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MiniPIX Timepix3 — a miniaturized radiation camera with onboard data processing for online characterization of wide-intensity mixed-radiation fields

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ABSTRACT: The miniaturized radiation camera MiniPIX TPX3 is designed for detailed and wide-range measurements of mixed-radiation fields present in many applications such as radiotherapy and space radiation in outer orbit. The highly integrated instrumentation utilizes a single connector for control and readout for flexible measurements and quick deployment. The device features an option to process the registered data on the same device with limited resolution and basic particle-type resolving power. A novel readout and data processing technique exploits the detector high granularity and double per-pixel signal electronics to measure and characterize radiation fields of high intensity over a wide range with basic particle-type discrimination.

KEYWORDS: dE/dx detectors; Heavy-ion detectors; Particle tracking detectors; Particle tracking detectors (Solid-state detectors)

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1 Motivation, goals

Applications such as space radiation research, radiotherapy, both environmental and radiation monitoring require flexible and simplified deployment of compact instrumentation of low mass, small size and low power. A suitable device ideally would provide particle-type resolving power and wide-range response in terms of particle flux and deposited energy. The radiation fields in these environments vary by many orders of magnitude in flux and deposited energy. In addition, the possibility to process the data online avoids extensive and time-consuming offline work and enables providing prompt evaluation of data and physics products during the measurement. This option, even with limited resolution, is valuable for several reasons, such as the verification of experimental settings and for quick evaluation of radiation field. Moreover, performing this task directly on the same device, simplifies further the deployment and expands the range and scope of uses. Such onboard data processing capability removes the need of an external data processing computer and also the presence and availability of an experienced operator/engineer. A tradeoff is however necessary between data processing resolution, data product resolving power, device performance, processing speed, power consumption and detector operation duty cycle.

2 Miniaturized radiation camera MiniPIX TPX3

The MiniPIX TPX3 is an integrated, miniaturized, low-power radiation camera (see figure 1) equipped with the hybrid semiconductor pixel detector Timepix3 (TPX3). The TPX3 ASIC chip [1] provides a high granularity active pixel matrix ($256 \times 256 = 65\text{k}$ pixels of pitch size $55\text{ }\mu\text{m}$) bump-bonded to a radiation sensitive semiconductor sensor of different material (Si, CdTe, GaAs)

and thickness (e.g., 100, 300, 500, 1000 μm Si or 1000, 2000 μm CdTe). The chip-sensor assembly provides quantum imaging sensitivity for high-resolution spectral tracking of individual particles in mixed-radiation fields.

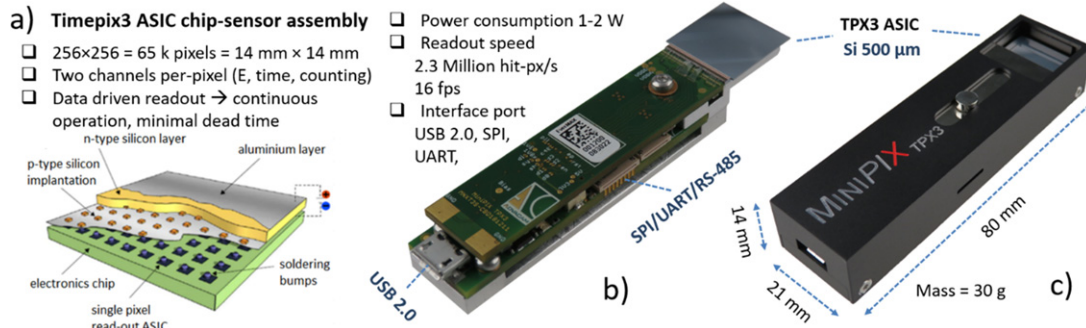


Figure 1. The MiniPIX TPX3 radiation camera: illustration (a) of the hybrid semiconductor pixel detector Timepix3 consisting of a semiconductor radiation-sensitive sensor — e.g., 300 μm silicon of full size 14.08 mm × 14.08 mm = 1.98 cm² — shown in yellow, bump-bonded to the TPX3 ASIC readout chip (shown in green). The detector provides a high granularity array of 256 × 256 pixels (total 65536 independent channels). The assembled detector consists of a chipboard with the TPX3-sensor assembly and the readout board equipped with several readout connectors. The miniaturized radiation camera MiniPIX TPX3 (b) has mass 30 g, power consumption <2 W, dimensions 80 mm × 21 mm × 14 mm and connects directly to a PC/laptop via standard USB port.

