First images from a $CeBr_3$ /LYSO:Ce Temporal Imaging portable Compton camera at 1.3 MeV

M.Z.Hmissi, A.Iltis, C.Tata, G.Zeufack, L. Rodrigues, B.Mehadji, C.Morel and H.Snoussi

Abstract–**During nuclear decommissioning or waste management operations, there is a need for imaging the contamination field while identifying and quantifying the contaminants. Our objective is to test a Compton camera within the energy range 300 keV-2 MeV that uses both light and timing distribution of fast scintillating monolithic crystals. In this experiment we use a 5 mm thick $CeBr_3$ scatterer plate and a 20 mm thick LYSO absorber plate. Our algorithms record for each scintillation event the full position and energy of the event including DOI, even in the thin plate and the relative timing between the detection in the two plate. Our CRT was measured at 293 ps FWHM in coincidence mode without DOI correction. This good time resolution allows for a stringent veto on real Compton event that must be recorded simultaneously in both the scatterer and the absorber plates, thus reducing background very efficiently. Acquisitions were performed with a Phillips Digital Photon Counter SiPM 3200 matrix with a delay-time correction map applied pixel by pixel. After accurate detection of gamma interaction coordinates (x,y,z) and energy in each plate, a list-mode maximum likelihood iterative reconstruction algorithm is applied to better estimate the gamma source activity distribution. Our Compton camera is a promising device for imaging high energy gamma rays, moreover, it can be also suitable for on-line monitoring due to its timing performance. The project TEMPORAL is funded by the ANDRA/PAI under the grant No. RTSCNADAA160019.**

Key words: Temporal Imaging, Compton camera, monolithic crystal, VETO, source reconstruction, spatial resolution.

I. INTRODUCTION

COMPTON cameras based on CZT are starting to be used in the nuclear industry. However, even if they are portable, their angular resolution is low and their sensitivity to high energy gamma is limited [1]. Our goal is to realize a Compton camera using three-dimensional (3D) position sensitive scintillator plates that can both provide a good angular resolution (< 6° FWHM) and a good sensitivity for high energy radiations (1 MeV). This requires to develop imaging solutions that provide at the same time the best energy resolution we can get from scintillators and a good localization of the gamma interaction position. We believe that using spatially resolved timing information is a key point in achieving this within monolithic crystals. Temporal Imaging is a new concept for gamma ray imaging, which exploits monolithic fast scintillator crystals for locating gamma ray interactions by using both the scintillation photon spatial distribution and their time of arrival [2]. In this experiment we are using a mixed configuration: 5 mm thick $CeBr_3$ scatterer plate and a 20 mm thick LYSO absorber plate. Being able to use a high nuclear background crystal such as LYSO in a Compton camera is a feat by itself, only feasible because of our timing veto.

II. MATERIALS AND METHODS

The Temporal Imaging Compton camera consists of two monolithic scintillator crystals. The scatterer, located in front of the source, is a $CeBr_3$ crystal from Hellma materials of a size 32 x 32 x 5 mm^3 wrapped in diffusive BRG reflector. The absorber is a LYSO:Ce crystal of a size 32 x 32 x 20 mm^3 wrapped with Teflon reflector. Each scintillator is coupled optically to a Philips Digital Photon Counter tile, DPC-3200-22 sensor. Both the absorber and the scatterer crystals are encapsulated hermetically in an Aluminum housing, so that the distance between the scatterer and the absorber plate can be modified. In the images presented here, the distance between the scatterer and the absorber plates is 30 mm. The first plate is 400 mm distant from a 0.38 MBq ^{22}Na source. The Compton camera is integrated in a system whose mass is < 5 kg that includes acquisition and processing electronics, detector cooling and power supply (figure 1).

Fig. 1. Portable Temporal Imaging Compton Camera currently being developed at Damavan Imaging.

The energy resolution of both plates was evaluated using the 511 keV line of a ^{22}Na source: the energy resolution was 8% FWHM for the $CeBr_3$ plate and 12% FWHM for the LYSO plate. Since the energy recorded in the scatterer plate is

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M.Z. Hmissi and H. Snoussi are with the University of Technology of Troyes, UMR CNRS 6281, 12 rue Marie Curie, 10010 TROYES, France (e-mail: mohamed_zied.hmissi@utt.fr, hichem.snoussi@utt.fr).

