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Towards a Timepix4 compact gamma camera for coded aperture 3D imaging

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Summary. — The Timepix4 readout circuit for hybrid pixel detector (448×512 pixels, 55 μm pitch) has been recently released by the Medipix4 Collaboration based at CERN. We have designed a compact gamma camera (CGC) based on a 1 mm thick CdTe semiconductor pixel detector for nuclear medicine tasks, *e.g.*, sentinel lymph node imaging, with Tc-99 m radiotracers. The detector is coupled to a coded aperture collimator (modified uniformly redundant array with 0.25 mm diameter round holes in 1 mm thick Tungsten plate). The real-time coded aperture image reconstruction is performed via autocorrelation deconvolution. The detector assembly works in minification for a variable field of view. Geant4 Monte Carlo simulations showed that for a Tc-99 m source, at 50 mm source-collimator distance, where the field is $88 \times 88\,\mathrm{mm}^2$, the collimator sensitivity is 290 times that of a single hole in the mask, and the spatial resolution is (1.67 ± 0.05) mm FWHM. Tests with a Silicon pixel detector bump-bonded to a Timepix4 chip with an Am-241 source showed energy resolution capabilities.

1. – Introduction

Portable gamma cameras are compact devices used in nuclear medicine to perform gamma-ray imaging of emitting objects, such as Sentinel Lymph nodes (SLNs), during Radio-guided surgeries [1-3] in order to reduce surgical invasiveness. In this work, we present the progress made towards the design of a new semiconductor-based CGC, MediPROBE4, and the first tests of this device for spectral imaging using a coded aperture collimator. MediPROBE4 uses a Timepix4 ASIC, which is an application-specific chip designed by the Medipix4 Collaboration for the electronic readout of single-photon counting semiconductor pixel detectors. Gamma-ray imaging applications with semiconductor hybrid pixel detectors of the Medipix and Timepix series have been demonstrated in the past for emission tomography [4-7].

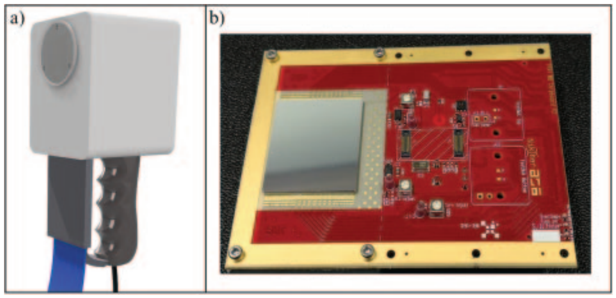

Fig. 1. – (a) MediPROBE4 hand-held gamma camera with a CA collimator and a Timepix4 semiconductor hybrid pixel detector. (b) Timepix4 ASIC with a monolithic Silicon sensor.

2. – Materials and methods

The MediPROBE4 camera head (fig. 1(a)) is a lead-shielded ABS box of size $94 \times 114 \times 72$ mm^3, which houses the Timepix4 chipboard. The device, which has an estimated weight of 1 kg, can be hand-held using a 3D-printed ergonomic handle. This camera uses Timepix4 [8, 9], a hybrid pixel detector readout ASIC (March 2022) composed of 448 $\times$ 512 pixels separated by a 55 μm pitch; it was designed to be bump-bonded to a semiconductor pixel sensor, for a total sensitive area of 6.94 cm^2 (fig. 1(b)). This ASIC can operate in Frame-based mode and Data-Driven mode; the latter allows knowing the Time-over-Threshold (ToT) of a single hit, *i.e.*, the time for which the charge signal generated by the particle in the semiconductor remains over a threshold, and the Time-of-arrival (ToA). With this mode, one can perform spectral imaging and particle tracking. The data stream coming from the chip is read out by a Spidr4 readout system [10].

The collimator we chose is a coded aperture mask (anty-symmetric NTHT MURA mask, rank 31) [11-13] made of 3D-printed Tungsten with round holes of 0.25 mm diameter. Images obtained using a CA mask need to be processed to obtain the activity distribution of the emitting object: to do this, we used the MURA correlation decoding algorithm. During the decoding procedure, one can select the distance at which the object must be reconstructed and eventually obtain a 3D image of the source as a sequence of planar images, *i.e.*, a laminography (fig. 2(a)).

2˙1. *Monte Carlo simulations*. – Monte Carlo simulations were performed with the Geant4 toolkit [14] (v. 10.6, physics list Option4). We simulated a system consisting of a pixel semiconductor detector and a CA mask, separated by a 10 mm air gap; we imaged a point-like radioactive source (Tc-99 m spectrum) placed at 50 mm from the collimator and analyzed the resulting picture. We evaluated the FWHM lateral spatial resolution (SR) of the system by performing a Gaussian fit on the source profile in the decoded image in fig. 2(b). Secondly, we computed the background-subtracted geometric efficiency of the collimator; we counted photons impinging on the detector when either the collimator or a 1 mm thick Tungsten plate was used. The latter were regarded as background. The geometric efficiency is computed as the fraction of emitted photons arriving at the detector when the background is removed. We evaluated the CA mask field of view, whose theoretical dimensions were 90.3×90.3 mm^2 at 50 mm. To such scope, we observed how the CNR varied for sources placed at different positions in the x-y plane.

