Maximum Likelihood Positioning for Gamma Ray Imaging Detectors with Depth of Interaction Measurement

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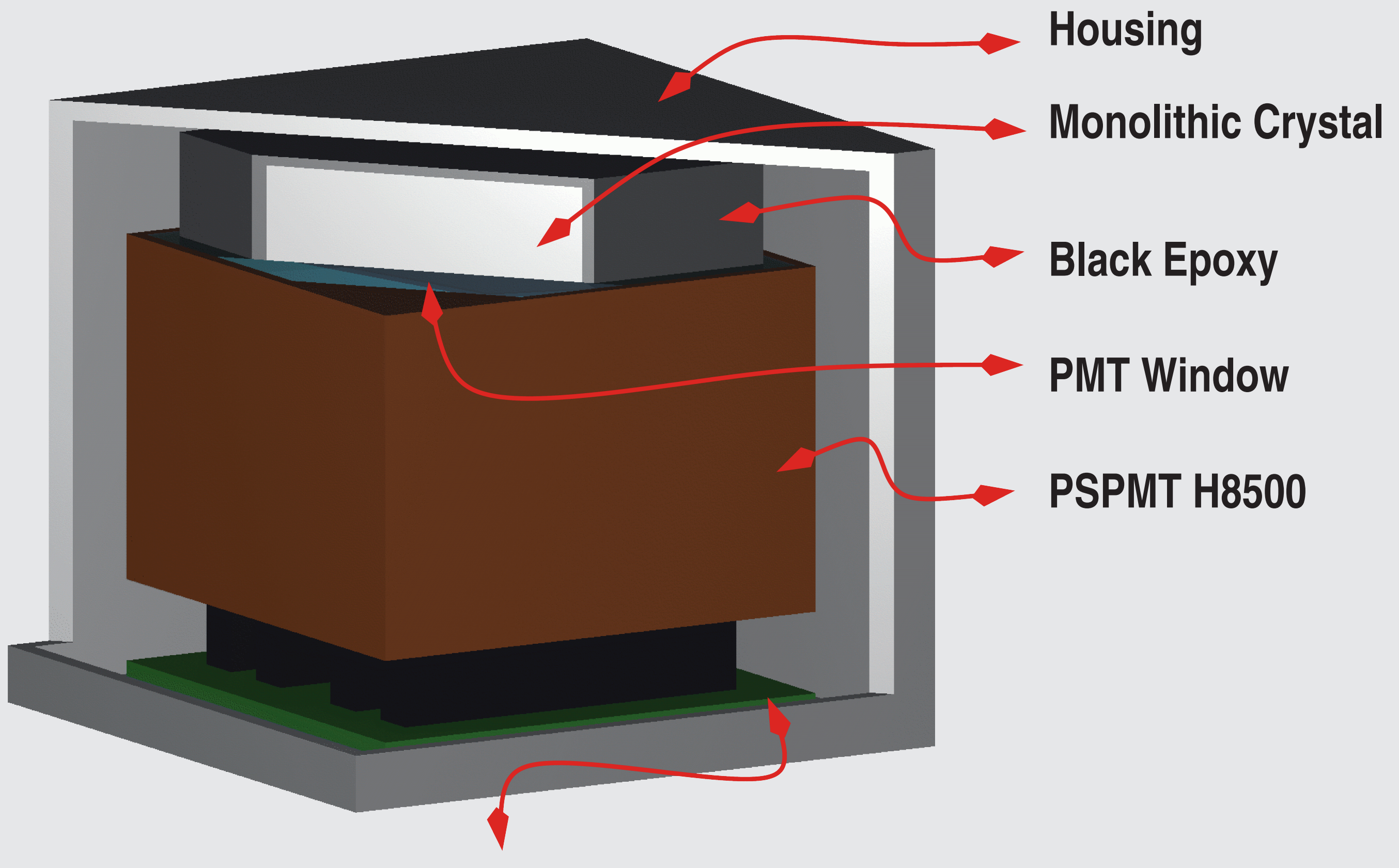
Introduction

Detector Design

Most detector designs for dedicated small animal PET scanners are based on arrays of small scintillation crystals. Disadvantages of this design are higher cost and lower detection efficiency. Alternatively, monolithic scintillation crystals together with position sensitive photomultiplier tubes (PSPMT) can be used.