A. Iltis, L. Rodrigues de Magalhaes, C. Tata Zafiarifety and G. Zeufack Tadonkeng are with Damavan Imaging, 2, rue Gustave Eiffel, 10430 ROSIERES PRES TROYES, France (e-mail: alain.iltis@damavan-imaging.com, luc.rodrigues@damavan-imaging.com, christian.tata@damavan-imaging.com, gislain.zeufack@damavan-imaging.com).

B. Mehadji and C. Morel are with Aix-Marseille Univ, CNRS/IN2P3, CPPM, Marseille, France (e-mail : mehadji@cppm.in2p3.fr, morel@cppm.in2p3.fr).

low (100-300 keV), it is important for this plate to have a high light yield and good energy resolution, hence to use $CeBr_3$.

The CRT was measured by placing a ^{22}Na source between the 2 plates. A value of 293 ps FWHM was found without corrections. The positions of the events in both plates were calculated using time corrected light distribution. The spatial resolution was 2.1 mm FWHM along X and Y for the $CeBr_3$ plate. Great care was taken in the 5 mm $CeBr_3$ plate to have a position free from distortion and artifacts. This translates in a very homogeneous flood image shown below: the position is expressed in pixel (4 mm pitch) and varies from 0.5 to 8.5.

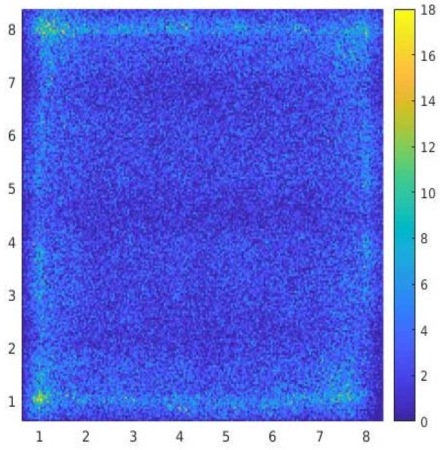

Fig. 2. Flood image measured in the 5 mm $CeBr_3$ crystal

The spatial resolution in the LYSO plate was 3 mm along X and Y.

For the absorber crystal, when we used a $CeBr_3$ crystal, even using time correction, there was too much image compression. Correction of this effect requires a better knowledge of the optical parameters of the $CeBr_3$ detector assembly. This work is in progress at Damavan. We have thus decided to use LYSO:Ce for the absorber crystal instead. LYSO:Ce is very well known and much easier to model. The problem is that LYSO contains ^{176}Lu, which is a gamma emitter at 202 and 307 keV. This precludes imaging of weak sources in this configuration below 0.7 MeV. Our target at this stage is to validate our Compton imaging concept. We have thus decided to make images at 1.3 MeV.

To be recognized as a valid Compton event, detection must pass the following criteria:

- It must be detected in both plates inside a stringent time window (500 ps).
- Acquisition must pass quality criteria in both the plates.
- Energy partition between the two plates must correspond to valid Compton deflection angles.

Considering the information collected by the Compton camera, it is possible to retrieve all the possible directions of the incident gamma ray, which are the generators of a cone [3]. The Compton cone is defined by its origin (x1; y1; z1) on the diffuser plate, its axis direction (α;φ) and its opening angle θ determined from the Compton equation:

$$\theta = arccos\left(1 - \frac{m_e c^2}{E_2} + \frac{m_e c^2}{E_1 + E_2}\right) \qquad (1)$$

where E_1 is the energy of recoil electrons measured in the scatterer and E_2 is the scattered gamma ray energy measured at the absorber.

This angle must respect our system geometry.

Iterative reconstruction algorithms such as LM-MLEM, are suitable for determining the activity distribution of radioactive sources as well as their incoming directions using Compton kinematics. This method was originally proposed by [4] as the following equation:

$$\lambda_j^{l+1} = \frac{\lambda_j^l}{s_j}\sum_i \frac{t_{ij}}{\sum_k t_{ik}\lambda_k^l} \qquad (2)$$

- λ_j^l is the image pixel content at iteration *l*.
- S_j is the probability that an emitted gamma by the pixel *j* will be detected. It is also defined as the sensitivity matrix.
- t_{ij} is the probability that an emitted gamma by the pixel *j* will be detected as an event *i*. It is also defined as the system matrix.

