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Detection resolving power of SiC Timepix3 detector to electrons, neutrons, ions and protons

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ABSTRACT. Silicon Carbide is a suitable semiconductor sensor for radiation measurement and nuclear applications. It has been recently implemented as a position-sensitive and radiation imaging device coupled to the Timepix3 ASIC chip in the form of a miniaturized radiation camera MiniPIX-Timepix3 SiC. In this work we systematically evaluate the detection resolving power to different radiation species: electrons, fast neutrons, ions and protons. Experimental calibrations were made at well-defined reference fields in terms of particle type, energy and direction. The spectral-sensitive tracking response and characteristic morphology of the particle tracks are analyzed by pattern recognition algorithms. The low thickness of the radiation sensitive volume (65 μm) of the SiC sensor limits the directional tracking response and angular resolution. Three broad classes of particle-type events are resolved. The detector together with suitable data processing can be used for radiation dosimetry and particle tracking tasks in space, particle therapy, nuclear physics and nuclear reactors and particle accelerator environments.

KEYWORDS: dE/dx detectors; Particle tracking detectors (Solid-state detectors); Neutron detectors (cold, thermal, fast neutrons); Particle identification methods

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1 Introduction

Detection and spectrometry measurements of mixed-radiation fields of high fluence and harsh radiation environments present challenges of detection selectivity, detector temperature operation and response as well as radiation damage. Silicon Carbide (SiC) as semiconductor radiation detection exhibits advantages [1, 2] of high radiation hardness and higher temperature operation. Developed first as single pad diodes [3, 4], a pixelated SiC sensor has been recently fabricated [5] as a position-sensitive imaging device [6] and spectral-sensitive tracking detector [7] in the form of a miniaturized radiation camera MiniPIX-Timepix3 SiC [7]. Of particular interest is the detection of neutrons [8, 9].

In this work, we examine the systematic response of the MiniPIX-Timepix3 SiC detector to a wider collection of radiations: electrons, neutrons, ions and protons. We evaluate the detector spectral-sensitive particle tracking response and analyse the particle-type resolving power for event discrimination. We derive the wide-range classification into three broad-type event classes.

2 Instrumentation, measurements

2.1 Radiation camera MiniPIX-Timepix3 SiC

The SiC sensor bump-bonded to the Timepix ASIC chip is operated as a miniaturized radiation camera MiniPIX Timepix SiC [5] shown in figure 1. The detector operates at room temperature and is controlled and readout by single USB 2.0 connector with the PIXET software tool [10]. The SiC sensor operates under reversed bias (+200 V) providing a 65 μm thick radiation sensitive volume on the side of the pixelated bump contact matrix — illustrated in figure 1(a). The remaining upper volume of the SiC sensor does not register radiation and shields low energy charged particles — e.g., electrons and protons below 1 MeV. The detector was per-pixel calibrated with X rays of discrete-energy [11].

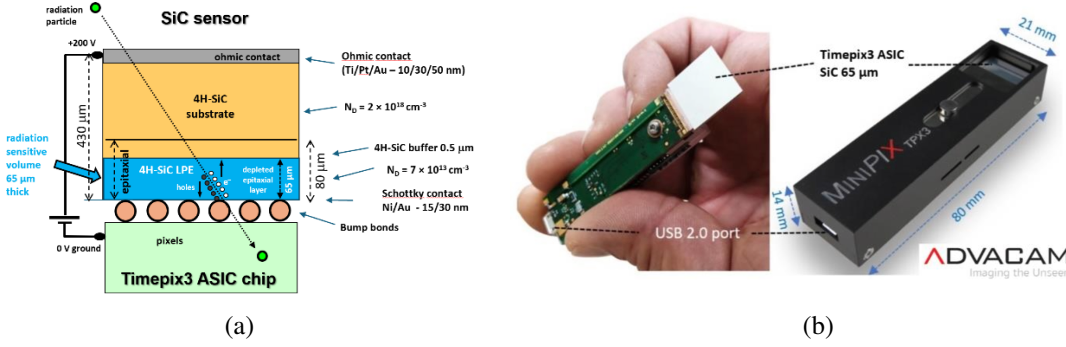


Figure 1. The Silicon Carbide Timepix3 detector: (a) illustration at the pixel level of the SiC sensor bump-bonded to the TPX3 ASIC chip. The radiation sensitive volume (65 μm thick) is highlighted — in blue. (b) The MiniPIX TPX3 SiC radiation camera operates at room temperature and in vacuum, connected to standard windows/Linux running PC/laptop via single USB 2.0 cable.