Resistive Charge Divider with DOI measure

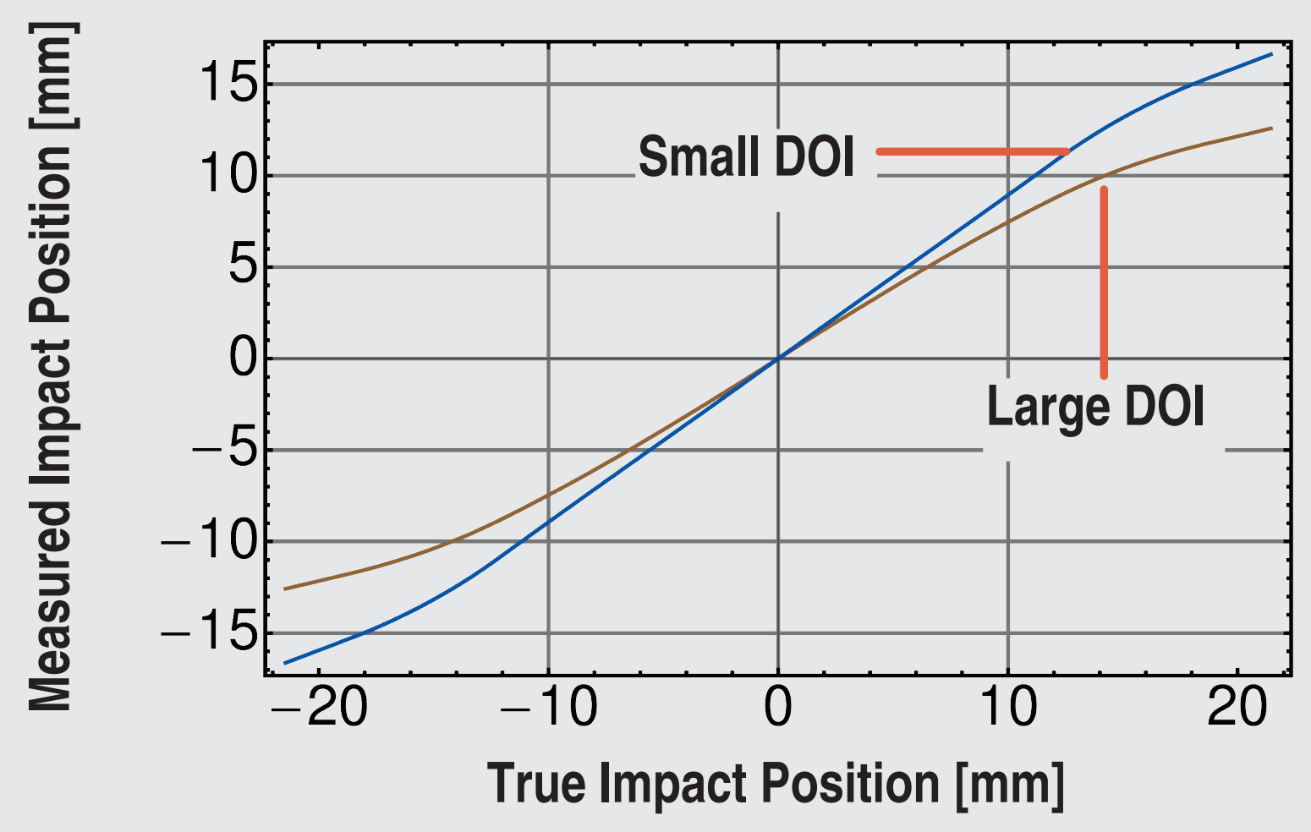
Center of Gravity Algorithm

Digitizing all PSPMT outputs corresponds to the complete sampling of the light response function (LRF) and therefore allows for highly exact 3D position estimation of the detected gamma-ray but requires a very complex and expensive data acquisition system. The center of gravity (COG) algorithm can be implemented with resistive charge division circuits (CDC) [1]. The CDC computes the lower-order moments E_{CoG} (Energy), X_{CoG} (X-Centroid), and Y_{CoG} (Y-Centroid) of the charge distribution $Q_{i,j}$. (r_0: true photo-conversion position of the detected gamma-ray, $q(r_0)$: light response function, $Q_{i,j}$: collected charge at PSPMT segment $A_{i,j}$.

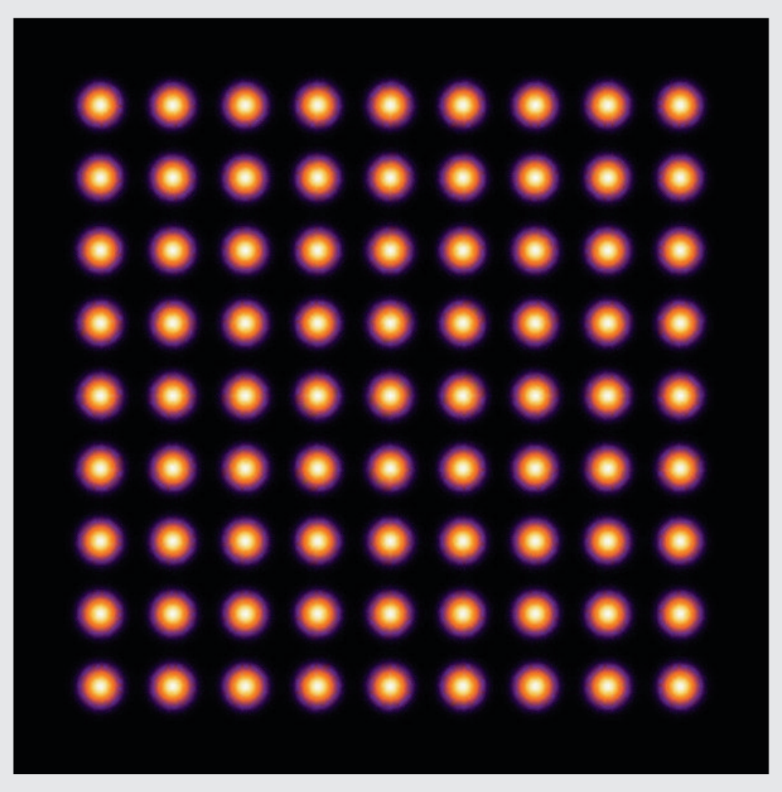
$$X_{CoG} = \mu_1^x = \frac{1}{\mu_0}\sum_{i,j}^{N,M} x_i Q_{i,j}(\mathbf{r_0}) \quad Y_{CoG} = \mu_1^y = \frac{1}{\mu_0}\sum_{i,j}^{N,M} y_i Q_{i,j}(\mathbf{r_0}) \quad \text{with} \quad E_{CoG} = \mu_0 = \sum_{i,j}^{N,M} Q_{i,j}(\mathbf{r_0}) \quad \text{and} \quad Q_{i,j}(\mathbf{r_0}) = \iint_{A_{i,j}} q(\mathbf{r_0})dxdy$$

