

Temporal Imaging CeBr₃ Compton Camera: A New Concept for Nuclear Decommissioning and Nuclear Waste Management

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Abstract—During nuclear decommissioning or waste management operations, a camera that could make an image of the contamination field and identify and quantify the contaminants would be a great progress. Compton cameras have been proposed, but their limited efficiency for high energy gamma rays and their cost have severely limited their application. Our objective is to promote a Compton camera for the energy range (200 keV – 2 MeV) that uses fast scintillating crystals and a new concept for locating scintillation event: Temporal Imaging.

Temporal Imaging uses monolithic plates of fast scintillators and measures photons time of arrival distribution in order to locate each gamma ray with a high precision in space (X, Y, Z), time (T) and energy (E). This provides a native estimation of the depth of interaction (Z) of every detected gamma ray. This also allows a time correction for the propagation time of scintillation photons inside the crystal, therefore resulting in excellent time resolution. The high temporal resolution of the system makes it possible to veto quite efficiently background by using narrow time coincidence (< 300 ps). It is also possible to reconstruct the direction of propagation of the photons inside the detector using timing constraints. The sensitivity of our system is better than 1 nSv/h in a 60 s acquisition with a ²²Na source.

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Index Terms—Compton camera, Fast scintillating crystals, Gamma ray imaging, Nuclear decommissioning, Temporal Imaging, Time resolution.

I. INTRODUCTION

THE concept of Compton camera was first investigated to detect gamma rays within the energy range 150 keV – 511 keV in the medical field [1]. It became then more and more used in other fields like astronomy [2] and industry [3],

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mostly by using semiconductors like CdTe or CZT. However, such detectors are limited by their small active size, detection efficiency and high background noise level. We propose here a new concept called Temporal Imaging to build a Compton camera based on fast monolithic scintillation crystals. In this concept in addition to light sharing, we also use, photon time of flight within the scintillation crystal to accurately calculate the location of every gamma ray event. This acquisition concept allows a good positioning resolution, not only within the plane of detection ($\Delta X, \Delta Y < 2$ mm FWHM), but also a good estimation of the depth of interaction (DOI) ($\Delta Z < 2$ mm FWHM). It is thus possible to use thick monolithic plates (20 mm LYSO or 25 mm CeBr₃) without compromising the spatial resolution of the Compton camera. The energy resolution obtained is quite good for large monolithic plates (11.0% FWHM with LYSO and 6.9 % FWHM with CeBr₃ at 511 keV).

We will also demonstrate in this paper, that a good DOI measurement allows to reaching very high timing precision (225 ps FWHM with LYSO at 511 keV) for each one of the scintillation plates and will show the benefit that can result for a Compton camera with such a good timing.

We report here first Compton images obtained with LYSO detectors and present first timing measurements with a first generation of windowless CeBr₃ detectors.

CeBr₃, has been selected against LYSO as the reference crystal for our Compton camera, because of its higher energy resolution, higher number of prompt photons allowing better timing and low radioactive background. Our target is to be able to acquire images of weak and/or distant radioactive sources. Nevertheless, CeBr₃ is highly hygroscopic. Therefore, we have developed a new encapsulation technology “Fluoral” that enables direct coupling of the Si-PM to the crystal without a glass window. The results presented here with CeBr₃ are obtained with this technology, but are still preliminary. Hence, we present also some results and images obtained using our LYSO demonstrator.

II. COMPTON CAMERA ARCHITECTURE

A. Principle of the Compton camera

The schematic outline of a Compton camera is described in Fig. 1.

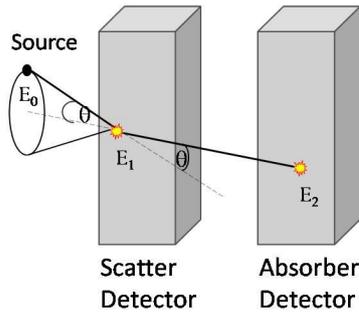


Fig. 1. Schematic outline of a two plate Compton camera

The impinging gamma ray with the initial energy E_0 interacts in the first detector at a well-defined position, resulting in the emission of a scattered photon of energy E_2 by an angle θ_s . The remaining energy $E_1 = E_0 - E_2$, which is transferred to an electron, is deposited in the first detector almost at the position of the Compton interaction. The scattered photon is then absorbed in the second detector, where it deposits its total energy E_2 .