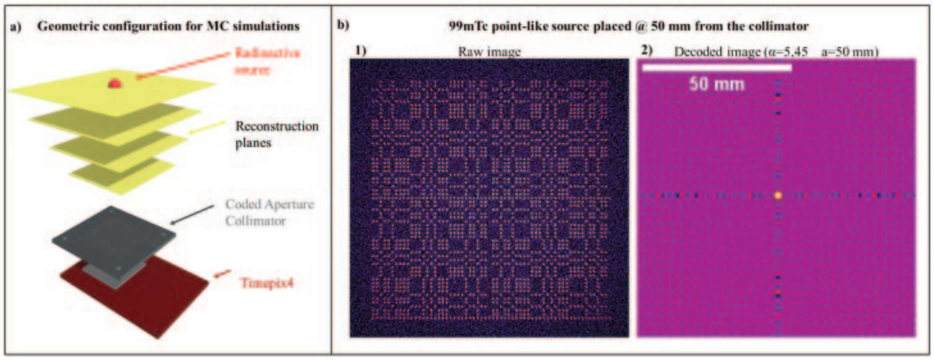

Fig. 2. – (a) Geometric configuration used for Monte Carlo simulations and measurements. The CA collimator allows obtaining a 3D image of the source by reconstructing the image at different distances. (1b) Projection of the mask on the sensor by a point-like Tc-99 m source at 50 mm from the collimator. (2b) Decoded image obtained using the reconstruction algorithm.

2˙2. *Experimental tests*. – Experimental tests for spectral imaging of radioactive sources were carried out using a prototype of the Timepix4 ASIC bonded to a 300 μm thick Silicon sensor. For collimation, we used a 110 μm thick Tungsten NTHT MURA mask of rank 31 with 80 μm diameter round holes, placed at 22 mm from the sensor. We imaged an Am-241 source (336 kBq) set at 55 mm from the mask. The acquired image was processed by removing the background noise and selecting events with a ToT between 50 ns and 400 ns (spectral line at $\sim$26 keV of the Am-241 source).

3. – Results

3˙1. *Monte Carlo simulations*. – For a 1 mm thick W mask with round holes of 0.25 mm and a point-like source placed on the axis at 50 mm from the collimator, the lateral SR was (1.67 $\pm$0.05) mm, while the background-subtracted geometric efficiency was 4×10^{-4}. Finally, we found that the exploitable FOV is 88×88 mm^2: for a source placed at 44 mm from the centre, the CNR was, indeed, $\sim$10, which is still sufficient to distinguish it. If we place a source outside this FOV, we either observe reconstruction artifacts or are unable to visualize the source due to inadequate CNR.

3˙2. *Experimental tests*. – Experimental tests conducted with a point-like Am-241 source showed that it is possible to perform spectral imaging. A first picture of the source was obtained from the unprocessed image acquired with the Timepix4 (fig. 3): in this case, the CNR was $\sim$ 14. For the processed image, the CNR was $\sim$24. From the laminography of this source, it was also possible to obtain the axial FWHM SR of the system, which was (3.7 ± 0.4) mm.

4. – Discussion and conclusions

We showed the design and optimization of a new portable gamma camera and the first test of the Timepix4 ASIC for coded aperture spectral imaging of radioactive sources. Test images obtained with a Timepix4 bonded to a 300 μm thick Silicon sensor showed an acceptable CNR and a good axial SR for an Am-241 source. With respect to the POCI scintillator-based CGC [15] (sensitivity of 0.19 cps/kBq, SR of 7.6 mm, FOV of

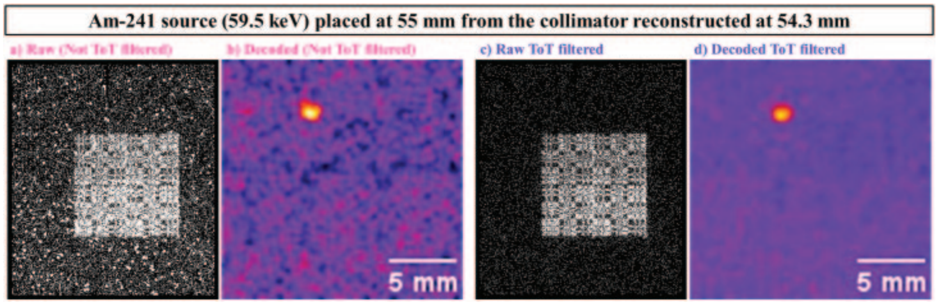

Fig. 3. – Unprocessed raw (a) and decoded (b) image of the Am-241 source; in (a) alpha particles from Rn-222 decay are visible as round spots. (c) and (d) result from the cleaning procedure. In (d), the source's CNR is increased by 70% with respect to (b).

40 mm in diameter), MediPROBE4 with CdTe detector is expected to feature comparable sensitivity, larger FOV, better SR and, in addition, will have a millimeter axial resolution. Future tests will investigate the performance with 1 mm and 2 mm thick CdTe detectors and the use of the CA mask designed in this work.

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