However, the COG introduces systematic errors at the edges of the monolithic crystal which are especially severe for thick scintillators. These systematic errors are actually due to the fact that the first order moments E_{CoG}, X_{CoG} and Y_{CoG} depend on the depth of interaction (DOI). As a consequence, impacts at the same 2D position (x_0,y_0) but at different DOI will differ in their centroids.

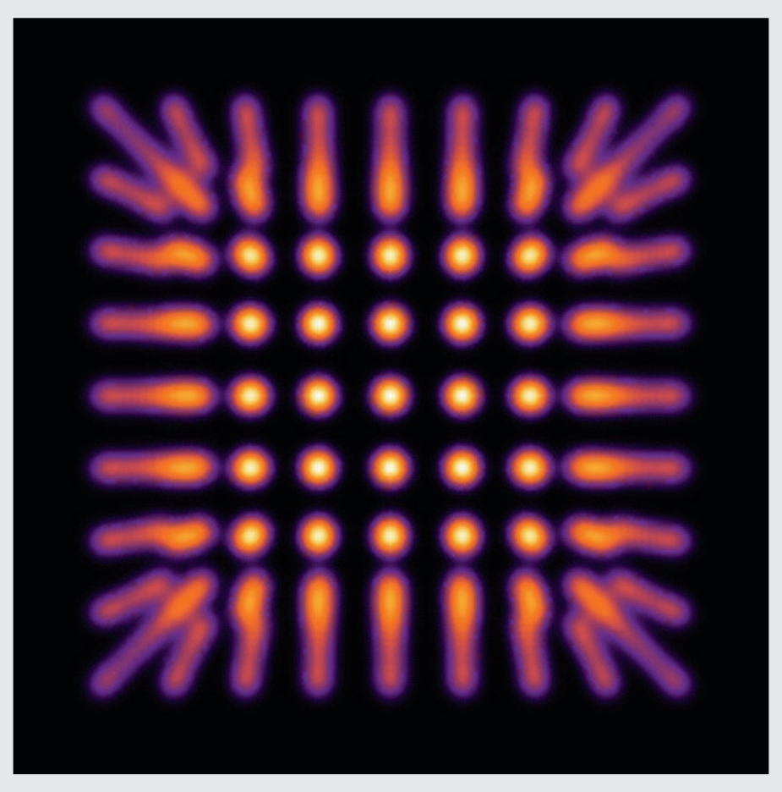
DOI Dependency of Centroids



Artifact-free Detector Response



Detector Response with CoG Artifact



Method

Recently, it was shown that the charge divider can be enhanced for simultaneously measuring the second order moment μ_2 of the LRF [2]. This allows to compute the variance var of the LRF which is approximately proportional to the DOI.

$$\mu_2 \simeq \frac{1}{\mu_0}\sum_{i,j}^{N,M}(x_i^2 + y_i^2)Q_{i,j}(\mathbf{r_0})$$

$$\text{var} \approx \mu_2 - (\mu_1^x)^2 - (\mu_1^y)^2$$

All moments (X_{CoG}, Y_{CoG}, and var) depend on x, y, and the distance d between the true photo-conversion position and the PSPMT window. This system of equations can be inverted with ML estimation as in [3,4,5]. We suppose that the probability distribution of observing the measured moments are independent Gaussian distributions with means m_1^x, m_1^y, and m_2 and errors s^x, s^y, and s^{var}. The log-likelihood is then given by a sum of mean squares that takes its maximum at $\underline{r}_0$.

$$\ln\mathcal{L} = -\left(\frac{m_1^x - \mu_1^x}{s^x}\right)^2 - \left(\frac{m_1^y - \mu_1^y}{s^y}\right)^2 - \left(\frac{m_2 - \text{var}}{s^{var}}\right)^2$$

