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Sub-3mm spatial resolution from a large monolithic $LaBr_3$ (Ce) scintillator

Abstract: A Compton camera prototype for ion beam range monitoring via prompt (< 1 ns) gamma detection in hadron therapy is being developed and characterized at the Medical Physics Department of LMU Munich. The system consists of a large (50x50x30 mm^3) monolithic $LaBr_3$(Ce) scintillation crystal as absorber component to detect the multi-MeV Compton scattered photons, together with a stack of 6 double-sided silicon strip detectors (DSSSD) acting as scatterer component. Key ingredient of the γ-source reconstruction is the determination of the γ-ray interaction position in the scintillator, which is read out by a 256-fold segmented multi-anode photomultiplier tube (PMT). From simulations an angular resolution of about 1.5^o for the photon source reconstruction can be expected for the energy range around 3 - 5 MeV, provided that a spatial resolution of 3 mm can be reached in the absorbing scintillator [1]. Therefore, particular effort was dedicated to characterize this latter property as a function of the γ-ray energy. Intense, tightly collimated ^{137}Cs and ^{60}Co photon sources were used for 2D irradiation scans (step size 0.5 mm) as prerequisite for studying the performance of the "k-Nearest-Neighbors" algorithm developed at TU Delft [2] (together with its variant "Categorical Average Pattern", CAP) and extending its applicability into the energy range beyond the original 511 keV. In this paper we present our most recent interaction position analysis in the absorbing scintillator, leading to a considerably improved value for the spatial resolution: systematic studies were performed as a function of the k-NN parameters and the PMT segmentation. A trend of improving spatial resolution with increasing photon energy was confirmed, resulting in the realization of the presently optimum spatial resolution of 2.9(1) mm @1.3 MeV, thus reaching the design specifications of the Compton camera absorber. The specification goal was reached also for a reduced PMT segmentation of 8x8 anode segments (each with 6x6 mm^2 active area), thus allowing to reduce the complexity of the signal processing while preserving the performance.

Keywords: hadron therapy, gamma-ray medical imaging, Compton camera, monolithic scintillator, spatial resolution.

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1 Introduction

Particle beam therapy is a radiation therapy modality that uses high-energy proton (or ion) beams for cancer treatment. It is considered an advantageous option compared to the conventional photon-based radiation therapy, because of its highly conformal dose delivery potential in the Bragg peak at the end of the particle beam stopping range, thereby reducing adverse effects to adjacent healthy tissues.

But a well-defined volume for the dose deposition in turn requires a higher quality control. Presently unavoidable uncertainties in the determination of the ion beam range force practitioners to add safety margins around the target volume. In order to reduce these margins and thus to allow for fully exploiting the beneficial properties of particle therapy, several projects are worldwide evaluating different techniques for real-time beam range monitoring.

These experimental approaches are aiming at providing precise information on the Bragg peak position: one of these techniques is based on the detection of prompt-γ rays emitted along the ion beam path, originating from nuclear interactions with the patients' tissues. In particular, different

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groups investigate the possibilities for a range verification and in-vivo dosimetry via prompt gamma radiation from nuclear reactions, either employing passively collimated imaging devices or electronically collimated systems based on the Compton-camera principle.

1.1 The Compton camera system

In general, a Compton camera setup consists of a scatter and an absorber component. In a conventional design only the photon interaction in the two detector components is registered, whereas our prototype aims at tracking the Compton electrons as well, in order to also be able to reconstruct the photon source position from incompletely absorbed photon events, thus increasing the reconstruction efficiency [5].

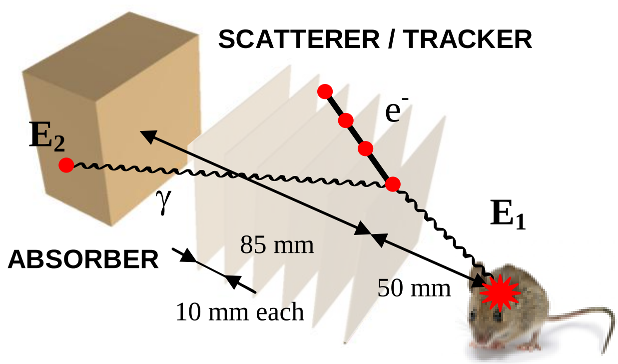

Figure 1: Schematic layout of our Compton camera prototype

The Compton camera system of LMU Munich is schematically shown in Fig.1. From the energy and momentum conservation, the Compton scattering formula is derived, and the Compton scattering angle can be expressed as a function of the energies of the initial (E_1) and scattered (E_2) γ-rays (Eq. 1).

$$cos\vartheta = 1 - m_e c^2 \left[\frac{1}{E_2} - \frac{1}{E_1}\right] \quad (1)$$

The Compton scattering angle defines a cone ('Compton cone'), whose surface is the origin of the impinging photon. From the intersection of different Compton cones, inferred from subsequent photon interactions originating from the same source, the γ-ray source position can be determined.

The work presented in this paper was focused on the absorber component of the Compton camera, in particular on the optimization of its spatial resolution determination, aiming to reach the design specification value required for an angular resolution of the whole camera equal to 1.5°.

