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# Performance improvement tests of MACACO: A Compton telescope based on continuous crystals and SiPMs

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A B S T R A C T

The IRIS group of IFIC-Valencia is developing a Compton telescope for treatment monitoring in hadron therapy. The system is composed of three detector layers, each of them consisting of a monolithic $LaBr_3$ scintillator crystal coupled to Silicon Photomultiplier (SiPM) arrays. A first version of the prototype was developed within the European project ENVISION. Tests with point-like sources and in-beam were carried out with successful results, demonstrating the feasibility of the proposed technology. The limitations of the system were also identified. A new version of the prototype is under development with the aim of improving the performance of the telescope detector planes. To this end, the initial tests of a detector plane based on a new SiPM array have been carried out. The first characterization, coincidence and imaging tests with this new version of the detector plane are presented. In addition, the suitability of $CeBr_3$ scintillator crystals for this application is being investigated.



## 1. Introduction

Hadron therapy is a cancer treatment technique based on the irradiation of tumors with light ions, generally protons or carbon ions. Such particles allow a more precise delivery of the radiation dose compared to photons, preventing the surrounding healthy tissue from suffering unnecessary damage. Compton imaging devices are being investigated for real time dose monitoring in hadron therapy [1–6].

A first version of a Compton telescope (multilayer Compton camera) for treatment monitoring in hadron therapy was successfully developed within the European project ENVISION (European NoVel Imaging Systems for ION therapy) by the IRIS group at IFIC-Valencia [7]. The prototype, known as MACACO (Medical Applications CompAct COmpton camera), was composed of three detector layers, each of them consisting of a monolithic $LaBr_3$ scintillator crystal coupled to Silicon Photomultiplier (SiPM) arrays. Tests with point-like sources and in-beam were carried out with promising results [8], demonstrating the feasibility of the proposed technology.

The limitations of the first prototype were also identified. The experimental and simulated results obtained [9] confirmed that energy resolution is a critical parameter in system performance. For this reason, a second version of the prototype based on a new SiPM matrix is under development with the aim of improving the performance of the telescope detector planes.

In addition, alternatives to $LaBr_3$ are being considered in order to explore more affordable scintillator crystals. $LaBr_3$ has very good energy resolution, fast response and high Compton probability, but its cost is high. $CeBr_3$ emerges as a serious competitor against $LaBr_3$, reporting a slightly worse energy resolution than $LaBr_3$ [10] with a significantly lower cost. Tests with both crystals have been performed with the aim of comparing their performance and assessing the suitability of $CeBr_3$ for the Compton telescope.

## 2. Detector plane description

The new detector planes are composed of a PCB containing the crystal, the SiPM array and the ASIC (Fig. 1). A temperature sensor is attached to the back of the PCB in order to monitor the temperature of the detector plane.

The SiPM is a Multi Pixel Photon Counter (MPPC) manufactured by Hamamatsu Photonics, model S13361-3050AE-08. It consists of 64 (8 × 8) pixels. Each pixel is 3 × 3 $mm^2$ size and it is composed of 3584 microcells of 50 × 50 $\mu m^2$ size. The pixel pitch is 3.2 mm in both directions. The external dimensions of the device are 25.8 × 25.8 $mm^2$. This MPPC array employs TSV (Through Silicon Via) technology and it improves several device characteristics in comparison with previous versions, e.g. reduced crosstalk and dark count rate, low afterpulse,

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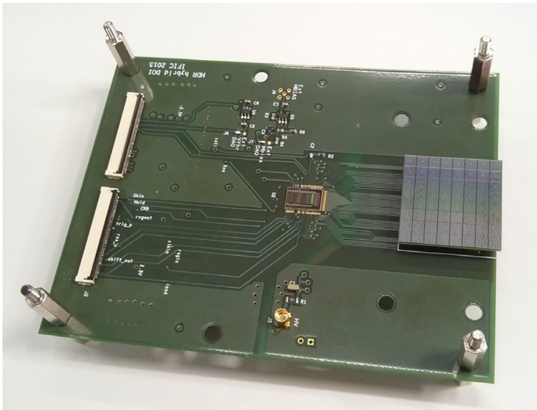

**Fig. 1.** PCB containing the Hamamatsu MPPC S13361-3050AE-08 and the VATA64HDR16 ASIC from IDEAS.

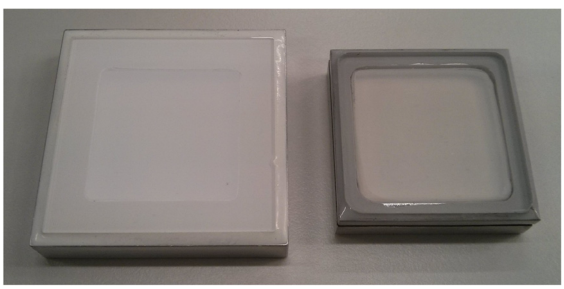

**Fig. 2.** Scintillator crystals of 25.8 × 25.8 × 5 mm$^3$ active volume: $LaBr_3$ from Saint Gobain (left) and $CeBr_3$ from Hellma Materials (right).

higher PDE, better uniformity among pixels and significant reduction of the dead space between the SiPM elements in the array.