Determining the parameters t_{ij} and s_j, which describe the response of the imaging system, becomes the key point for Compton reconstruction accuracy. Uncertainties due to Doppler effect in the first crystal, finite position resolution and finite energy resolution of the detector are taken into account to correctly estimate the system matrix t_{ij}.

III. RESULTS AND DISCUSSION

Our ^{22}Na source is 5 mm diameter and 6 mm high. It is located inside a lead disc 80 mm in diameter. The ^{22}Na source reconstruction is shown on a 100 x 100 image representing 800 x 800 mm² plane at 400 mm from the entering face of the camera. The acquisition time was 20 min. We have tried two image reconstruction configurations:

- The source is located at (0, 0, 400) mm^3 from the front face of the camera.
- The source is located at (-150, 0, 400) mm^3 from the front face of the camera.

Each configuration is reconstructed using 20 LM-MLEM iterations. Only 1.3 MeV energy is observed. Results are showed in the figure 3.

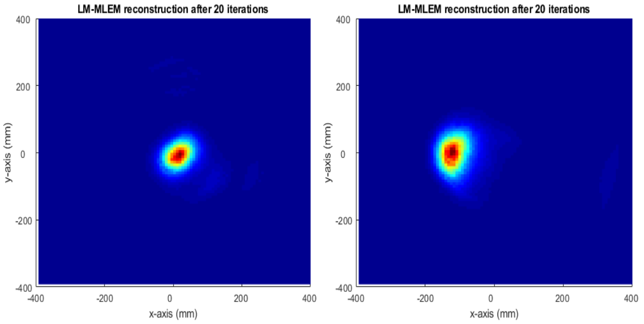

Fig. 3. Compton image reconstruction of ^{22}Na source located at (left) (0, 0, 400) mm^3 and at (right) (-150, 0, 400) mm^3 from the front face of the camera using 20 LM-MLEM iterations.

In order to characterize the camera angular resolution, the line profiles of the presented spots along the X direction are extracted and the FWHM of their Gaussian fits are calculated.

Figure 4 shows the current angular resolution of our dedicated system for high energy measurements.

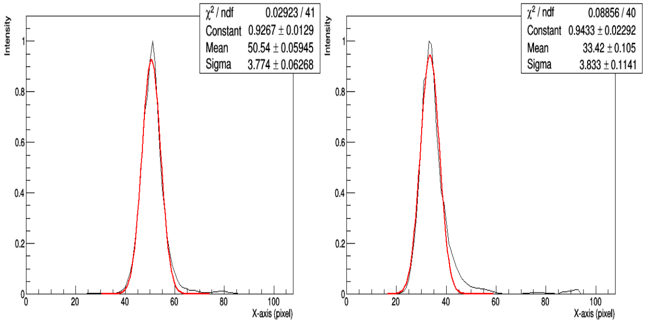

Fig. 4. Line profile along X direction (left) of the first configuration showing an angular resolution of 10.16° and (right) of the second configuration showing an angular resolution of 10.31°.

Subsequently, the intrinsic efficiency of our Compton camera is defined as the fraction of valid Compton events over the total number of events crossing the detector. Thus, given the source activity of 0.38 MBq, an acquisition time of 20 min and the 231 detected valid events we can calculate an efficiency equal to 10^{-3}.

IV. CONCLUSION

We present here first images obtained with a portable Compton camera based on monolithic scintillators that uses both the time and the light distributions within the crystal plates.

The configuration studied here is a 5 mm $CeBr_3$ scatterer plate and a 20 thick LYSO:Ce absorber plate separated by 30 mm. Great care has been taken to have a very homogeneous optical response in the $CeBr_3$ scatterer plate.

Images have been obtained with a cylindrical ^{22}Na source 400 mm from the camera, using the 1.3 MeV gamma line. The LM-MLEM algorithm is applied to reconstruct the source activity distribution by taking into account the spatial and energy uncertainties of the device. After LM-MLEM, the source is detected with an angular resolution of ≈10° FWHM.

We are currently working on a full $CeBr_3$ version of the Compton camera.

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