2.1 USB configuration, high data rate, high-level control and readout

Standard configuration makes use of the USB 2.0 readout port which provides ease of use and flexible connectivity with high data rate capability. Control, operation and readout are provided by an external PC or laptop computer. The software PIXET tool [3] provides integrated high-level control, data acquisition and online visualization of the radiation field. The maximum data rate is 2.3 M hit pixels per second. This sets, in the detector continuous data driven readout mode, the upper data rate of pixels registering particles (called hit pixels). In frame mode the upper data rate is up to 16 fps. The resulting event rate is lower as the particle track clusters generally occupy more than one pixel depending on the particle type (field composition), radiation field intensity and incident particle direction to the sensor plane. Raw data are readout and stored on an external PC/laptop where pre-processing can also be performed online by extended plug-in tools within the PIXET package. Configuration and operation are pre-set by firmware (FW) programming and upload.

2.2 Space configuration, SPI/UART port, low-level control and readout

The space configuration of the device makes use of the SPI/UART interface port connector. It is intended for low-level control and operation of the device such as onboard computers (OBC) on board satellites. The overall data rate speed is lower than that provided by the USB 2.0 standard. This onboard data processing option is performed at the embedded FPGA and microcontroller and

is enabled by FW re-configuration. A customized low-power configuration is intended for satellite deployment in low (LEO) and geostationary (GEO) Earth orbits [4].

2.3 Per-pixel operation and readout modes

While the first generation Timepix ASIC chip [2] provides one signal chain per pixel, Timepix3 [1] provides two signal channels per pixel. The pixels can be set to operate in two of four supported modes: deposited energy (ToT), time of interaction (ToA), counting (C), and off (masked pixel). Besides the frame-based readout mode, Timepix3 also newly supports the event-based data driven mode which provides continuous operation and minimal readout deadtime. Various combinations of per-pixel level operation and readout modes can be exploited for precise measurements of different particles, including mixed-radiation fields. The response of the detector [5] can be thus extended over a wide dynamic range in terms of particle-detection variables (or degrees of freedom [6]):

- (i) Particle type: light- and heavy-charged particles such as electrons, muons, protons, ions as well as X rays and gamma rays (in limited energy range) and neutrons (using neutron converter mask)
- (ii) Deposited energy
- (iii) Direction
- (iv) Flux.

3 Low-intensity fields: spectral-tracking imaging detection of single particles

Radiation fields of limited intensity can be registered in detailed event-by-event mode. In this mode the individual signals by single particles in the form of pixelated clusters are separately and fully recorded. One example is the precise spectral-tracking mode shown in figure 2. Details and further examples can be found in e.g., refs. [5–7]. The energy-sensitive tracks of single particles across the pixelated sensor are visualized and registered at the pixel-level scale. The per-pixel energy response is displayed in color. Data from different particles produced at different well-defined sources were used (see figure caption).

Depending on the particle event rate on the detector, single particles can be registered separately (i.e., as isolated tracks) or as integrated pile-up events where two or more tracks merge by partly or even fully overlapping (examples shown in figure 2). Accurate and complete information is obtained when single particles are registered as isolated single cluster tracks. Such signals carry characteristic spectral- and tracking-morphology [5]. The resolving power sensitivity and dynamic range are determined by the radiation field detection variables [6] listed in section 2.3. Pattern recognition analysis together with physics-based model descriptions and suitable calibrations in well-defined radiation fields over a wide range [6] enable resolution of several particle-type groups [5] where up to 8 classes are distinguished.