2.2 Measurements: electrons, neutrons, ions, protons

Testing and selected calibration measurements were performed at reference and well-defined radiation fields in terms of radiation type, selected particle/beam energy and direction to the detector-sensor plane [13].

- Fast mono-energetic electrons, in the range 3–22 MeV (at the Microtron accelerator, Nuclear Physics Institute NPI, Czech Acad. of Sciences CSA, Rez) — figure 2(a).
- Mono-energetic fast neutrons in selected energy regions in the range 0.5–18 MeV produced from D-D, D-T and p-T reactions (at the Van-de-Graaff light ion accelerator, IEAP CTU Prague) — see figure 2(b),(c),(d).
- Low-energy protons, in the range 8–31 MeV (at the light ion cyclotron, NPI Rez) — figure 2(e),(f). See also ref. [7].
- Energetic protons and light ions (^{12}C) < 300 MeV/u (at MedAustron, Wiener Neustadt) — figure 3(a),(b) and figure 3(d),(e).
- Energetic light and heavy ions > 500 MeV/u (at the NSRL radiation facility, Brookhaven Nat. Lab.) — figure 3(c),(f).

For charged particles, low energy is used in this work when the particle trajectory and range in the sensor material (SiC) are comparable or smaller to the detector pixel size (55 μm) [13]. Energetic or high-energy particles are when the particle trajectory and range are greater than the pixel size. In the later case, the particle track in the detector sensor involves many pixels for which high-resolution single particle tracking can be performed [12].

The visualization of the measured radiation fields and spectral-imaging information of the single particle tracks are valuable for comparison and evaluation of the detector characteristic response. This can be done even by visual inspection — see figures 2 and 3, and in high resolution by detailed track pattern morphology and spectral-tracking analysis — see section 3.

The directional response is full field-of-view i.e., 2π . The incident direction of the particle beam/radiation source relative to the detector-sensor plane, called elevation pitch angle [12], can range from perpendicular direction (0°) to parallel (90°) — see also illustration in figure 4(a).

The radiation detected, the particle-type resolving power of the detector and the field decomposition analysis are addressed and presented below — section 3.