2 Materials and methods

2.1 The monolithic $LaBr_3(Ce)$ scintillator

The absorber component of the Compton camera prototype is a 50 x 50 x 30 mm^3 $LaBr_3$(Ce) monolithic crystal, produced by Saint-Gobain Ceramics & Plastics Inc. (BrillanCe^{TM} 380 [4]).

The $LaBr_3$(Ce) scintillator material outperforms other commonly used scintillators in terms of timing and energy resolution properties, showing a decay time τ=17 ns, a light yield LY=63000 ph/MeV, a reasonably high mass density and effective atomic number (ρ=5.29 g/cm^3, Z_{eff}=47). These characteristics resulted in an excellent time resolution (<300 ps) and a very good energy resolution ($\Delta E/E$~3.8%)[3], which is favourable for an optimized reconstruction of the prompt γ origin and efficient background discrimination.

The crystal was coupled to a 256-fold segmented multi-anode photosensor (Hamamatsu H9500 PMT, 16x16 segments, each 3x3 mm^2), which operated at a bias voltage of -1000V (in Fig.2 a photo of the detector is shown). In addition the PMT provided a sum signal, extracted via the 'sum dynode' output.

The 256 (+1, the sum) signals were fed into 16-channel amplifier and Constant Fraction Discriminator modules (Mesytec MCFD-16), generating both amplified charge signals and amplitude-independent timing gates. Subsequently, the charge signals were fed into VME-based Charge-to-Digital converter modules (Mesytec MQDC-32). The data acquisition was performed through a frontend CPU (Power-PC RIO-3) and the MBS- and ROOT-based acquisition and analysis system MARABOU [6].

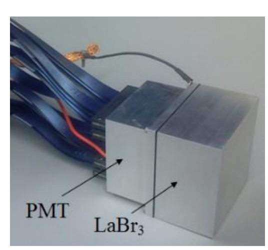

Figure 2: Monolithic LaBr3(Ce) scintillator coupled to the 256 multi-anode photo-sensitive PMT.

2.2 Spatial information from the monolithic scintillator

As described before, the Compton camera principle requires the energy and position information from both detector components. In order to determine the photon interaction position in the monolithic crystal, we applied the k-Nearest-Neighbors (k-NN) algorithm [2,5].

We studied and characterized the position determination as a function of the k-NN parameters and the PMT segmentation, extracting the spatial resolution value for each of these different parameter configurations. We also demonstrated that the "Categorical Average Pattern" (CAP) version of the algorithm provides us the best results [5].

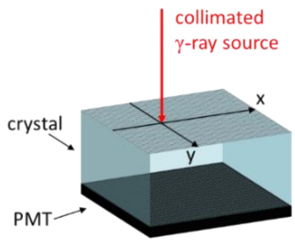

Figure 3: Scheme of the two-dimensional crystal scan with a collimated source, to compile the reference library for the k-NN algorithm.

2.3 Reference library acquisition

To apply the algorithm and retrieve the spatial resolution information, as a first step the spatially dependent detector response had to be determined by acquiring a light amplitude reference library [5]. A collimated radioactive source (Fig. 3, ^{137}Cs or ^{60}Co) was scanned across the front surface of the detector, as described in our previous work [5].

In the process of acquiring and post-processing light amplitude reference libraries, a sequence of 5 correction steps was applied on the raw data [5]: gain matching, QDC pedestal subtraction, PMT non-uniformity correction, spatial inhomogeneity correction and photopeak energy gating.

Each library corresponds to a large number of measured values, considering the 102x102 irradiation positions with the 400 photopeak events acquired at each position and the 256 channels of the PMT. We observed that among this large amount of data, artifacts could occur as pixel entries not recording a light amplitude, but just recording a zero value ("blank pixels", in Fig.4 an example is shown with blank pixels for an individual event). These artifacts were not systematically reproducible, therefore it was important to determine a procedure to assure, and if necessary restore, the integrity of the data set.

2.4 Characterization and correction of "blank pixel" events

Two kinds of "blank pixels" were identified, depending on the preceding correction steps applied to the raw data.

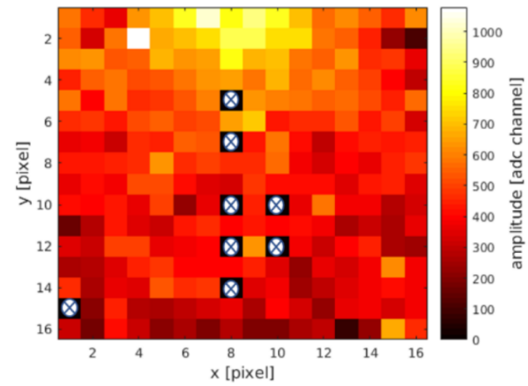

Figure 4: 2D light distribution of an individual event measured for a source position in the upper part of the crystal. "Blank pixels" were marked with crosses.