The detection and analysis of particles as single isolated tracks provide extensive and complete spectral and tracking information [8, 9]. Results and data products can be derived at the detailed event-by-event level according to the radiation field detection degrees of freedom [5, 6] such as

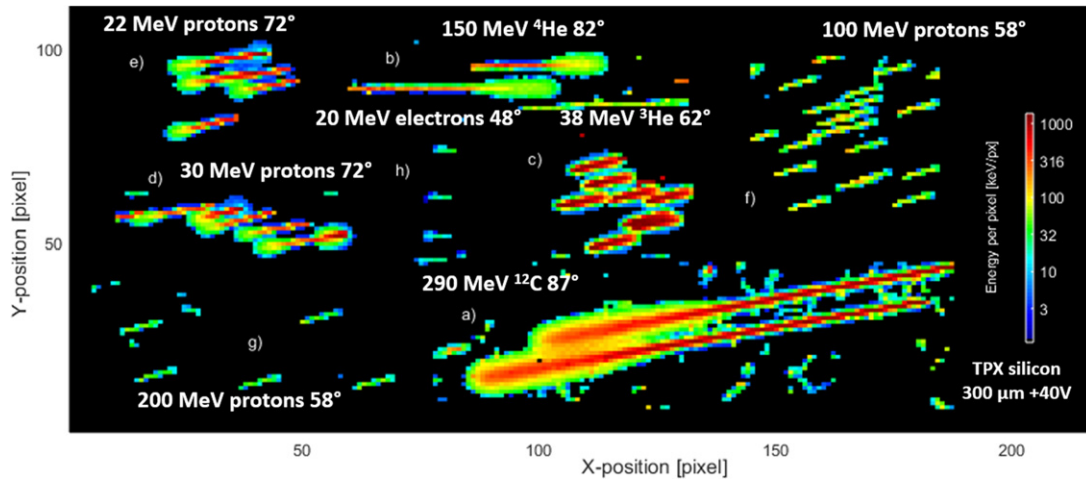


Figure 2. Detection and track visualization of energetic charged particles by a MiniPix Timepix 300 μm Si detector: (a) 290 MeV/u ^{12}C ions at 87° , (b) 150 MeV/u ^4He ions at 82° , (c) 38 MeV ^3He ions at 62° , (d) 31 MeV protons at 72° , (e) 22 MeV protons at 72° , (f) 100 MeV protons at 58° , (g) 200 MeV protons at 58° , (h) 20 MeV electrons at 48° . Data taken at the Microtron (h) and Cyclotron (c)–(e) accelerators at the NPI-CAS Rez-Prague, Cyclotron IFJ-PAN Krakow (f) and (g) and ion synchrotron at HIMAC Chiba (a) and (b). The per-pixel energy response is shown by the color bar (in keV/pixel, log scale). About one third of the sensor matrix is shown (110×215 pixels = $6 \text{ mm} \times 12 \text{ mm}$, pixel pitch size $55 \mu\text{m}$).

(i) particle-event type, (ii) deposited energy (energy loss), (iii) direction (pitch angle to the sensor plane), (iv) deposited dose, (v) linear energy transfer (LET). Deposited energy and high-resolution LET values are derived namely for energetic charged particles, i.e., particle with range and track length greater than the detector pixel size. This high-resolution approach can be exploited and operated for radiation fields of limited flux. The limit varies according to the particle-event type.

For the Timepix3 detector operated with the miniaturized and low-power MiniPIX TPX3 readout electronics, the overall particle flux upper levels [particles/cm²/s] are: X rays = 1×10^6 , electrons including light charged particles (LCPs) and minimum ionizing particles (MIPs), gamma rays = 3×10^5 , protons = 1×10^5 , ions and other heavy charged particles (HCPs) = 1×10^4 . The values given are overall in wide range of particle incident direction. The measuring time of 1 sec for the values above, can be reduced by e.g., safely one order of magnitude, which can thus increase the particle flux upper level correspondingly by a factor of 10.

4 High-intensity fields: wide-range spectrometry, integrated fields

The detector response and detection sensitivity of different radiation fields in varying wide-range intensity are shown in figure 3. Data are displayed in integrated mode shown in per-pixel deposited energy, summed per-pixel event count mode, and per-pixel mean energy.