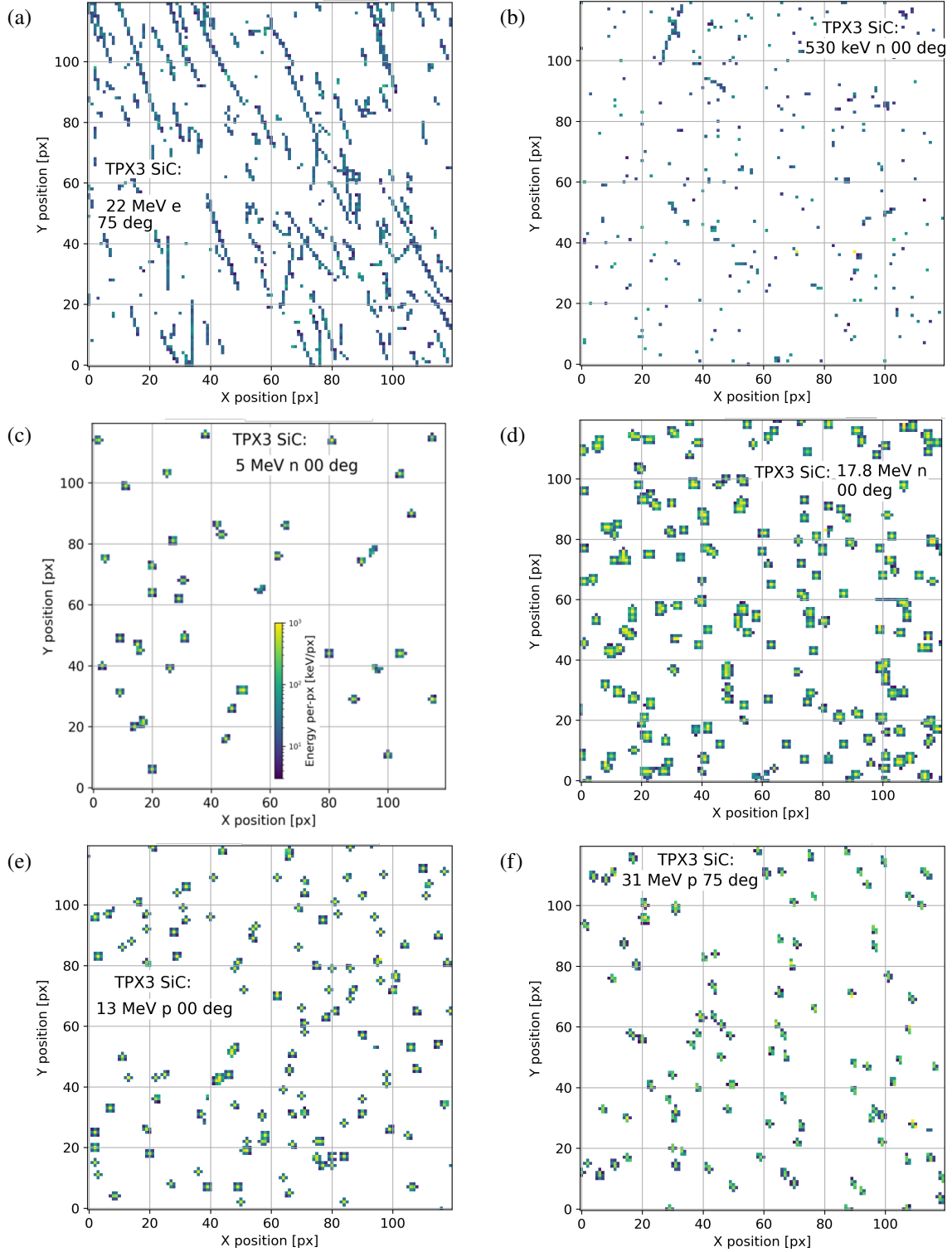


Figure 2. Detection and track visualization by Timepix3 SiC, 65 μm thick sensitive sensor volume: (a) 22 MeV electrons at 85°; perpendicular (0°) fast neutrons of energy: (b) 530 keV, (c) 5.0 MeV and (d) 17.8 MeV; (e) 13 MeV protons perpendicular (0°) and (f) 31 MeV protons at 75°. All detected particles are shown (no event filters applied). Only a part (22%) of the detector pixel matrix is displayed ($120\text{ px} \times 120\text{ px} = 6.6\text{ mm} \times 6.6\text{ mm} = 0.44\text{ cm}^2$). The per-pixel registered energy is shown by the color scale.