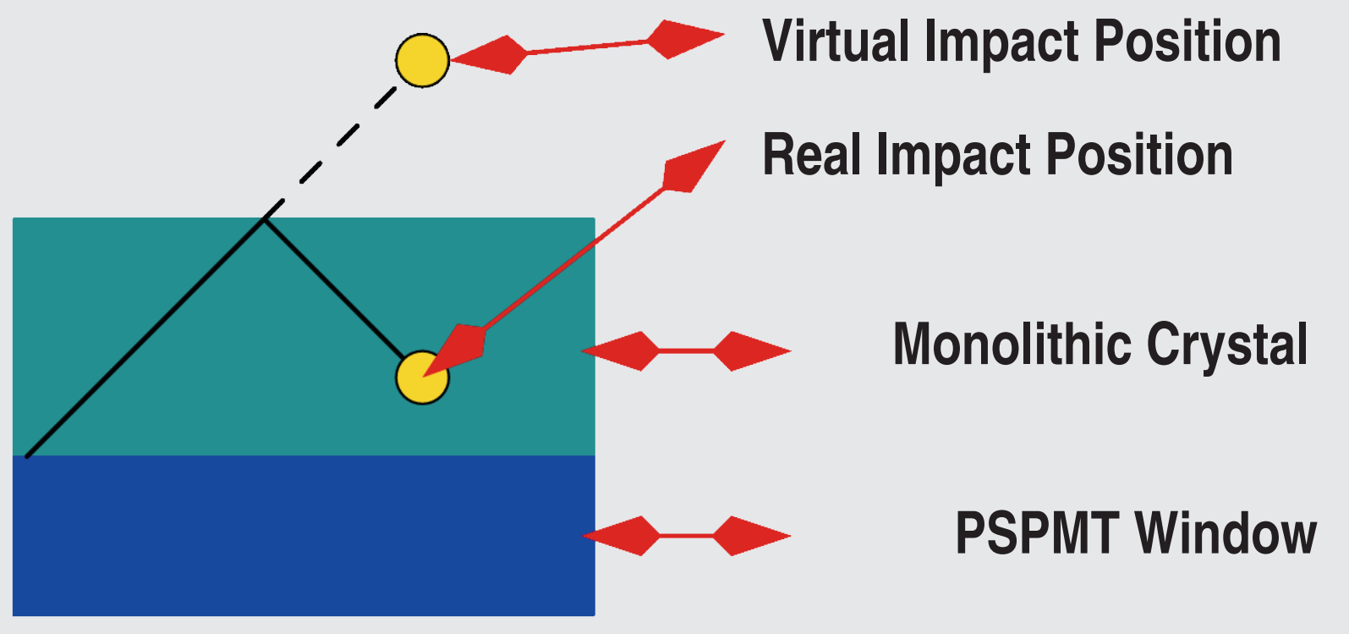
$$\underline{\mathbf{r}}_0 = \underset{\mathbf{r_0}}{\text{argmax}} \ln\mathcal{L}$$

Light Response Function

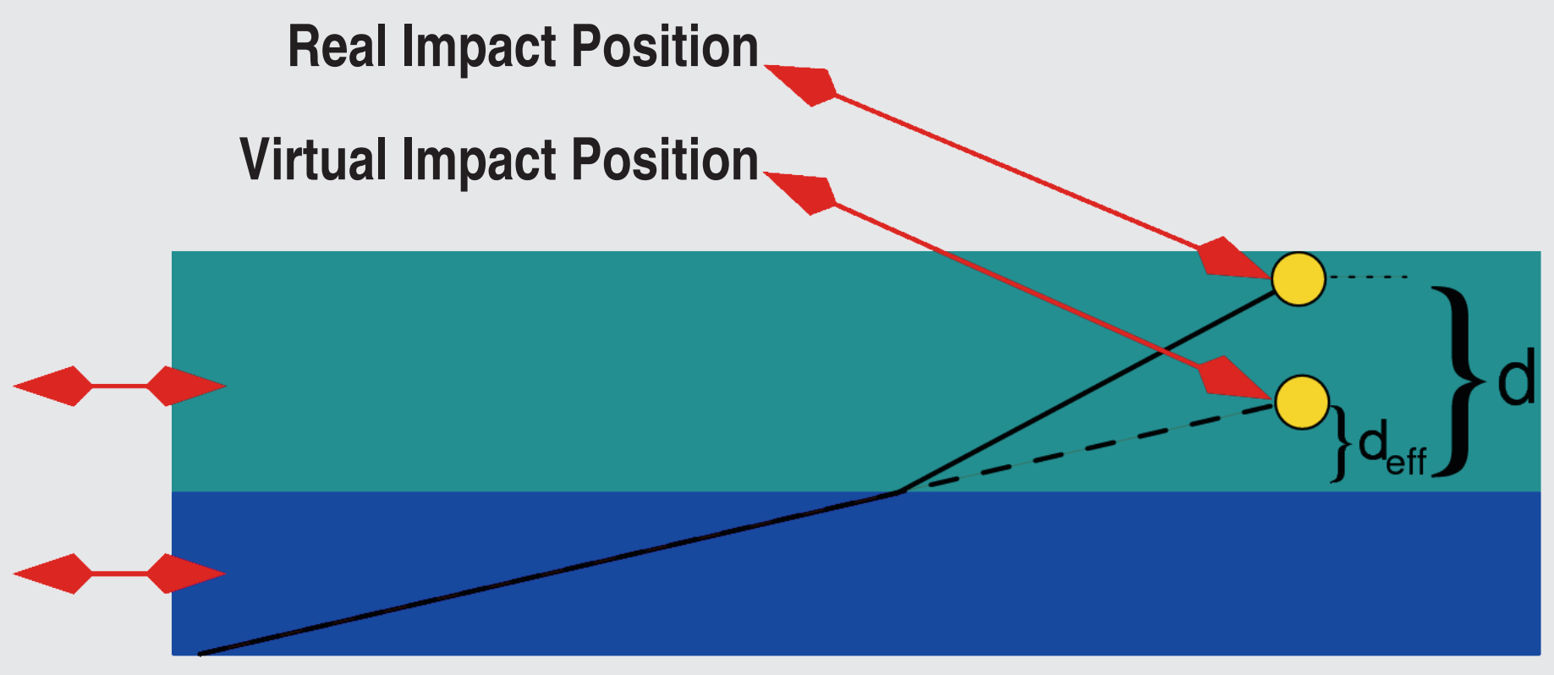
In monolithic crystals, the scintillation light transport obeys the inverse square law. However, additional effects like absorption, reflections and refraction at the optical interface formed by the crystal and the photo-detector's window have to be considered too. The LRS's moments were computed at a coarse 3D grid and trilinear interpolation is used during ML-estimation.

