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PIXIE III: a very large area photon-counting CMOS pixel ASIC for sharp X-ray spectral imaging

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ABSTRACT: PIXIE III is the third generation of very large area ($32 \times 25 \text{ mm}^2$) pixel ASICs developed by Pixirad Imaging Counters s.r.l. to be used in combination with suitable X-ray sensor materials (Silicon, CdTe, GaAs) in hybrid assemblies using flip-chip bonding. A Pixirad unit module based on PIXIE III shows several advances compared to what has been available up to now. It has a very broad energy range (from 2 to 100 keV before full pulse saturation), high speed (100 ns peaking time), high frame rate (larger than 500 fps), dead-time-free operation, good energy resolution (around 2 keV at 20 keV), high photo-peak fraction and sharp spectral separation between the *color* images. In this paper the results obtained with PIXIE III both in a test bench set-up as well in X-ray imaging applications are discussed.

KEYWORDS: Solid state detectors; X-ray detectors; Pixelated detectors and associated VLSI electronics; X-ray radiography and digital radiography (DR)

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1 Introduction

Spectroscopic imaging is the new frontier in X-ray and γ -ray imaging applications. Indeed, spectral information adds a new, powerful dimension to the image. High speed photon-counting with pixel detectors is the natural technology choice to try to implement this new modality. However, adding sharp *color* sensitivity to a very finely segmented pixel sensor is highly demanding in terms of complexity and transistor density of its read-out electronics which has to cope with the charge sharing effect. The sharing is due to the finite size of the charge cloud and the unavoidable diffusion process occurring during its transport from the conversion point to the collecting pixel anode [1].

To solve the problem of charge sharing a new generation of very large area ($32 \times 25 \text{ mm}^2$) pixel ASICs, PIXIE III, has been developed by Pixirad Imaging Counters srl. Pixirad detectors are based on the hybrid assembly of a CMOS VLSI ASIC to suitable X-ray sensor materials (Silicon, CdTe, GaAs) via the flip-chip bonding technique [2]. PIXIE III can be configured in several counting modalities. In “Pixel Summing Mode” (PSM) it is possible to recover the charge (energy) shared between one pixel and its neighbors (mostly one) and get a sharp X-ray spectral imaging.

A PIXIE III based Pixirad unit shows several advances compared to what has been available up to now. It has a very broad energy range (from 2 to 100 keV before full pulse saturation), high speed (100 ns peaking time), high frame rate (larger than 500 fps), dead-time-free operation, good energy resolution (around 2 keV at 20 keV), high photo-peak fraction and sharp spectral separation between the *color* images.

2 The large area photon-counting CMOS ASIC, PIXIE III

The chip is fabricated in $0.16 \mu\text{m}$ CMOS technology and it is organized as a matrix of 512×402 square pixels at $62 \mu\text{m}$ pitch. Each pixel incorporates an octagonal electrode (top layer of metal) connected to a charge-sensitive shaping amplifier feeding two discriminators and two 15-bit counter/registers allowing to collect two *color* images in a single exposure. The events are counted into a first counter (counter#0) if their energy falls inside the window defined by a lower (V_{th0}) and an upper threshold (V_{th1}), and counted into a second counter (counter#1) when their energy is higher than V_{th1} .

Table 1. PIXIE III electrical characteristics.

Equivalent noise charge	50 electrons rms
Linear range	> 12000 electrons
Saturation level	> 18000 electrons
Residual offset after auto-calibration	± 30 electrons
Shaped pulse duration (at the base)	450 ns (adjustable)

To reduce unavoidable DC offset variations from pixel to pixel at the discriminators input, a self-calibration circuit is implemented in each pixel. In this way global threshold levels can be applied to the whole matrix with the noise fluctuations as the main limiting factor to the device sensitivity.

During the data acquisition, the shift registers, in conjunction with a proper XOR feedback, are used in pseudo-random generator mode, clocked by the trigger coming from their respective discriminators. After initialization, the number of events or clock periods recorded is uniquely linked to the register contents, with a maximum of 2^{15} counts per counter.

In read-out mode, the registers of each column of pixels are serialized and their content pushed out of the circuit under the control of an external clock signal.

Table 1 lists the main features of PIXIE III.