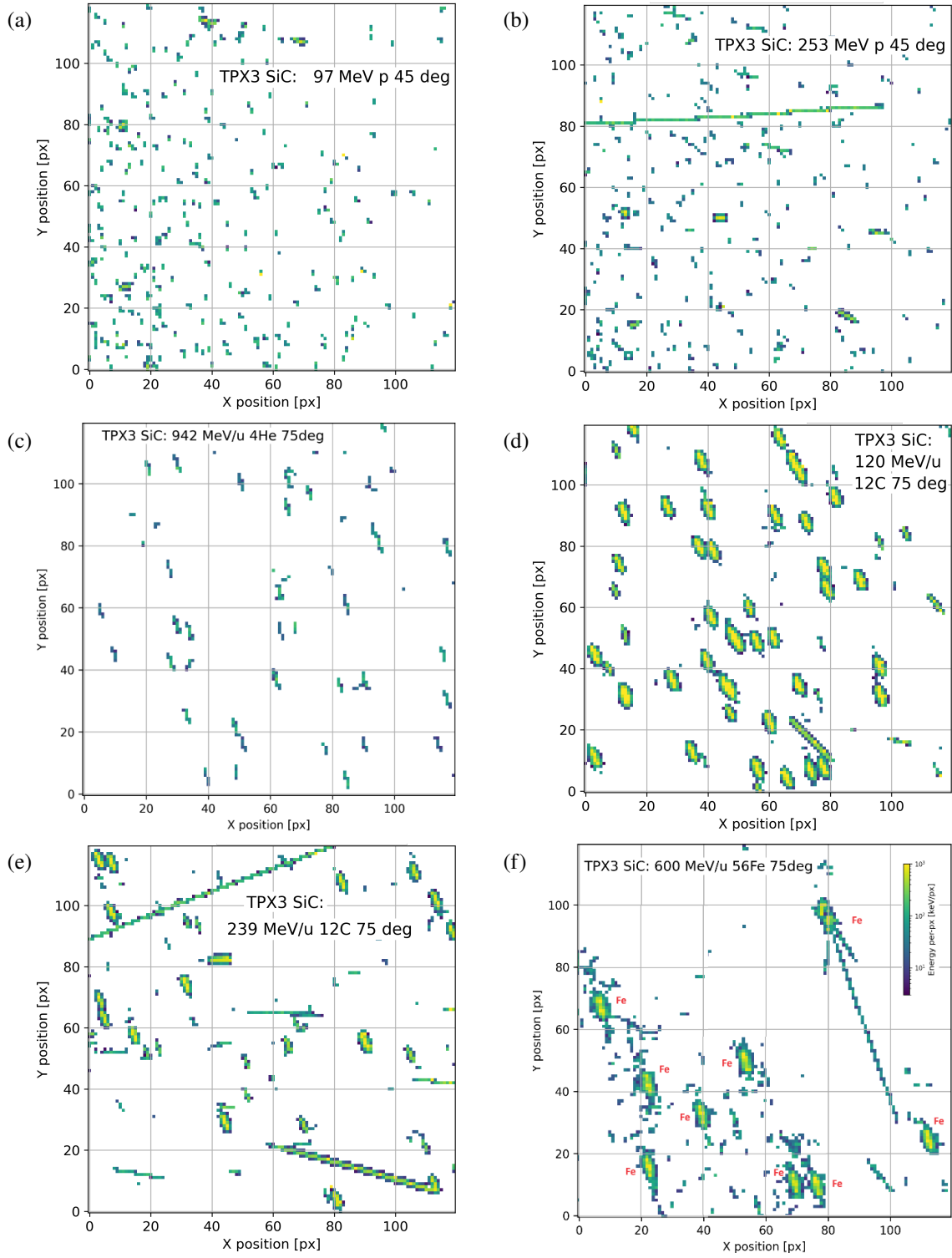


Figure 3. Same as figure 2 for: (a) 97 MeV and (b) 253 MeV protons at 45°; (c) 942 MeV/u 4He ions at 75°; (d) 120 MeV/u 12C ions at 75°; (e) 239 MeV/u ^{12}C ions at 75°; and (f) 600 MeV/u ^{56}Fe ions at 75°.

3 Results, techniques

3.1 Quantum-imaging detection, spectral-sensitive particle tracking

The noiseless detection and per-pixel signal electronics of Timepix3, enable to register single particle tracks with high sensitivity in wide field-of-view (FoV), essentially full 2π , and per-pixel spectral response in wide range. The registered particle tracks exhibit pattern morphology and spectral-tracking characteristics determined by radiation-detection degrees of freedom [13]: (i) particle/radiation species, (ii) energy loss/deposited energy, and (iii) direction to the detector sensor plane.

High-sensitivity single particle registration (figure 4), track visualization and spectral response (deposited energy, particle energy loss) together with pattern recognition algorithms and the performed radiation-response calibrations, provide resolving power for broad discrimination of event types [13].

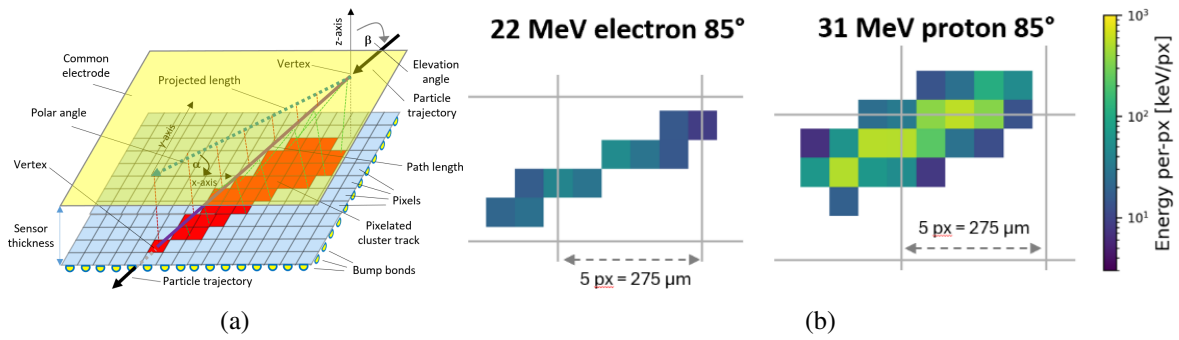


Figure 4. (a) Illustration of detection and particle tracking of energetic (i.e., penetrating) charged particles. (b) Spectral-sensitive registration (energy loss) of an electron and proton incident at large direction -85° . The deposited energy by the particle in the sensor is registered and analyzed.