$$q(\mathbf{r_0}) = \frac{q_0 d_{eff}}{4\pi|\mathbf{r} - \mathbf{r_0}|^{3/2}} + \text{reflections}$$

(Specular) Reflection

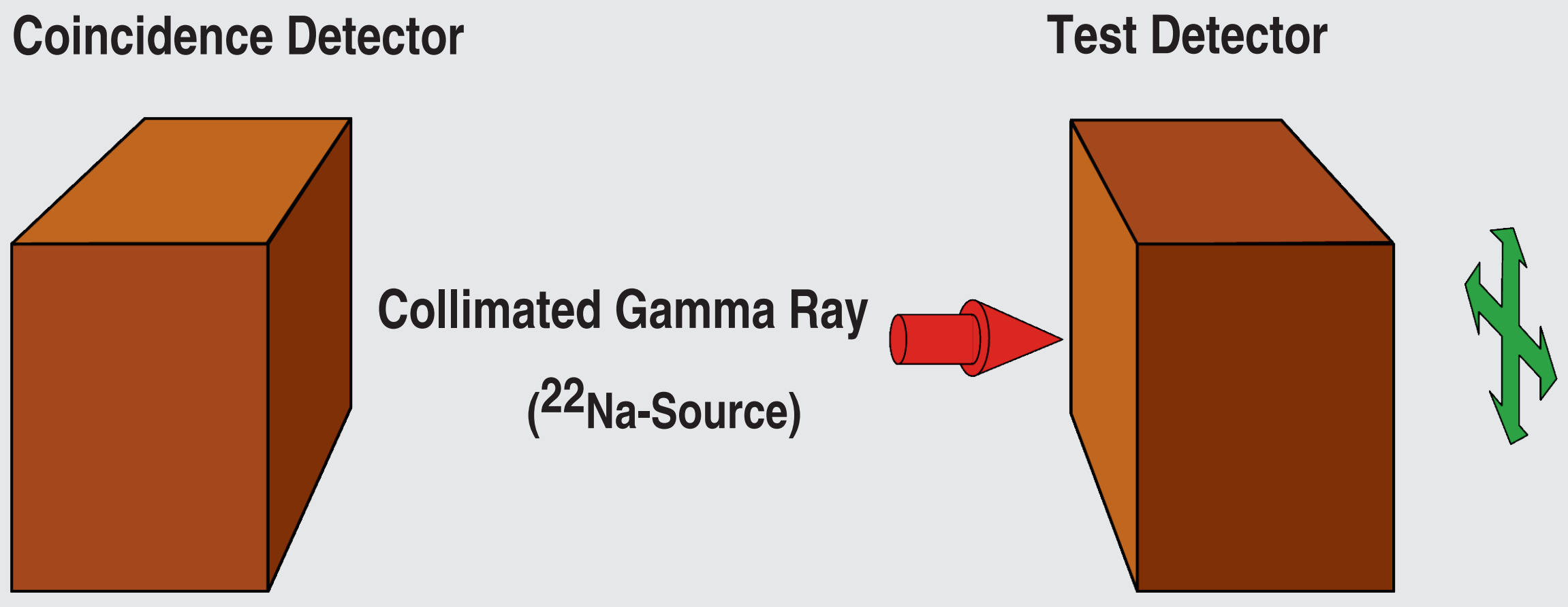


Refraction



Experimental Setup

Two identical gamma ray detectors were used to evaluate the performance of the proposed position estimation method. Each module consists of a single monolithic LSO scintillator block with spatial dimensions 42x42x10 mm^3. The five crystal surfaces that were not coupled to the PSPMT were fine ground and covered with black epoxy resin. The LSO block was coupled by optical grease to the entrance window of the H8500.