Two different scintillator crystals have been employed for the measurements performed. $LaBr_3$ from Saint Gobain (Fig. 2 left) and $CeBr_3$ from Hellma Materials (Fig. 2 right) have been tested, both of them with a surface of 25.8 × 25.8 mm$^2$ and 5 mm thickness. Both crystals are surrounded by reflective material and presented in an aluminum housing due to their hygroscopicity.

The readout system is based on the 64-channel VATA64HDR16 ASIC from IDEAS. A complete study of the configuration parameters has been performed in order to determine the operating parameters for each crystal [11].

## 3. Detector characterization

Characterization tests have been carried out to determine the performance of the new detector plane. The $LaBr_3$ crystal has been coupled to the SiPM array employing Saint Gobain BC-630 optical grease.

The measurements have been performed inside a black box after the stabilization of the temperature inside it, which was 29.0 °C. No temperature corrections have been applied to the data since the temperature variation during the measurements was less than 0.1 °C.

The operating bias voltage applied to the whole MPPC matrix has been determined through a bias scan, in which the best detector performance has been obtained at 54.4 V. This value is 1.7 V lower than the operation bias voltage recommended by the manufacturer (56.1 V). The detector is thus operated below the recommended bias voltage in order to adjust its output to the dynamic range of the ASIC and avoid its saturation. The equalization of the response of the MPPC elements has been done by individually adjusting the bias voltage of each pixel [11].

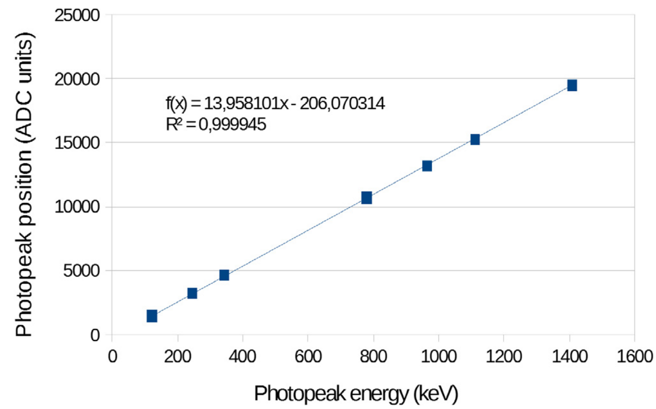


**Fig. 3.** Photopeak positions as a function of the different photopeak energies of a $^{152}Eu$ source obtained with the $LaBr_3$ crystal. The detector shows a linear behavior up to 1408 keV.

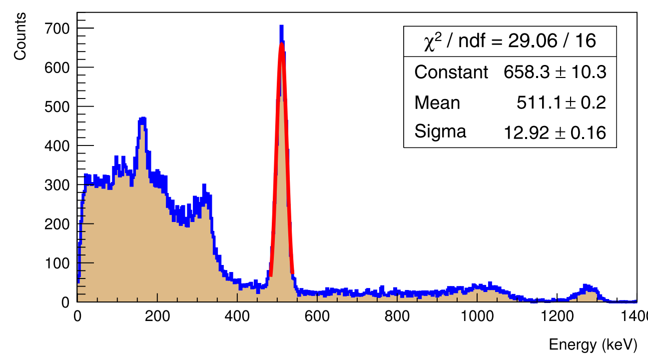


**Fig. 4.** $^{22}Na$ energy spectrum obtained with the $LaBr_3$ crystal. The energy resolution is 5.9% FWHM at 511 keV.

### 3.1. Linearity

The linearity of the detector has been tested employing a $^{152}Eu$ source. The position of its different photopeaks in ADC units has been plotted as a function of their respective energies, which range from 122 up to 1408 keV.

The detector shows a linear behavior up to 1408 keV, as it can be seen in Fig. 3.

### 3.2. Energy resolution

The energy resolution of the detector has been measured employing a $^{22}Na$ point-like source. The 511 keV photopeak has been fitted with a Gaussian function.

The energy resolution obtained is 5.9% FWHM at 511 keV. Fig. 4 shows the $^{22}Na$ spectrum measured with the detector.

### 3.3. Position determination

Position determination tests have been carried out. A $^{22}Na$ point-like source of 0.25 mm diameter was electronically collimated by operating the detector in time coincidence with a second detector. The second detector consisted of a 1 × 1 × 10 mm$^3$ LYSO crystal coupled to a single SiPM of 1.3 × 1.3 mm$^2$ area. The distance between the $^{22}Na$ source and the $LaBr_3$ crystal was 5 mm and the distance between the source and the second detector was 30 mm. The source was placed at five different positions of the detector surface along a diagonal line.

The position determination was carried out with an analytical method based on a model of the solid angle subtended by the interaction point with each pixel, taking into account the photons that reach the



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