The chip can be configured in different operation modes, the most important being:

1. *Pixel Mode (PM)*: in this modality each pixel counts independently from the others. The pixel works in windowed counting mode and each counter can be read-out in less than 1 ms, allowing for very high frame rates. PM is the modality showing the highest count rate capability (higher than 1 MHz input rate per pixel) but it could suffer for some multiple counts effect when working at very low thresholds with polychromatic beams. The sharpness of the color separation is limited by the tail of the pixel charge collection efficiency due to charge leak to neighbor pixels because of diffusion.
2. *Neighbor Pixel Inhibit mode (NPI)*: in this modality only one counter per event is allowed to count. This is accomplished by exploiting the duration (Time-Over-Threshold) of the discriminator output pulse. In case an event spreads over several pixels, the hit is allocated to the pixel receiving the highest fraction of the total charge. This modality has the highest position resolution and the lowest possible noise, but the problem of the sharpness of the color separation is not yet completely solved.
3. *Pixel Summing Mode (PSM)*: in PSM mode the signals of 4 neighbor pixels are summed together to correctly evaluate the total energy of any event involving up to 4 pixels. Because the sum is performed in each pixel, i.e. at the same pitch of $62 \mu\text{m}$ in both X&Y directions, when used in combination with NPI the PSM ensures that both the spatial accuracy and energy resolution are finally preserved. The unavoidable trade-off is an increase of a factor 2 in the pixel noise and a factor 4 in the pulse pile-up probability. For this reason special attention has been paid to reduce the input amplifier shaping time to less than 450 ns (total duration of the pulse at the base) and the noise of the FE amplifiers.

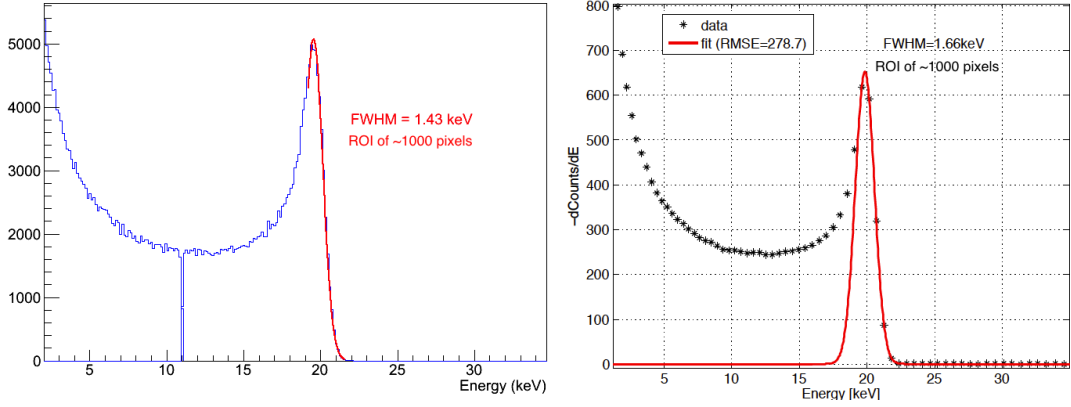


Figure 1. Charge sharing effects at 20 keV. Comparison between Monte Carlo predictions for a ROI of 1000 pixels (left panel) and experimental results (right panel).

To obtain two sharp *color* images in a single exposure, a third discriminator and a ‘sum’ amplifier have been added in each pixel. The summing amplifier collects the 4 signal currents which are dispatched by the front-end amplifier (FE) of the pixel itself and by the FEs of 3 neighbor pixels (at East, South and South-East) and converts the sum back into a voltage. The latter is then discriminated against the ‘windowed’ energy thresholds to assign the hit to a unique *color* pixel counter. The additional discriminator is used to resolve the ambiguity, which occurs when only one pixel collects the full charge figure 1 shows a comparison between Monte Carlo predictions and experimental data of the charge sharing effect with 60 μm pixels and 20 keV X-ray photons. The experimental data have been acquired with a Pixirad detector based on the large area ASIC PIXIE II [2].

As figure 1 shows, there is a good agreement between real data and Monte Carlo simulation that takes into account also gain variations and residual offset dispersions.

A Monte Carlo detailed model has been also developed to simulate the different modes of operation of PIXIE III; in particular to check how efficiently the Pixel Summing Mode can recover the charge (energy) shared between pixels, respect to the standard Pixel Mode. The MC results for 26 keV X-ray photons and a CdTe sensor of 750 μm thickness are shown in figure 2 where the blue line refers to photons with energy between 5 and 13 keV and the red one to photon with energy greater than 13 keV. The energy and spatial distributions obtained with the PSM show clearly how this mode allows preserving both energy resolution and spatial accuracy.