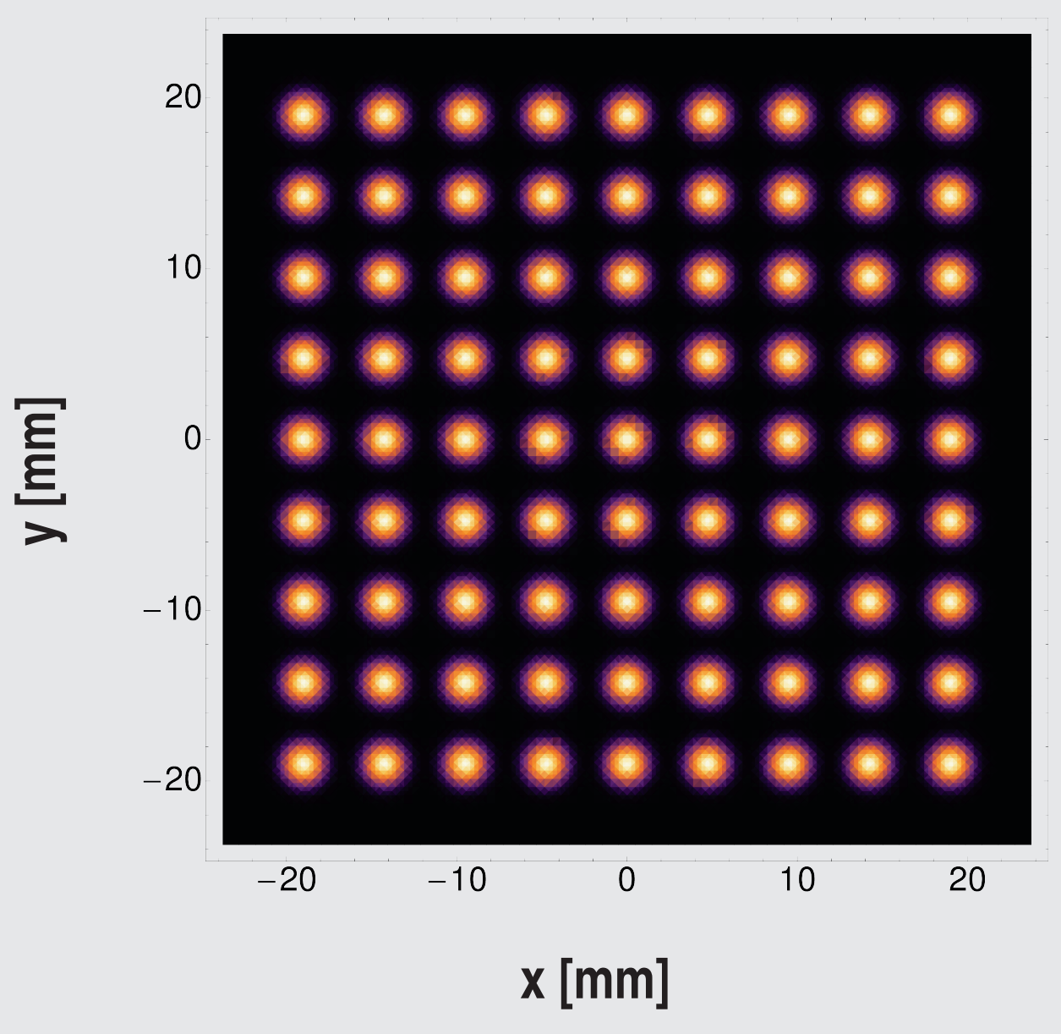


The test detector is moved to 9 x 9 different position of a regular grid with a pitch of 4.75 mm. Energy, centroids and DOI were measured at these positions. Only full-peak events are accepted. (Axis of collimated gamma ray beam is taken as z-axis).

