Design Optimization of the PMT-ClearPET Prototypes Based on Simulation Studies With GEANT3

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***Abstract*—Within the Crystal Clear Collaboration (CCC), four centers are developing second generation high performance small animal positron emission tomography (PET) scanners for different kinds of animals and medical applications. The first prototypes are photomultiplier tube (PMT)-based systems including depth of interaction (DOI) detection by using a phoswich layer of lutetium oxyorthosilicate (LSO) and lutetium yttrium aluminum perovskite (LuYAP). The aim of these simulation studies is to optimize sensitivity and spatial resolution of given designs, which vary in fields of view (FOVs) caused by different detector configurations (ring/octagon) and sizes. For this purpose the simulation tool GEANT3 (CERN, Geneva, Switzerland) was used.**

The simulation has shown that all PMT designs with no homogeneous axial coverage obviously have a very nonlinear corresponding axial sensitivity profile. By shifting every other detector module by a quarter of a PMT length in axial direction the sampling of the FOVs became more homogeneous. Applying an energy threshold of 350 keV, the regression coefficient increases from 0.818 for the nonshifted to 0.993 for the shifted design. Simulating a point source centered in the FOV (threshold: 350 keV) resulted in sensitivities of 4.2% for a 4 $\times$ 20PMT (LSO/LuYAP à 10 mm) and 3.8% for a 4 $\times$ 16PMT (LSO/LuYAP à 8 mm) ring design. The 3-D MLEM reconstruction of a point source shows the enormous improvement of resolution using a crystal double layer with DOI [3.1 mm at 40 mm from center FOV (CFOV)] instead of a 20 mm single layer (7.1 mm).

***Index Terms*—Axial shift, ClearPET, depth of interaction (DOI), GEANT3, LSO/LuYAP phoswich, simulation, small animal positron emission tomography (PET).**

I. Introduction

THE PrimatePET project is proposed by working groups of the Hermann von Helmholtz Association of National Research Centers (HGF centers), namely the Research Center Juelich (FZJ) and Max-Delbrueck-Center of Molecular Medicine (MDC). The aim of this project is to apply the noninvasive positron emission tomography (PET) technique to *in vivo* investigations of signal transduction in nonhuman primates under physiological conditions. While in recently developed dedicated small animal PET systems a high spatial resolution of about 2 mm was the main research interest, it has become evident that it is equally important not to sacrifice the sensitivity of the scanners since the specific activity of the radio tracers used may be limited.

In the framework of the Crystal Clear Collaboration (CCC) we are developing a second generation high performance PET scanner and use new technologies to design and build a total of five more or less identical small animal PET scanners, called ClearPET, for the associated medical institutes. For this purpose, we are currently designing prototypes based on lutetium oxyorthosilicate (LSO)/lutetium yttrium aluminum perovskite (LuYAP) [1], [2] phoswich detectors. The first prototypes will be based on detector modules coupled to multichannel photomultiplier tubes (PMTs). In parallel, work in progress aims at evaluating the potential of avalanche photodiodes that allow higher packaging fraction and higher quantum efficiency than PMTs.

The aim of this work is to perform Monte Carlo (MC) simulation studies to optimize sensitivity and spatial resolution of given designs, which vary in fields of view (FOVs) caused by different detector configuration (ring/octagon) and size. By computer based simulations it is possible to study and check several designs considering various technical specifications long before the first detector module is produced.

In the field of PET there are several public domain MC codes which can be divided into different groups. Codes like SORTEO [3] are especially written for existing scanners, in this case for the ECAT EXACT HR+. Other codes like SimSET [4], OpenGATE [5], Eidolon [6], PETSIM [7], which, in some cases, can be used for both PET and single photon emission computer tomography (SPECT), are mostly still under development and/or not sufficiently validated. EGS [8], [9] and MCNP [10], which are said to be general purpose tools, have the main focus in calorimetry.

For these reasons here the simulation tool GEANT3 [11] was used for the mentioned purpose. The GEANT3 package is a design tool for detector development in middle and high energy physics, which was developed in the 1970s at CERN (Geneva, Switzerland). It is ever since permanently updated and used by many groups around the world. The advantages of GEANT3 over the other codes are the concept of specifying volumes and materials and the intrinsic calculation of physical interactions, as the path length of photons in a medium, which, in programs like EGS, have to be programmed by the user.

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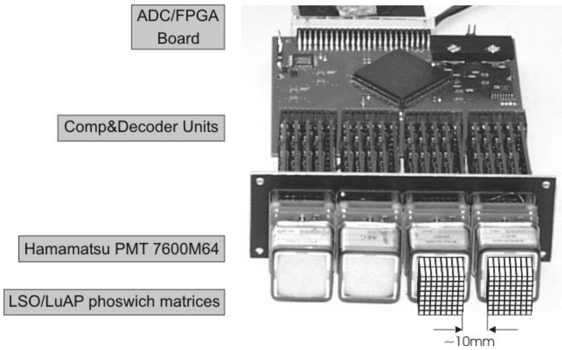

Fig. 1. PMT-ClearPET prototype detector cassettes.