2.1 Results in test bench set-up

Threshold scans with charge injection have been performed to study the basic characteristics of PIXIE III. Figure 3 shows the normalized pixel counts as a function of the threshold for the single pixel (left panel) and for all pixels (right panel) in a CdTe-PIXIE III detector.

The difference between 16% and 84% in the cumulative distribution function (the sigmoids in figure 3) gives an estimation of the noise.

The measured single pixel noise, corresponding to the amplifier noise, is 0.85 keV FWHM, while the overall noise (averaged over all the pixels) is 1.61 keV FWHM (CdTe equivalent). The

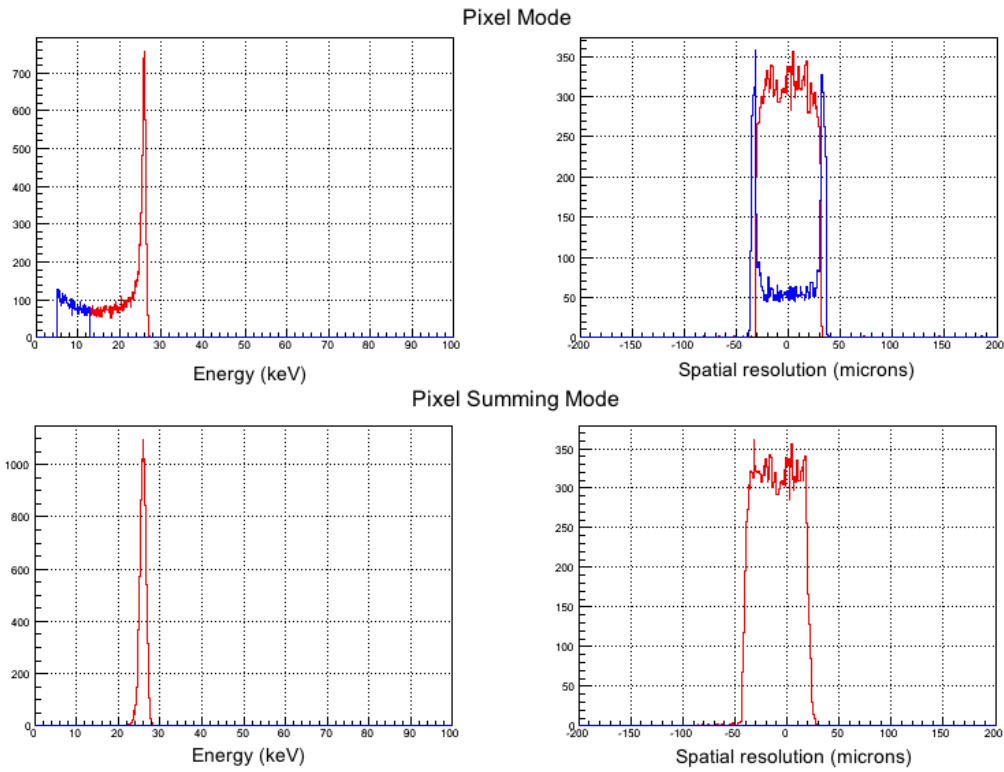


Figure 2. Monte Carlo simulation of PIXIE III Pixel Mode functionality (top) and Pixel Summing Mode (bottom). The simulation has been performed with 26 keV photons and 750 μm CdTe. In the figure, the label “Spatial resolution” refers to the difference between true and reconstructed MC points.

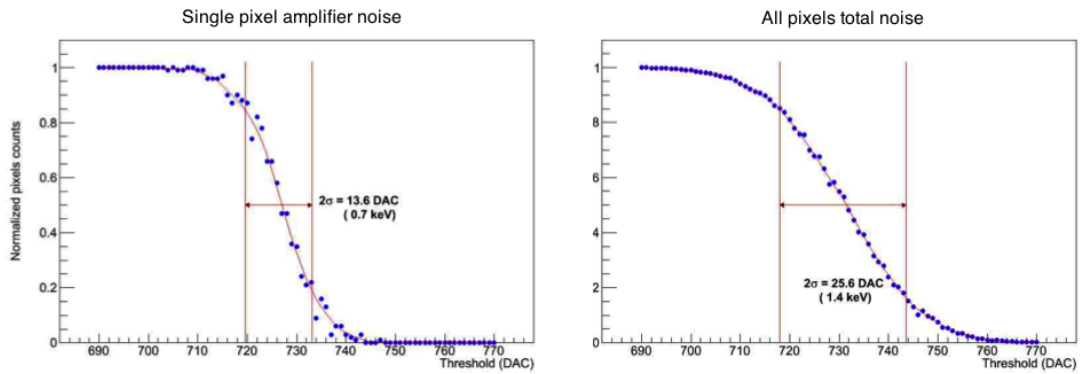


Figure 3. Noise measurements: single pixel (left) — all pixels (right).