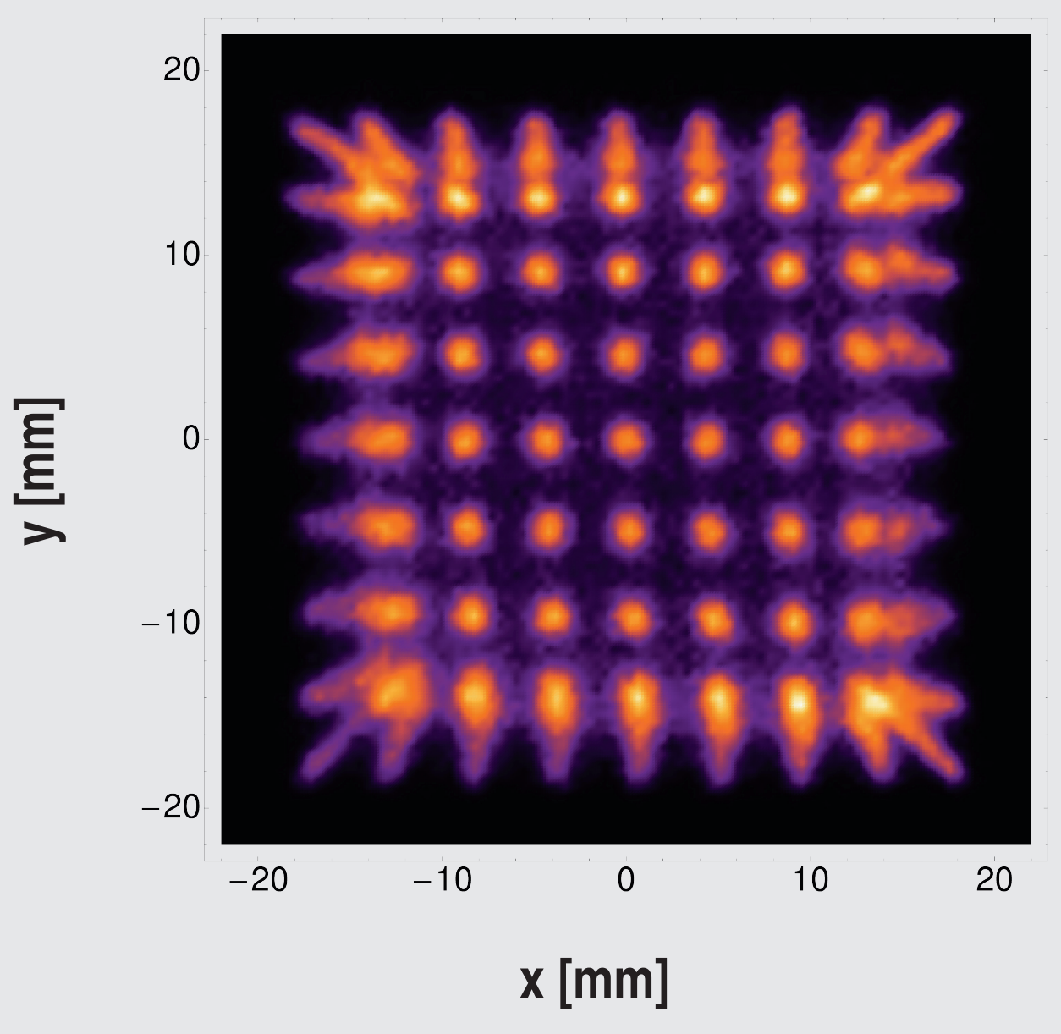
Results

The maximum search algorithm was implemented both in standard C for CPU's and with CUDA [6] for NVIDIA GPU's. By implementation for GPU's a performance gain of factor 10 is achieved. The presented method corrects the CoG artifacts only partially. This is mainly due to the simplified LRF model and a suboptimal calibration scheme. Nevertheless, almost all 81 gamma ray positions can be identified in the reconstructed image.