Each Compton event results in a cone shape defined by:

- A vertex, which is the Compton interaction position of the impinging gamma ray in the scatter detector.
 - An axis defined by the interaction positions in both the detectors (diffuser and absorber).
 - An angle θ_s determined by the Compton equation:
- $$\theta_s = \cos^{-1} \left[1 + m_0 c^2 \left(\frac{1}{E_0} - \frac{1}{E_2} \right) \right] \quad (1)$$
- A time delay related to light propagation between E1 and E2

The true path of the impinging gamma ray lies on the mantle of the cone defined by the axis and the angle θ_s .

B. Experimental set-up

Our camera consists of a LYSO or a CeBr₃ monolithic crystal ($32 \times 32 \times 5$) mm diffuser plate and a ($32 \times 32 \times 20$) mm LYSO or a ($32 \times 32 \times 25$) mm CeBr₃ monolithic crystal absorber plate. Both are encapsulated in an aluminum housing. For the Compton camera configuration, the 5 mm and the 20 mm detectors are in front of each other. Hence, taking into account the mechanics, the spacing between the two plates is 5 mm.

The photodetector is a digital SiPM Phillips DPC-3200-22. This digital detector consists of 16 independent die sensors arranged in a 4×4 array. Each die sensor contains four pixels arranged in 2×2 array, and each pixel contains 3200 SPAD cells. A delay-time correction map is applied pixel by pixel to get good timing.

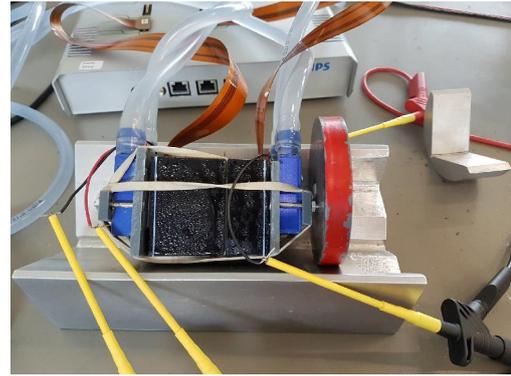


Fig. 2. The Compton camera setup: a ^{22}Na source is located in the red disc 40 mm away from the first detector

The Temporal Imaging Compton camera is designed as shown in Fig. 3. It is subdivided into two parts: a small block on the left including the detectors and a large block on the right where one finds the associated electronics.



Fig. 3. Picture of the TEMPORAL Delta Compton camera

Data acquisitions were performed using a 0.5 MBq ^{22}Na source, which was located 40 mm away from the diffuser plate. The distance between the diffuser and the absorber plate was set to 5 mm. Images were acquired during 200 s. The Compton camera setup is shown in Fig. 2.

III. PERFORMANCE OF THE TEMPORAL DETECTOR

Accurate Compton camera reconstruction requires high precision positioning and energy measurements in the diffuser and absorber plates. In this section, we present the spatial and energy resolutions achieved with our setup.

X and Y positions are determined from the spatial distribution of the scintillation photons and the distribution of their time of arrival. The estimated precision on X and Y is 1,98 mm FWHM. DOI (position along Z) is obtained by using a least root mean square method on simulated images [4]. The estimated precision on DOI is 2 mm FWHM.

For energy measurements, a FWHM resolution of 11.0% at 511 keV was observed in the LYSO crystal (see Fig. 4).

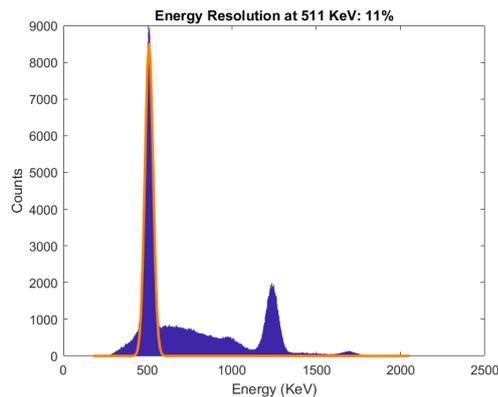


Fig. 4. Energy spectrum of ^{22}Na with the LYSO crystal: we use a Gaussian fit to determine the energy resolution

For the CeBr_3 crystal, the energy resolution at 511 keV was 6.9 % FWHM. The discrepancy from published values for CeBr_3 comes from the low quantum efficiency of the Phillips digital SiPM at the 370 nm peak emission of CeBr_3 .

IV. TIMING PERFORMANCE

In this section, we present the results of our detectors in terms of timing resolution. In order to calibrate our detectors in time, we use a coincidence setup and measure the coincidence resolving time (CRT) of the detection of electron-positron annihilation pairs.