latter is the sum squared of different contributions:

$$(\text{Total noise})^2 = (\text{amplifier noise})^2 + (\text{residual offset dispersion})^2 + (\text{gain dispersion})^2$$

The equivalent noise for Silicon can be derived from the single pixel noise for CdTe, by scaling with the ratio of the average energy per hole-electron pair (4.43 eV for CdTe, 3.62 eV for Si). The Si equivalent single pixel noise is (FWHM) = 0.69 keV, the total noise (FWHM) = 1.31 keV.

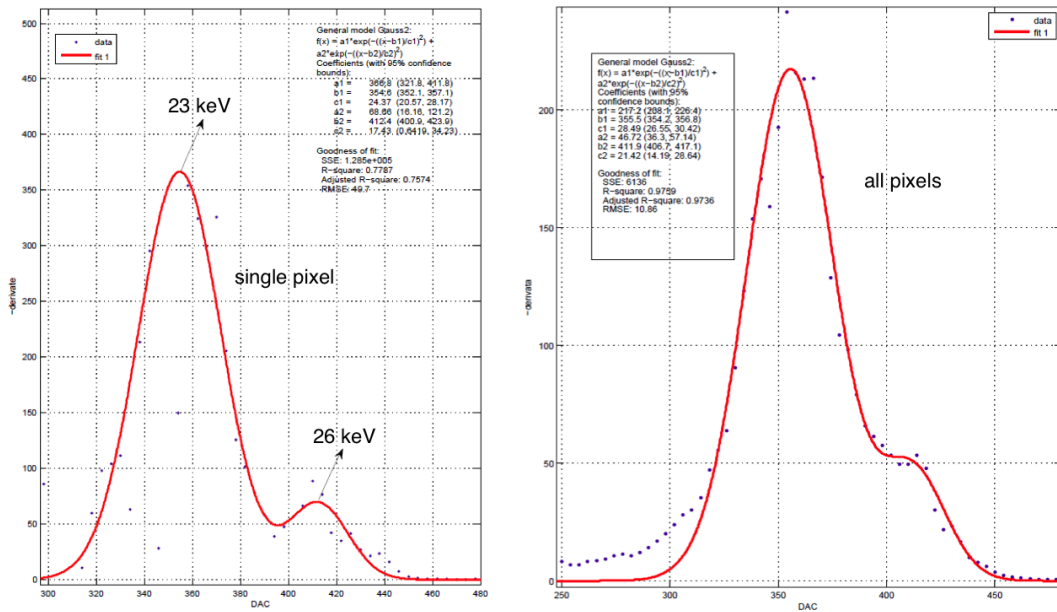


Figure 4. Experimental energy distribution for single pixel (left) and all pixels (right), obtained exploiting the cadmium fluorescent lines at 23 and 26 keV.

2.2 X-ray energy resolution and spectral imaging

The total noise still has a not negligible contribution due to offset dispersion and gain variation as figure 4 shows. Improvements in the energy resolution are foreseen in the second part of the first engineering run with the implementation of a minor modification to the pixel offset compensation algorithm.

Nevertheless a good energy resolution of 6.6% (FWHM) at 60 keV has been measured (figure 5) while keeping the high spatial resolving power provided by the 62 microns pixels. The energy distributions of figure 5 refer to a region of ~ 1000 pixels and two different acquisition modalities of PIXIE III: Pixel Mode (left panel) and Pixel Summing Mode (right panel). The two spectra have been obtained by differentiating the integral raw counts acquired through a fine threshold scan.

The PIXIE III unit has a good spectral capability as it is demonstrated in figure 5 where also the fluorescence and the escape peaks of the cadmium and tellurium components are shown together with the Am241 main line at 59.6 keV.

The imaging capability of the Pixirad CdTe-PIXIE III assembly has been tested in the PSM configuration under high flux of X-ray radiation. As it can be seen in figure 6, the detector can resolve up to 8 line pairs/mm with high modulation factor.

To demonstrate the spectral imaging power of the new detector a series of energy resolved X-ray diffraction experiments have been conducted. Diffraction methods are a powerful tool to investigate the crystal structure of compounds as for example the caffeine. By using a sharp selection of energy windows in a polychromatic X-ray spectrum, possible with a PIXIE III-based Pixirad detector, the structure of an anhydrous caffeine powder has been detected.