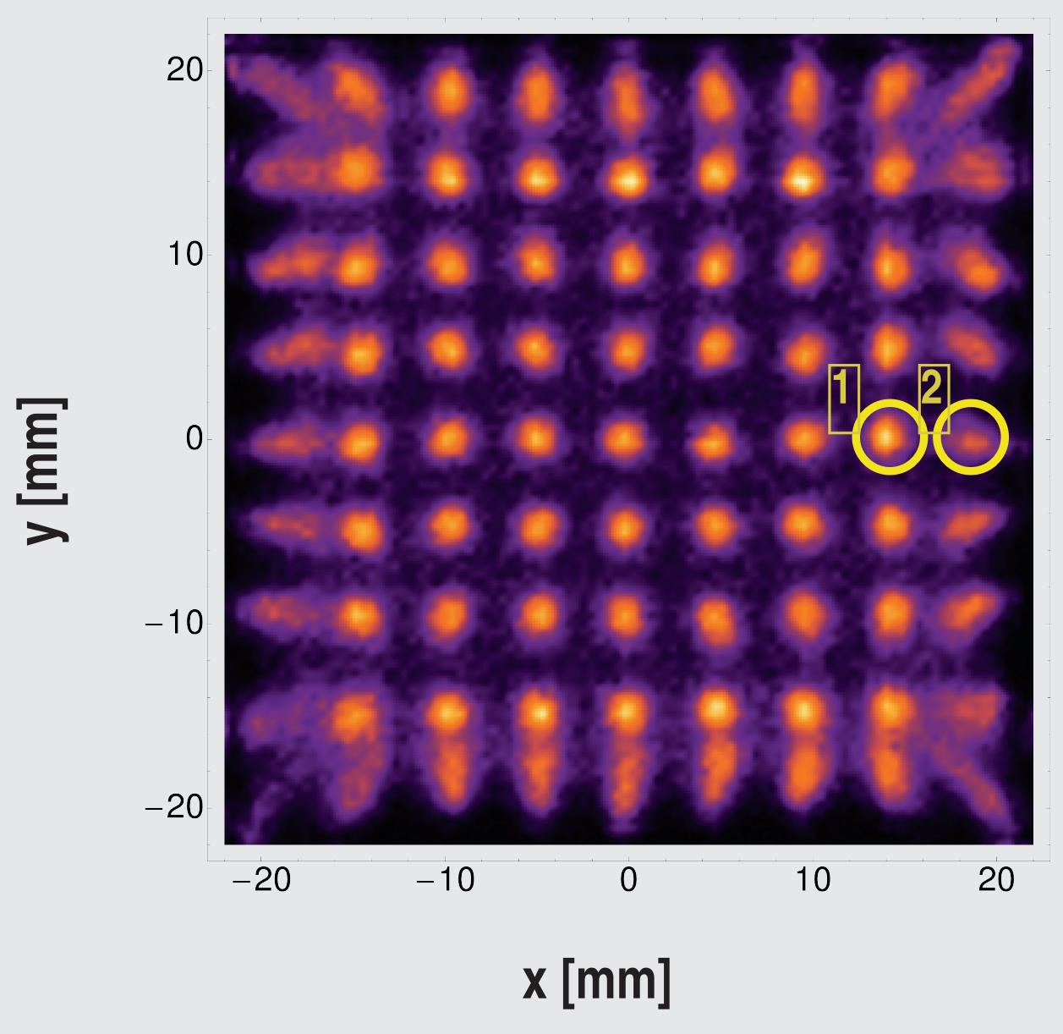
True Positions



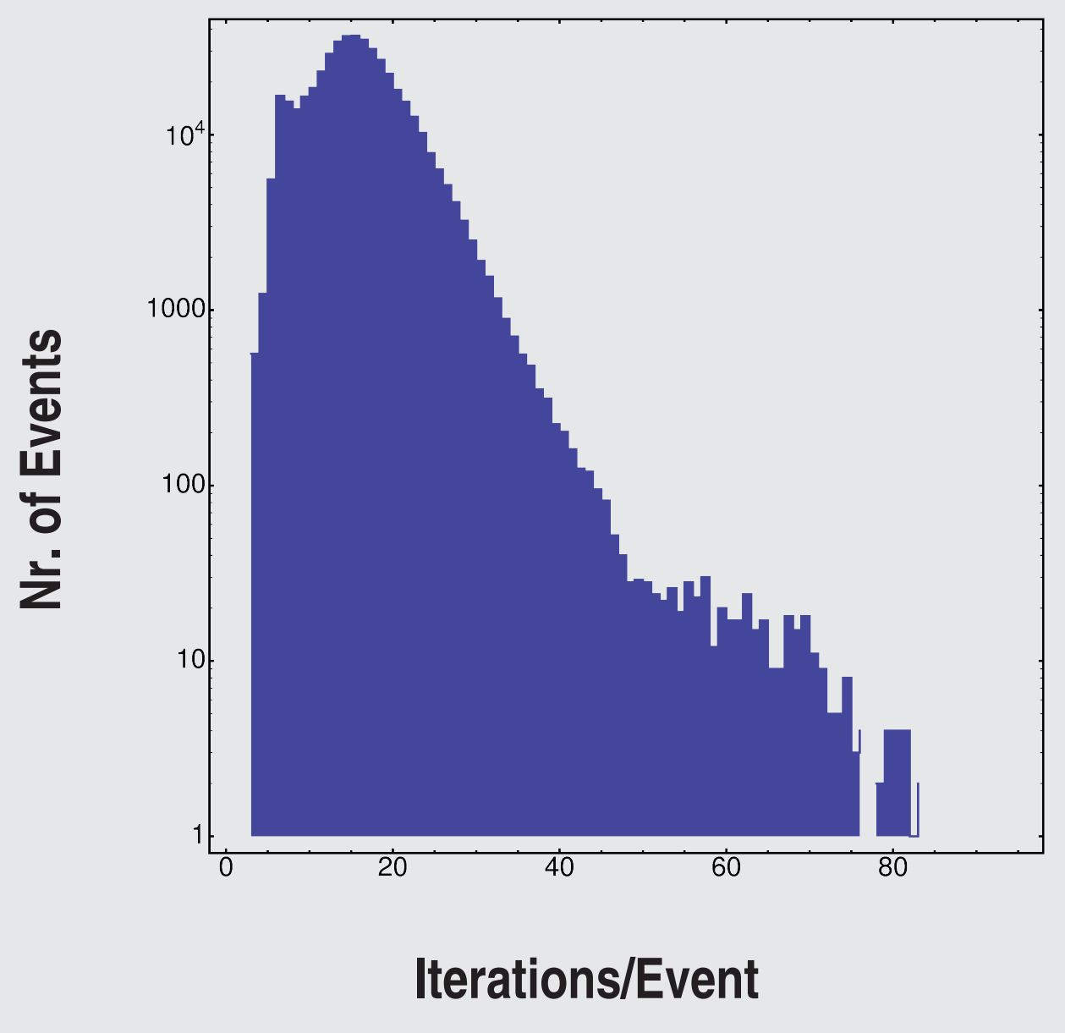
Detected Positions (Centroids)



ML-Estimates



Iterations



Spatial Resolutions at Edges

Position	Resolution (Centroids)	Resolution (ML-Estimates)
1	2.2 mm	1.7 mm
2	4.7 mm	3.5 mm

Benchmark

Processor	Events per Second
NVIDIA GeForce 8800 (multi-threaded implementation)	200000
AMD Athlon 64 X2 3800+ (single-threaded implementation)	20000

References

[1] S. Siegel et al., IEEE Trans. Nucl. Sci. 43, 1634 (1996).
[2] C. W. Lerche et al., IEEE Trans. Nucl. Sci. 52, 560 (2005).
[3] D. Gagnon et al., IEEE Trans. Med. Imag. 12, 101 (1993).
[4] S. Moehrs et al., Phys. Med. Biol. 51, 1113 (2006).
[5] J. Joung et al., Nucl. Instr. and Meth. A 489, 584 (2002).
[6] NVIDIA CUDA Programming Guide, Online available http://www.nvidia.com/object/cuda_develop.html

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