Data shown in the figure correspond to electrons, protons and light ions (^3He) registered at high-, low-, and medium-intensity, respectively. The particle flux levels displayed are at level

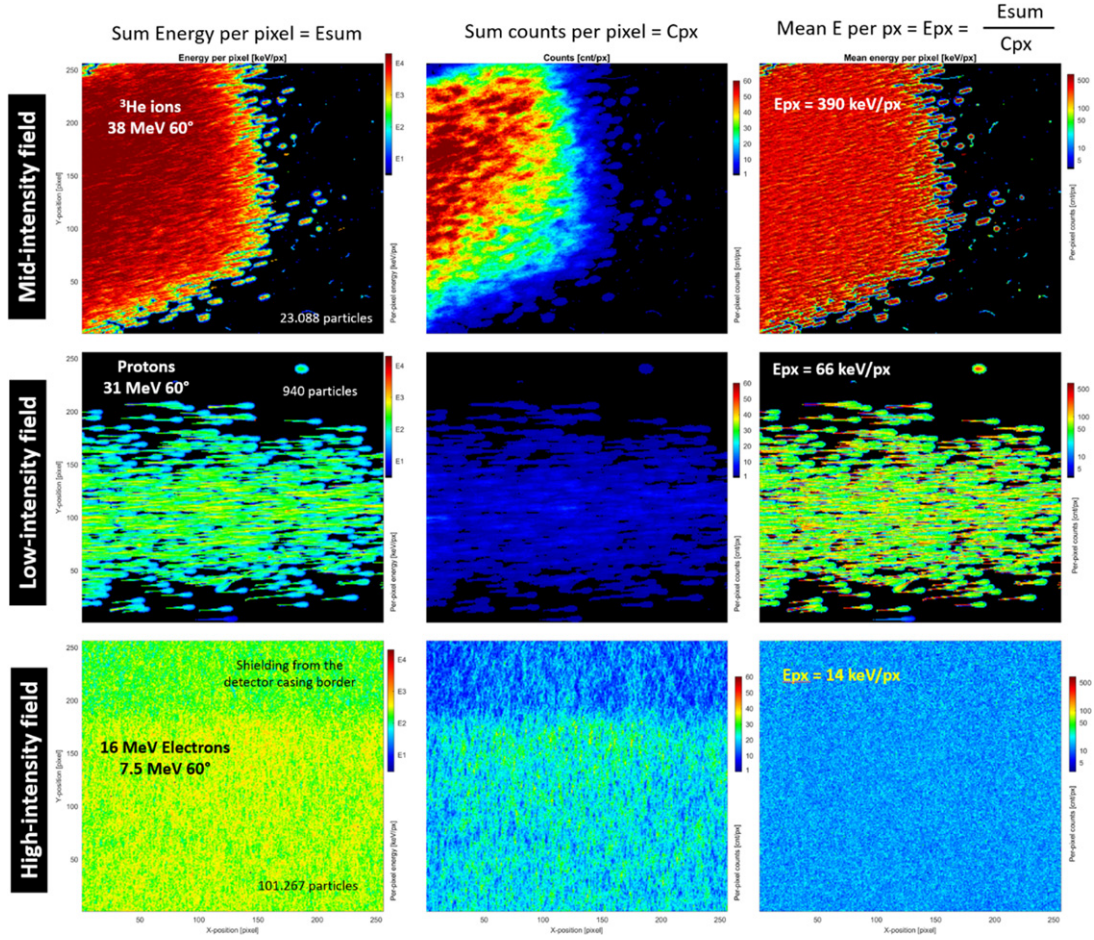


Figure 3. Detection and radiation field visualization of electrons (bottom row), protons (mid row) and ^3He ions (top row) of varying intensity and selected energy and direction (see inset labels in the plots on left column). The recorded data are shown integrated in per-pixel deposited energy mode (left column) and per-pixel event count mode (mid column). The derived quantity mean energy per-pixel is included (right column). Plots for the entire detector sensor area ($14.08 \text{ mm} \times 14.08 \text{ mm} = 1.98 \text{ cm}^2$) are shown.

10^7 , 10^4 and 10^5 [particles/ cm^2/s], respectively. Data are shown integrated where the registered particles are summed and displayed as a single frame. In this regime, the particles are no longer processed as individual isolated tracks, but as integrated pile-up events as shown in figure 3.

The radiation fields used had different beam size: around 10 mm and 8 mm focal spot size for the ^3He ions and protons, respectively. The electron field was de-focused with beam size greater than the detector size (i.e., $>14 \text{ mm}$). The broad distinct pattern on the top region of the electron data (summed energy per-pixel and summer per-pixel event count) is due to the partial shielding by the detector casing border (2 mm Al thick) — see figure 1(c).