Figure 7 (bottom panel) shows the unfiltered spectrum generated at 40 kVp by the X-ray tube with a tungsten anode (W) used in the experiment. Different energy windows have been selected

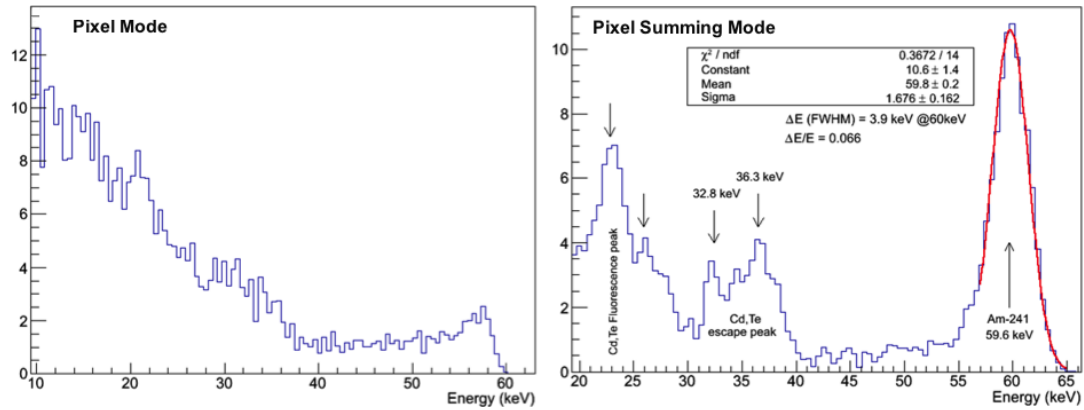


Figure 5. Energy distribution of 60 keV X-ray photons from Am241. Data have been acquired in Pixel Mode (left) and Pixel Summing Mode (right). The distributions refer to a ROI of nearly 1000 pixels.

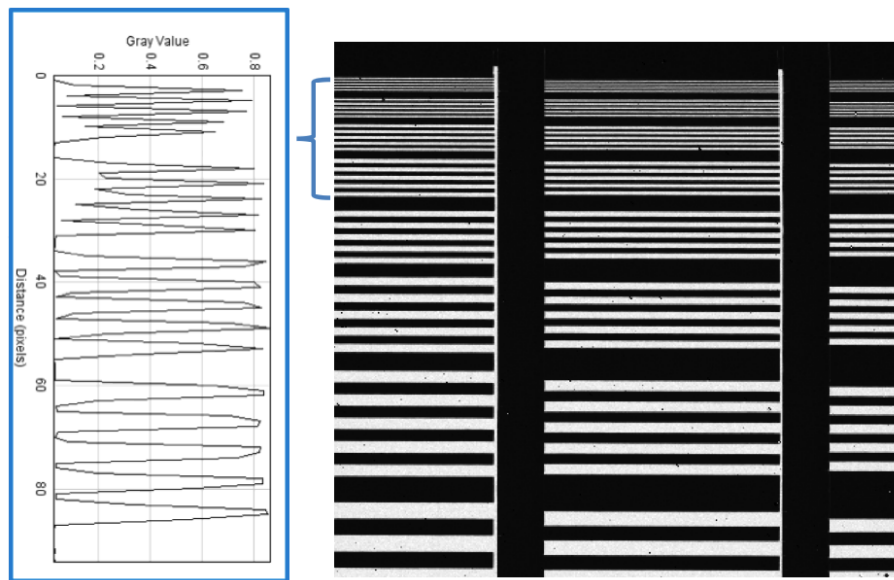


Figure 6. Imaging capability in Pixel Summing Mode. The highest density in the graph on the left, corresponds to the 8 lp/mm of the Huttner line-pairs test object.

in the spectrum by using PIXIE III as an electronic monochromator. In the top panel of figure 7 the caffeine diffraction patterns (two rings with energy dependent radii) are shown.

In the 8–12 keV energy range, data show the two rings, each one split in three sub-rings corresponding to the three W energy lines of around 8, 9 and 12 keV, while in the 9–10 keV energy window the two rings correspond to the main W line only.

The two caffeine rings have been also visualized in a different setting, with photons taken from the continuum only, but using a sharp energy selection between 20 and 21 keV (figure 7, top panel, rightmost image).