A. CRT correction for CeBr_3 and LYSO detectors

The CRT was measured in another study [5], in which two ($32 \times 32 \times 25$) mm CeBr_3 crystals were used in coincidence. Each detector was coupled to a Philips Digital Photon Counter tile, DPC-3200-22 sensor with the windowless FluoralTM technology [6].

We used the DOI measurement in order to correct for the delay time introduced by the scintillation photon travelling along the crystal at a speed of c/n , assuming that the gamma ray travels at the speed of light in vacuum c .

Without corrections, the measured CRT for CeBr_3 was 519 ps FWHM. As shown in Fig. 5, the result was obtained by fitting the raw CRT curve with Gaussian distribution.

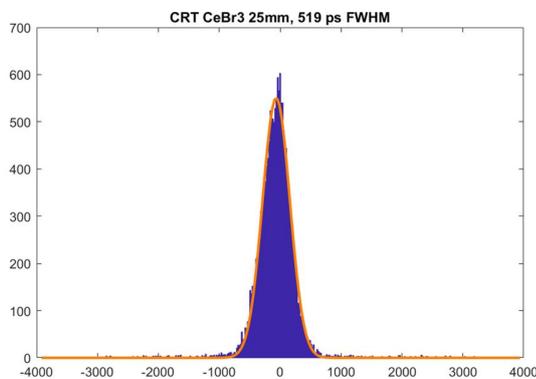


Fig. 5. FWHM of the raw data CRT: no DOI corrections were applied. The FWHM is deduced from the Gaussian fit [5].

When taking DOI into account, the CRT was reduced to 275 ps FWHM [5]. This value is preliminary. We believe it is possible to reach a corrected CRT below 200 ps FWHM with CeBr_3 . For LYSO detectors using the same setup, the CRT value was 225 ps FWHM when corrected for the 20 mm thick detector plates. The corrected CRT value is part of our Compton image processing.

B. Advantages of corrected CRT

For a Compton camera, a good timing resolution provides three advantages:

- It allows to identifying events with a Compton diffusion in the absorber plate [7].
- It places a stringent coincidence selection of Compton events, which have to be detected on the two plates within a time window smaller than 500 ps. This allows for a very strong reduction of background and thus to acquire high contrast images with few photons, even when using a crystal with a high intrinsic background like LYSO.
- It allows to determining in which crystal has undergone the first interaction, hence recognizing the direction of light propagation between the two plates.

V. GAMMA RAY SOURCE RECONSTRUCTION

Many gamma ray source reconstruction techniques have been developed based on iterative or analytic algorithms [8], [9]. In our study, we have used the COMPTONREC software package, which consists in a direct method to reconstruct the source position [10].

A. Principle of reconstruction

As presented in [10], the analytic direct method for source reconstruction we have used consists in computing the intersection of the conical surface defined by the Compton event with the plane that contains the source. This plane must be located inside the field of view of the Compton camera.

Then, we have selected the events for which the sum of the energy deposited in both the diffuser and absorber crystals is within $511 \text{ keV} \pm \delta E$, with δE equal to 11% of 511 keV, which corresponds to the energy resolution of the detection system. We have also selected direct Compton events only, which interact at first in the diffuser and then as a photoelectric event in the absorber. Timing information was used to perform this selection.

B. Compton image reconstruction

In the reconstruction process, for each selected Compton event, possible incidences of the impinging gamma ray are all located on a cone. The position of the gamma ray source is then given by the intersection of cones. In Fig. 6, we show the intersection of the conical surfaces with the source plane for some of the selected Compton events.

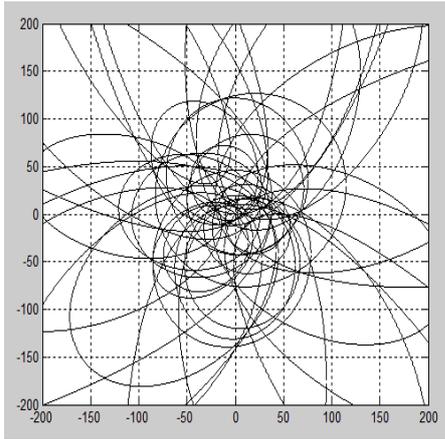


Fig. 6. Reconstruction with the COMPTONREC software package calculating intersections of conical sections with the source plane

All the reconstructed cones intercept at the real source position, which is located in the center of the field of view of the camera.

This kind of representation is difficult to analyze in order to study the performance of the Compton camera such as its spatial resolution. Therefore, in the rest of this work, the reconstructed image will be represented as a density image display where we compute the number of intersections between reconstructed cones per pixel (see Fig 7).