- "pedestal zeros": caused by an accidentally too high, compared to the real signal, software threshold introduced when applying the dark current ('pedestal') subtraction. Part of good signal was therefore suppressed.
- "raw zeros": zero values that appeared already in the raw data, without any software modification applied. This indicated a signal loss or an unphysically large signal exceeding the dynamic range of the QDC ('overflow' returned as zero).

To achieve a meaningful determination of the photon interaction position in the crystal, it was mandatory to reconstruct the physical contents of these pixels.

2.5 Categorical Gaussian Distributed Replacement algorithm (CGDR)

Since the source of the unphysical "blank pixels" could not be traced to a specific hardware component, we developed a software solution to reconstruct their contents in any of the measured light distributions. In order to determine the most realistic replacement value for any blank pixel independently from the source irradiation position, a study of the light amplitude distribution of all 400 events per irradiation position was performed.

The idea behind the Categorical Gaussian Distributed Replacement algorithm (CGDR) is to first identify the position of blank pixels in a given reference library and then

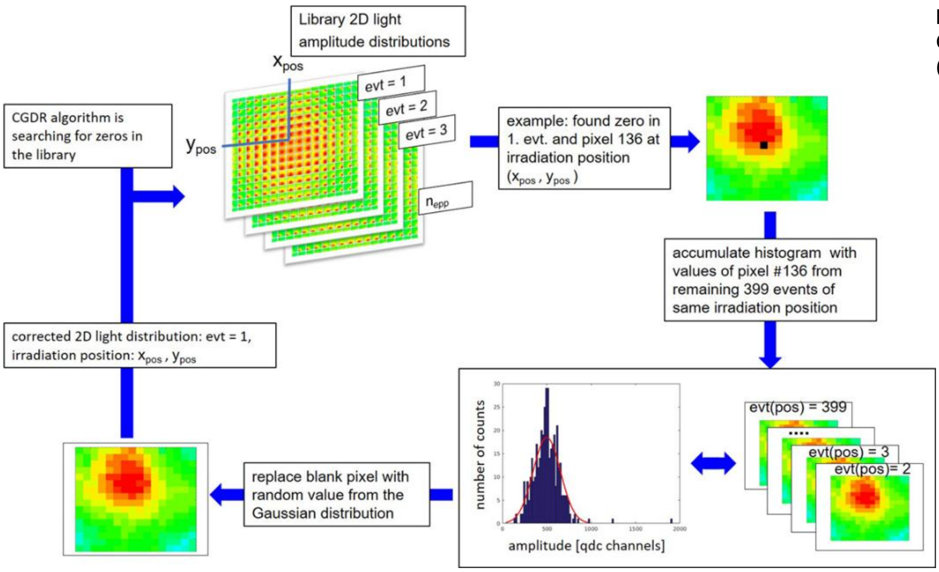

Figure 5: Flowchart of the Categorical Gaussian Distributed Replacement (CGDR) algorithm

generate the distribution of all complementary non-zero values of a specific blank pixel position amongst the overall 400 measured events per irradiation position.

We parametrized the empiric distribution using a Gaussian fit. After a normalization, to generate a probability curve, a random amplitude value was selected in the range between the standard deviation values -3σ and +3σ of the Gaussian distribution. This amplitude value was then used to replace the blank pixel value belonging to the irradiation position. A flowchart of the procedure is shown in Fig.5.

3 Results

The implementation of the CGDR algorithm provided a substantial improvement of the spatial resolution compared to a previously used simply averaging algorithm, as illustrated by Fig. 6.

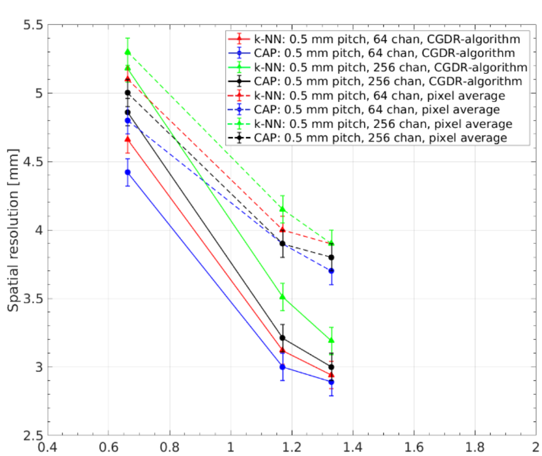

Figure 6: Comparison between spatial resolution values obtained using the CGDR algorithm and values from the previous data set.

For both evaluated PMT segmentation granularities (8x8 and 16x16), and for the highest photon energy studied (1.3 MeV), a corresponding spatial resolution of less than 3 mm was observed, thus reaching the design specification goal of the Compton camera absorber component.

4 Discussion and conclusion

A considerable improvement of the spatial resolution of the monolithic $LaBr_3$(Ce) scintillator was reached by an improved data analysis procedure. Thereby the initial design specification goal of 3 mm for the spatial resolution in the monolithic scintillator, acting as absorber component of the LMU Compton camera prototype, could be demonstrated.

Further studies will be directed towards determining the spatial resolution for even higher energies (3-6 MeV), of interest in prompt-γ medical imaging techniques.

Author's Statement

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