Registered events can be also analyzed and classified in terms of origin of the particle beam/radiation source as primary particles and secondary events. The later are understood background and unwanted events such as scattered primary particles, multiple pile-up events and partly collected tracks e.g., at the pixel matrix borders.

The relatively small thickness of the sensor radiation sensitive volume (65 μm) reduces the tracking sensitivity and the angular resolution for directional measurements of charged particles [12]. The full (2π) FoV can be mapped with reduced angular binning i.e., fewer broader bins. Along the elevation angle β : $0^\circ-30^\circ$, $30^\circ-45^\circ$, $45^\circ-60^\circ$, $60^\circ-75^\circ$, $75^\circ-80^\circ$, $80^\circ-85^\circ$, $85^\circ-88^\circ$, $88^\circ-90^\circ$. Along the azimuth direction α (over the detector sensor plane) in bins approximately of 30° along the pixel matrix rows or columns and 10° in between.

3.2 Particle-event type classification

The developed SiC Timepix3 detectors exhibit spatial homogeneity [7] and good energy resolution (at the level 5–10% FWHM). This makes it possible to be used for detailed spectral and particle tracking measurements [7] and radiation imaging applications [6]. In this work, we analyzed the detector resolving power for particle-type discrimination intended for composition characterization of mixed-radiation fields. We elaborated the detector response matrix and resulting particle-type classification — summarized in the table 1. The basic and robust classification is provided.

Charged particles, both light and heavy charged particles, of low energy (i.e., below few MeV) as well as X rays are partly shielded by the non-sensitive sensor volume. They are registered provided their trajectory reach the sensor radiation sensitive volume, which is beneath, on the inner side facing the chip contact bump bonds. Proton and ion tracks are resolved mainly by their high-energy transfer interaction. Electrons on the other hand are low-energy interacting particles and moreover undergo multi-scattering [16] resulting in elongated curly tracks of low per-pixel amplitude (energy loss).

Photons, consisting namely of X rays and low-energy (< 100 keV) gamma rays, are partly detected in the sensor radiation sensitive volume. Their detection efficiency is limited by the sensor low density material and small thickness.

Table 1. Particle-event classification for Timepix3 SiC detector with a $65\ \mu\text{m}$ thick sensitive sensor volume. Assignments are determined by the nature of interaction and spectral-tracking characteristics of the pixelated tracks registered. The corresponding radiations, expressed in terms of particle type, energy and direction of incidence to the detector sensor plane, are listed. See labels in the footnote.

<i>Class</i>	<i>Morphology</i>	<i>Interaction</i>	<i>Radiations</i>	<i>Energy (direction)</i>
A	Any morphology large tracks (≥ 4 px)	HETP	protons ions neutrons*	> 5 MeV (OD) > 20 MeV/u (OD) $> \text{few MeV}$ (OD)
B	Elongated large tracks (≥ 4 px)	LETP	electrons protons high-energy/MIPs gamma rays low-energy [#]	> 1 MeV () > 70 MeV/u (NPP) < 100 keV (OD)
C	Round small tracks (≤ 3 px)		X rays ^{&} electrons PP protons PP high-energy neutrons*	< 100 keV (OD) > 1 MeV (PP) > 70 MeV (PP) ≈ 10 's– 100 's keV (OD)

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

[#] = limited DE $\leq 1\%$, limited energy range < 100 keV

[&] = limited DE, partly shielded by the sensor non-sensitive volume

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

PP = perpendicular, NPP = non-perpendicular, px = pixel ($55\ \mu\text{m}$), MIP = minimum ionizing particle

Fast neutrons are registered with limited detection efficiency ($< 1\%$) via direct interactions in the sensor semiconductor material [15]. Energetic ($> \text{few MeV}$) fast neutrons produce high-energy transfer particle (HETP) interactions — see figure 2(c),(d). Lower energy neutrons (≈ 10 's– 100 's keV) produce low-energy transfer particle (LETP) interactions — see figure 2(b).

