in silicon of the detector sensor via (n,p) and (n, α) reactions in ^{28}Si [18]. The calculated proton component corresponds to classes D, B and C without the admixture of fast neutron interactions produced in the detector sensor. The ion component appears with limited yield (nearly $3 \times$ orders of magnitude) which in the

experimental data is not separated in this work from the dominant proton component in classes A and C. The calculated LETP component consists namely of secondary electrons and exclude the photon interactions, namely X rays and low-energy gamma rays registered in the detector sensor.

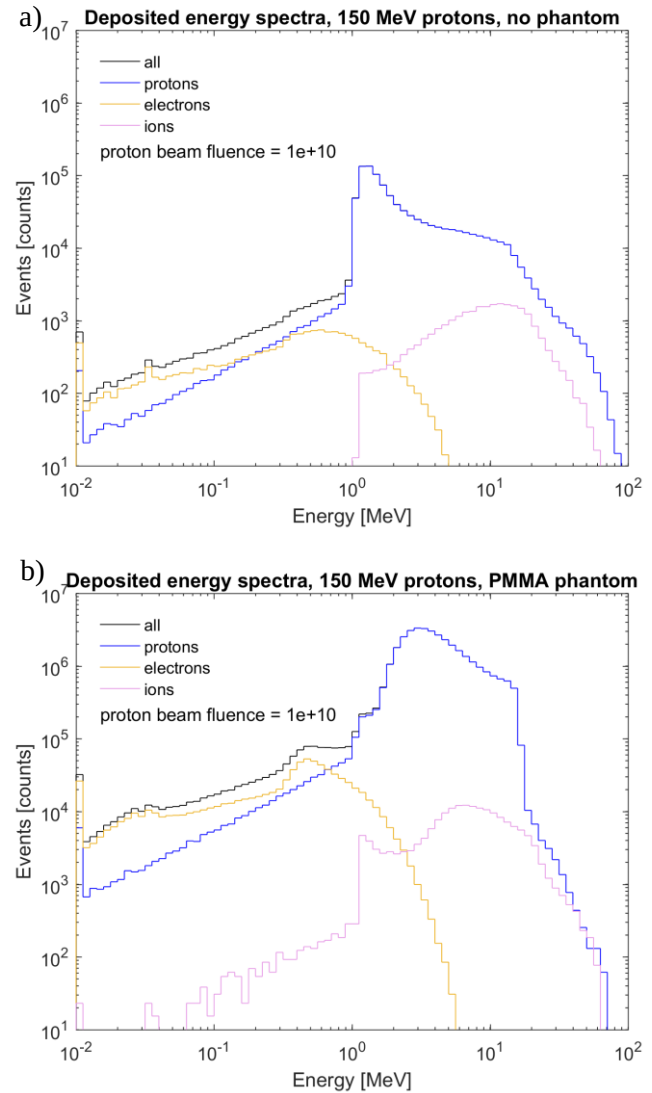


Fig. 9. Monte-Carlo calculation of deposited energy spectra for the particles given in Fig. 8 in the detector sensor (500 μm silicon) for the experiments performed with 150 MeV protons (a) without and (b) with the PMMA phantom. Results shown for all particles and selectively for protons, electrons and ions – listed in inset.

The MC simulations do not include the detector components including the detector electronics and the camera casing nor radiation interactions in them. Discrepancies consist in the underestimation of the LETP component and the reduced secondary electron production in the calculations observed for both setups. This may be due to limitations in the model of the radiotherapy hall used which also excluded the detector and nearby material such as the detector backing holder and setup supporting bench.