4.1 Mean per-pixel energy

Setting the per-pixel operation and readout configuration to energy and count mode, Timepix3 measures simultaneously the deposited energy and event rate as shown in figure 3 (see left and mid columns). This technique is valuable in measurements of radiation fields of high intensity i.e., when the individual particle tracks of single particles can no longer be registered as an isolated distinct track. The ratio of these two quantities gives the mean energy per-pixel as shown in figure 3 (right column). The range and histogram distribution of this quantity for the data used in figure 3 are shown in figure 4.

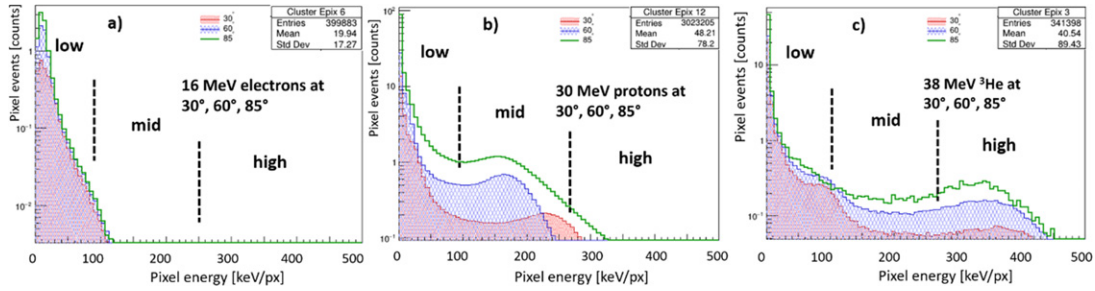


Figure 4. Mean per-pixel energy spectra for electrons (left), protons (mid) and ^3He ions (right) data used in figure 3. The per-pixel range is shown on the X axis, the pixel-level events are shown on the Y axis. Additional directions are included (see color and labels in the plots). See text.

In the per-pixel energy spectra shown, three broad regions of characteristic response are identified: low (below 100 keV/px), mid (between 100 and 250 keV/px) and high (above 250 keV/px). The region borders shown in the plots correspond to preliminary values based on analysis of the selected (and limited) radiation energy and types and can be refined by addition of more reference and calibration data and further analysis (see below).

The evaluation of various high-intensity data including light- and heavy-charged particles as well as X ray and gamma ray data, are given in figure 5. Data from well-defined calibrating fields is compared with mixed-field data collected in space at LEO orbit.

Besides the experimental data, well-defined and mixed-field, also Monte-Carlo simulation data are used. Numerical simulation data, shown in blue and green squares, correspond to pure (i.e., 100%) electron and pure proton fields, respectively over a wide energy range from few MeV to few tens of MeV of omnidirectional directional distribution. The mixed-field LEO orbit space radiation data [10, 11] (shown in turquoise diamonds) correspond to one full day (around 14 full orbits, in total about 3k data frames) registering wide gradients in intensity [11]. Charged particle data are given for protons of low-energy (i.e., near the Bragg peak) and high-energy (approaching the MIP range) given in dark blue and red color, respectively, electrons (green) and light ions/ ^3He ions (purple) each at several groups of selected energies and incident directions (see inset in figure 6). Data used cover a wide range in terms of field composition and intensity which are displayed on the Y axis and X axis, respectively. In this integrated pile-up mode suitable for high-intensity fields the particle-type resolving power discriminates three broad particle-type classes:

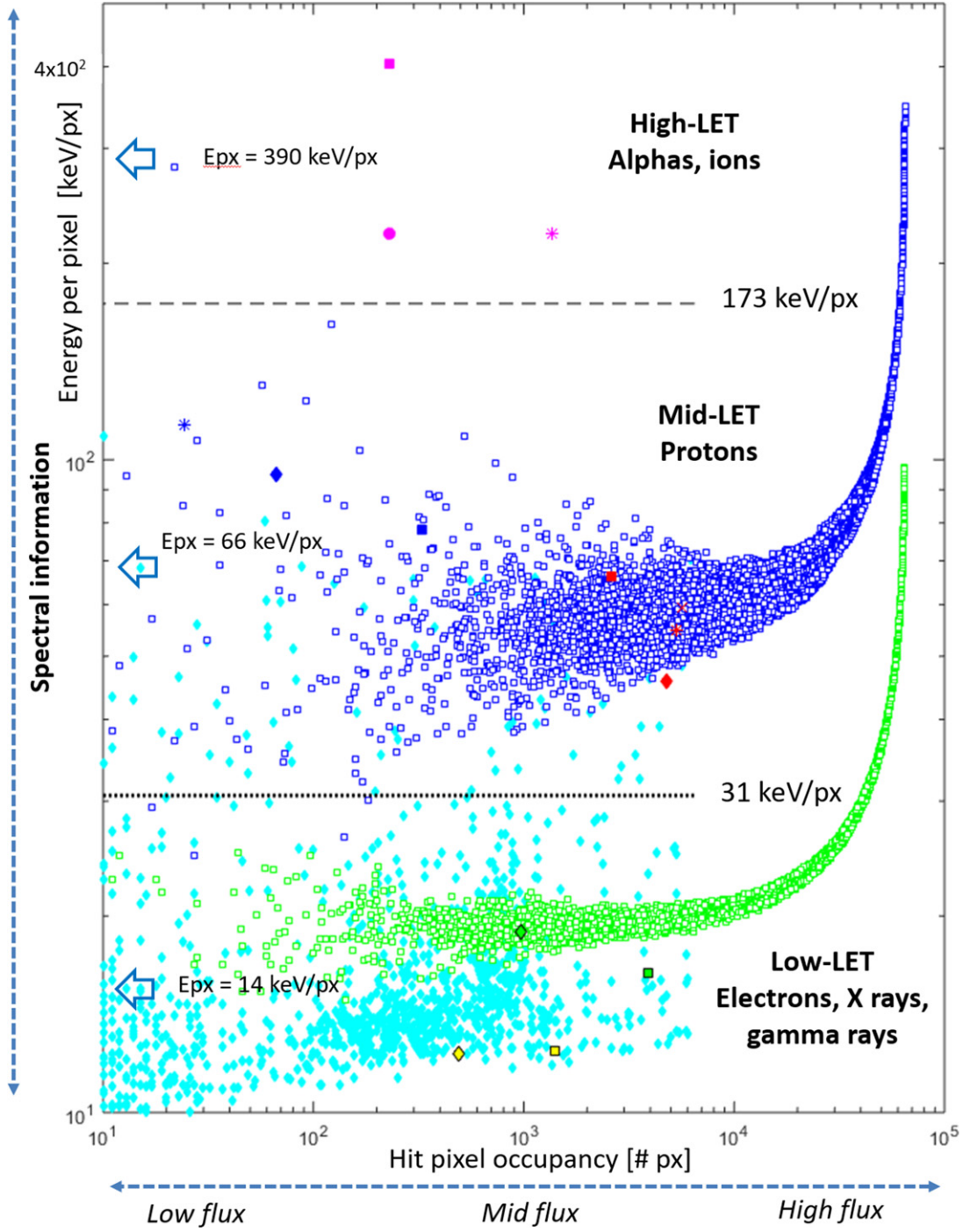


Figure 5. Per-pixel mean energy (Y axis) for various experimental and Monte-Carlo simulation data. Data shown for a Timepix 300 μm silicon detector and consist of well-defined calibrating (particle accelerator beams, X ray, gamma rays) as well as mixed-field (space radiation in LEO orbit, SATRAM-TPX payload [10, 11] onboard ESA’s Proba-V satellite) — see labels in inset in figure 6, see also text. The hit-pixel occupancy (X axis) is proportional to the radiation field intensity in broad range.

(i) low-LET particles (electrons, X rays, gamma rays), (ii) mid-LET particles (protons), and (iii) high-LET particles (light and heavy ions). Mean values and border regions of characteristic mean per-pixel energy according these broad particle types are derived — see arrows and labels and the dash horizontal lines in figure 5. The values derived of per-pixel mean energy correspond to the data sets used in figure 3.