The sharp *color* separation achievable with PIXIE III is shown also in the two images reported in figure 8. With the detector operating in Pixel Summing Mode there is no high energy photon leaking in the low energy window due to charge sharing. In the low energy photons image (left

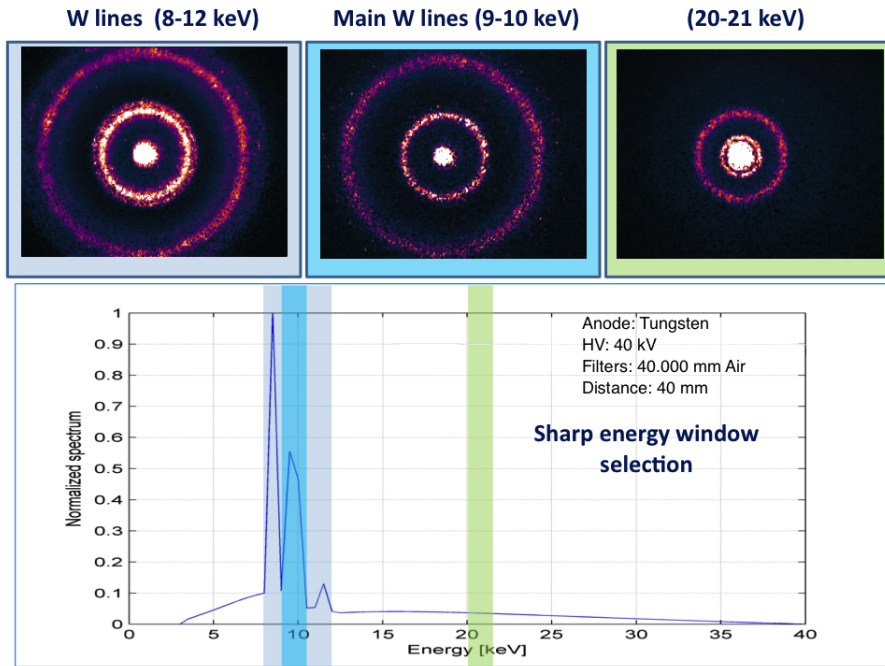


Figure 7. Caffeine diffraction patterns: two rings with energy dependent radii.

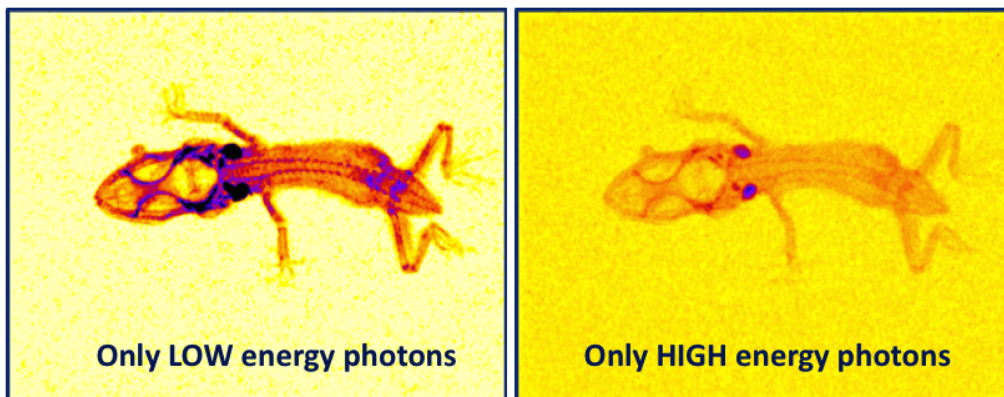


Figure 8. X-ray spectral imaging of a small animal obtained with the PIXIE III-Pixirad detector operating in Pixel Summing Mode.

panel) bony structures are better visualized due to a higher bone-tissue contrast while at higher energies the contrast is highly reduced (right panel).

3 Conclusions

PIXIE III is a new generation of large area ASICs developed by Pixirad Imaging Counters srl. Its main feature is to provide sharp X-ray color imaging while working with very small pixels (62 μm). PIXIE III architecture is very flexible and various operation modalities can be selected to better suit the specific application needs (lowest energy threshold, highest rate capability, highest frame rate).

When working in Pixel Summing Mode it allows a full recover of the charge sharing effect at $62\ \mu\text{m}$ pitch and provides two *color* images in a single exposure with a high chromatic purity. The residual spread of the pixel DC offsets after auto-calibration needs to be further optimized. It will be done with the second wafer batch of the first pilot engineering run.

References

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