In the data without the phantom, the dominant part of the proton spectrum reproduces the narrow and asymmetric (right tail) distribution. However, this main proton part appears at a

higher energy (1–3 MeV) than in the experimental data (around 400–900 keV). This may be due to overestimation of scatter and energy loss in the simulations. The experimental data from the detector is calibrated and within the well-described proportional range [10,31] with limited effect of per-pixel spectral distortion and saturation for high deposited energy registration [22,41]. The calculated LETP component reproduces the broad spectrum with right side asymmetry. It is however partly shifted towards higher energies. The maximum appears at around 700 keV while in the experimental data the LETP spectrum maximum appears at around 200 keV. This could result from the exclusion of the photon component in the simulations mentioned above. The X-ray and gamma-ray spectrum registered by the detector, equipped with a 500 μm silicon sensor, corresponds to the low-energy region (in the range 3–50 keV).

In the setup with the phantom, the calculated HETP component, dominated by protons, reproduces the broad distribution and right-side asymmetry. It however exhibits also a shift to higher energies (2–15 MeV) compared to the experimental data (700 keV – 8 MeV). This can also be due to overestimation of particle scatter and proton energy loss in the calculations. The localized proton component (class B) in the experimental data at around 800 keV (Fig. 7b) is not reproduced. This and further quantitative interpretation of results are subject of future work. As in the data without the phantom, the calculated LETP component is also underestimated which can be due to similar reasons as addressed above. The low-energy part registered in the experimental data, centered at about 20 keV, corresponds to the X-ray component excluded in the calculations.

VIII. DISCUSSION

Timepix3 can produce valid and detailed radiation data in high resolution and wide range. To this end, it is necessary to register single particle tracks for which the particle count rate on the detector should not be too high. When operated in frame mode, this corresponds to keeping the maximum hit-pixel occupancy per frame below to a limited level (below 15 %, preferably below 10 %). The upper limit of event rate on the detector is 10^5 and 10^6 particles $\times \text{cm}^{-2} \times \text{s}^{-1}$ in terms of particle flux for HETP and LETP, respectively. This limit can be kept by suitable setting of the detector frame acquisition time.

The ability to detect and resolve broad particle-type classes on the same compact detector is provided with enhanced discrimination. This is possible by exploiting the spectral-sensitive and particle-tracking response of the detector together with verification by track visualization and quantum-imaging detection of single particles.

In the application chosen, secondary radiation fields in proton radiotherapy, the identification of radiation components is further aided and complemented by physics consideration of the beam-target-detector geometry. This served for the identification and assignment of event classes A and B primarily as neutron induced interactions.

Similarly, the experimental results and data products obtained are compared and valuably extended with MC simulations. Calculations of the composition and spectral

distribution of the radiation field can be analyzed and related with experimental data of energy loss. Moreover, the numerical simulations produce also detailed angular fluxes of the particles arriving to the detector position. Evaluation and comparison with experimental results will be subject of future work. The simulations will include a more complete and realistic model to account for discrepancies in the LETP component.

The methodology and obtained results validate and complement previous work with Timepix3 and Timepix detectors performed on highly complex environments at the ATLAS-LHC experiment [11] and space radiation in LEO orbit [49,50] as well as neutron fields in wide range of energies [30]. The improved methodology and the refined response matrix can be adjusted and applied for previous chip-sensor configurations to process existing Timepix data acquired in these complex radiation environments and provide extended and more precise physics results.

IX. CONCLUSIONS AND OUTLOOK

Timepix3 can be used to measure and analyze complex radiation fields to provide detailed information on composition, spectral (energy loss) and directional characterization. Data are produced in high resolution and wide range which are valuable for applications of radiation dosimetry and LET measurements. The spectral-tracking methodology has been developed for this detector-sensor configuration (Timepix3 with a silicon sensor 500 μm thick) together with derivation of the response matrix of particle-type classification. These tools combined were applied for analysis and characterization of the mixed-radiation fields of the experiments studied. Results include detailed distributions of deposited dose, dose rate, derived LET spectra and directional particle flux which will be presented elsewhere.

The MC simulations performed served to compare and verify the experimental results with a more complete interpretation of the experimental results. The results and combined information serve for research and detailed radiation measurements in a wide range of environments in radiotherapy, radiation testing, outer space and accelerator-based applications.

ACKNOWLEDGMENTS

We thank the work by the operators of the Krakow CCB cyclotron accelerator.

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