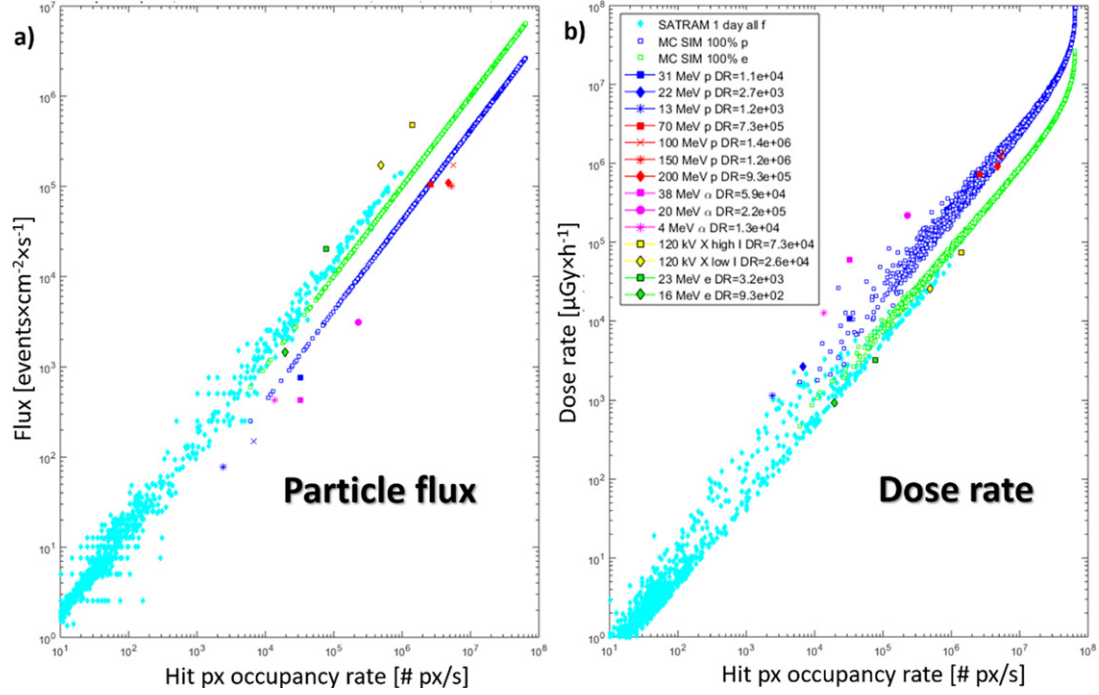


Figure 6. Particle flux (left) and dose rate in silicon (right) derived for a wide collection of data. Data sets include Monte-Carlo simulations and experimental calibrations from well-defined fields as well as mixed-field space radiation data measured in LEO orbit — see labels and colors given in list in inset. See text.

4.2 Particle fluxes, dose rates in wide range

Using the integrated per-pixel summed energy and summed event count mode, the resulting particle fluxes and particle dose rates in silicon can be derived as shown in figure 6. The radiation field intensity is proportional to the hit pixel occupancy quantity (displayed on the X axis). The resulting particle flux (left) and dose rates (right) are derived in wide range over many orders of magnitude up to 10⁷ particles/cm²/s and 10⁸ μGy/h, respectively.

5 Conclusions

The miniaturized low-power radiation camera MiniPIX TPX3 provides a flexible platform for detailed and wide-range measurements of different radiation fields, including mixed-fields and space radiation in LEO orbit. The device can be configured for operation in low- and mid-intensity fields, where single particles can be registered separately and analyzed in high-resolution, or high intensity fields, where particles are registered in integrated pile-up mode. In the later mode, and

the detector per-pixel configuration set to energy- and counting-mode, the derived results and data products are provided with limited resolving power (three broad particle-type classes are resolved). This is made possible by exploiting the detector high-granularity and per-pixel double-signal channels. The newly introduced quantities per-pixel mean energy and hit-pixel occupancy yields information on the radiation field composition and intensity. The technique was evaluated and compared with broad range of well-defined experimental and Monte-Carlo data as well as mixed-field space radiation data measured in LEO orbit. The operation of the detector can be extended and re-configured to provide onboard data processing of limited resolving power in wide range including high intensity fields.

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