One broad group of resolved events (class A) consists of all high-energy transfer particles (HETP). These are produced by heavy charged particles namely protons and ions as well as fast neutron ($> \text{few MeV}$) direct interactions in the semiconductor sensor. For simplicity all track morphologies are considered — understood namely in terms of the track shape from round to elongated tracks.

The remaining particles consist of low-energy transfer particles (LETP) which are resolved into two classes: large elongated tracks (class B) and small round tracks (class C). The corresponding radiations and approximate range of energy and direction are given in table 1.

3.3 Resolving power, detector-sensor-radiation response matrices, AI/ML analysis

In the measured data (figures 2, 3) it can be seen the main dominant component produced by the specific primary radiation. Other events are also registered and resolved such as scattered primary particles — see the directionally random tracks in figure 2(a) (produced by scattered primary beam electrons, see also figure 4(b)), the large thin straight track (from left to right) in figure 3(b) (produced by an energetic primary proton scattered at large angle) and several ion tracks of visible distinct orientation in figure 3(d). Further events are detected and resolved produced by background and secondary particles such as the small few-pixel tracks in figure 2(a) and figure 3(d),(f) (produced by X rays and low-energy (< 300 keV) background electrons [16]) and the long thin tracks in figure 3(e),(f) (most of them are secondary scattered protons) and the broader large track at bottom right in figure 3(e) (produced by an energetic light ion [17] scattered at large direction).

The detector-radiation response matrices (section 3.2 and table 1) are based on the experimental in-beam calibrations performed on well-defined radiation fields [7] including those presented in this work (section 2.2). The analysis and resulting detector-sensor-radiation model include AI/ML techniques. For the SiC Timepix3 detectors, which are relatively newly developed, it can be partly used the extensive response matrices and look-up table for the Si Timepix3 detectors which similarly are based on extensive experimental calibrations [14, 18] including AI/ML techniques [13, 14]. Thanks to the very similar sensor material (namely density) between the SiC and Si sensors, the physics and radiation interactions by the main radiation species (charged particles — both heavy and light, X rays, gamma rays) are for the most part highly similar. The effect by the different sensor thickness can be taken into account and corrected/normalized.

The response matrix and particle-type classes for the SiC Timepix3 detector are simpler and fewer ($3\times$ classes — see table 1) than those for the Si Timepix3 detectors [13, 14]. This is due to the smaller sensor thickness of the SiC detectors which reduces the spectral-tracking sensitivity and particle-type resolving power [13–17].

In complex and mixed-field environments, most events, overall 9 of 10, can be unambiguously resolved and identified. For these, the confidence levels of particle-type classification for all detector-sensor-chip configurations, i.e., Si Timepix3 and SiC Timepix3, is high ($\geq 95\%$) [14]. For a remaining $\approx 10\%$ of events, there can be overlaps i.e., duplicity in the assignments such as the small-round tracks of low amplitude produced by energetic (> 100 MeV) protons perpendicular to the detector-sensor plane [19] which partly overlap with medium energy neutrons (figure 2(b)) and low-energy (< 300 keV) electrons [16].

3.4 Deposited energy and LET spectra

Detailed spectrometry (deposited energy) of the registered tracks can be performed in wide range — of particle types, energy loss and direction [7]. Deposited energy distributions can be provided for all particles and newly for the resolved particle-type classes. The particle LET in the detector sensor material (SiC) in units ($\text{keV}/\mu\text{m}$) is obtained from the measured particle deposited energy and track length [17]. Results, distributions and spectra are similar to those obtained with Si sensor Timepix detectors [17].

4 Conclusions

We examined the detection response of the SiC Timepix3 detector for different particles in wide-range of radiation species, energy and direction. In particular, we analyzed and describe the detection resolving power for particle-type discrimination. The derived three broad classes of particle-types based on corresponding assignments to groups of radiations of given energy and direction. The detector together with the developed methodology, based on experimental calibrations, enable the use of SiC as a particle tracking and imaging detector. This can be applied for composition characterization of mixed-radiation fields including neutrons. Intended applications include complex and harsh radiation environments found in outer space and those produced at particle accelerators, nuclear reactors, radiotherapy facilities, radionuclide-source environments including neutrons. Future developments include thinning of the sensor non-sensitive volume, to reduce the shielding effect especially for low-energy charged particles, and extending the sensitive volume, to improve the tracking sensitivity.

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