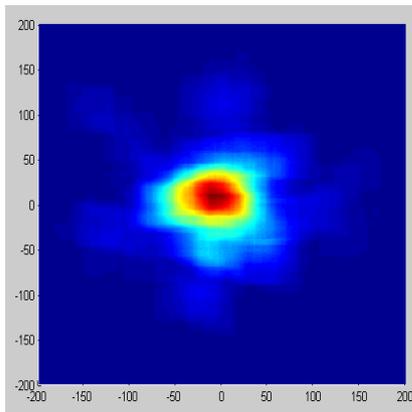


Fig. 7. Density image representation of the ^{22}Na source by selecting 511 keV Compton events: 148 events are used to reconstruct the source.

We can clearly identify the source position as well as the point spread function using this representation.

To determine the source-detector distance, we have used an algorithm described in [11] that is using the solid angle subtended by the reconstructed image as a function of the source-to-detector distance, assuming that an image reconstructed at the correct distance has a smaller solid angle than an image reconstructed at any other distance from the detector. The expected size of the image is minimized when the correct image plane is used.

With the same processing, 1.3 MeV gamma rays were also used to reconstruct the position of the ^{22}Na source. Its density image is shown in Fig. 8. The diffuser plate size is changed from $(32 \times 32 \times 5)$ mm to $(32 \times 32 \times 20)$ mm in order to

increase its efficiency. Two 0.06 MBq ^{22}Na sources are used to determine the spatial resolution of our detector at 1.3 MeV. Thus, we have determined the minimum distance after which we cannot resolve anymore the two ^{22}Na sources. The first plate (diffuser) is 50 mm distant from the ^{22}Na sources, which are separated by a 4 mm metallic plate.

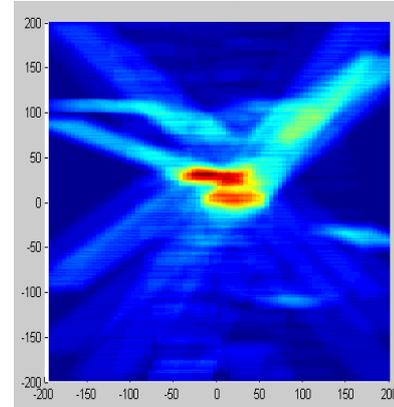


Fig. 8. Density image representation of two ^{22}Na sources using 1.3 MeV Compton events: the two sources are separated by 4 mm metallic plate and distant 50 mm away from the first crystal.

An angular resolution of 4.5° was obtained with our camera for the detection, of 1.3 MeV Compton events. It demonstrates the effectiveness of our use of the time information. Moreover, angular resolution will be improved when CeBr_3 crystals will be used.

VI. CONCLUSION

Reconstruction of Compton events detected by a Compton camera depends on the precision of the gamma ray localization and energy measurement in both the diffuser and the absorber detectors. However, with a standard setup, many of the impinging gamma rays may not be recorded. Here we present a Compton camera based on two high density thick scintillator plates. This setup absorbs more than 50% of the 1.3 MeV impinging gamma rays from a ^{22}Na source. Interaction positions are obtained by using a new concept: Temporal Imaging, which is exploiting both the scintillation photon light distribution and their distribution of time of arrival. This concept allows for good position resolution in three dimensions (< 2 mm FWHM), including DOI. It also allows to recovering an energy resolution close to the intrinsic performance of the scintillators. Timing resolution of this setup is very high (CRT < 225 ps FWHM).

Moreover, the time information in a small detector geometry can be used to discriminate Compton events from LYSO background. This improves the performance of our Compton camera for low energy gamma rays. Thus, we can obtain an image with only few Compton events, resulting in shorter acquisition times needed to localize a gamma ray source.

We have obtained our first images at 511 keV and 1.3 MeV with a functional prototype made of two LYSO crystals: Temporal Delta. The measured angular resolution was at least 4.5° for 1.3 MeV Compton events. We have also presented a

first characterization of windowless CeBr_3 detector for timing: a CRT of 275 ps FWHM was achieved as a preliminary result after taking into account scintillation light travelling time inside the crystal. A CRT below 200 ps FWHM is expected to be achieved for future developments with CeBr_3 crystals.

CeBr_3 will be preferred for our future systems to LYSO, because of its better timing and energy resolution potential. Moreover, CeBr_3 does not have a radioactive background like LYSO and should thus allow for imaging gamma ray source with very low activities.

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