II. Materials and Methods

A. PMT-ClearPET Prototype Detector Cassette

Initially the PMT prototype detector cassette was designed by arranging a unit of four multichannel PMTs (R7600M64, Hamamatsu) in-line including the corresponding front-end electronics (Fig. 1). For optimal readout the dual layer of crystals is coupled directly to the PMTs. The dual layer phoswich matrices consist of 8 $\times$ 8 LSO and LuYAP crystal elements, the latter being closest to the PMT. Each crystal element has a face surface of 2.0 $\times$ 2.0 mm^2 and the element pitch is 2.3 mm. The length of the crystals for the different ClearPET designs varies between 8 and 10 mm. As reflector material $\sim$0.3 mm Tyvek® [12] paper is used. The PMTs have a sensitive area of 18.1 $\times$ 18.1 mm^2 which is well suited for the crystal matrices. For the multiring ClearPET versions these cassettes can be arranged in different designs.

B. Monte Carlo Simulation: GEANT 3

For the simulation the different scanner designs are only composed of the crystal matrices including the reflector material. The scanners are arranged in an environment of air with no magnetic field. In the four-ring designs a PMT center-to-center distance of 28 mm in axial direction is adopted. An ideal β^+-source ignoring momentum and positron range is used and all possible interactions down to 10 keV are taken into account. The information about the energy deposition and the crystal identification is stored in a list mode file format specified by CCC. Timing information and light transmission are not provided by GEANT3.

C. Multiring Versus Multihead Design Simulation

1) Octahedron versus Ring Design: For the design of the PMT-ClearPET prototypes the axial sensitivity profile and the sensitivity in the center field of view (CFOV) were the decisive factors. For the ClearPET-Primate version a FOV of 12 cm diameter was required. This led to two possible designs, an octahedron or a ring with 24 cassettes each (Fig. 2).

2) Shifting in Axial Direction: To compensate for the 10 mm axial gaps between the crystal matrices (Fig. 1) an axial movement of either gantry or object could be considered. This would, however, decrease the temporal resolution of the system. Instead the shifting of every other detector cassette in axial direction is considered as a design parameter and the simulation was used to find the optimal translation (Fig. 3).

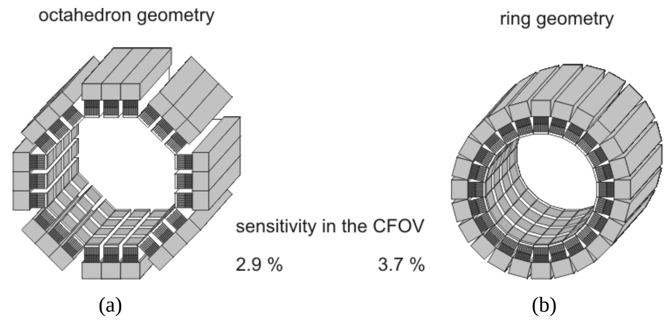

Fig. 2. Arrangements of 24 detector cassettes. An octahedron design with (a) eight detector heads three cassettes each or (b) a ring design (right).

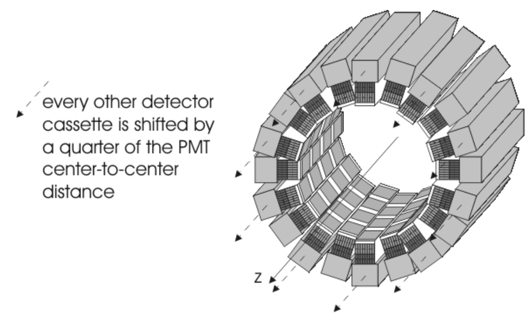

Fig. 3. In this simplified illustration of ClearPET primate version, the axial shifting of every other detector cassette in axial direction is shown. Only the PMTs and crystal matrices are shown.

D. Comparison With Existing Concorde MicroPET Designs

Beside several single ring designs the CCC also favors two four-ring ClearPET systems, one with 20 PMTs (LSO/LuYAP à 10 mm) and flexible detector diameter for primates and one with 16 PMTs per ring for rodents (LSO/LuYAP à 8 mm) both with the axial shift shown in Fig. 3. In parallel, the two microPET scanners R4 and P4, described by Tai *et al.* [13] and Concorde Microsystems [14] are simulated for comparison (Fig. 4).

1) Sensitivity: In order to study the axial sensitivity in detail, a point source in air positioned along the scanner axis and emitting 1 000 000 positrons every 2 mm is simulated.

2) Image Resolution: To determine the image resolution of the different designs six point sources are positioned separated by 1 cm starting in the CFOV, each emitting 5 000 000 positrons. Events are labeled to differentiate the crystal layer they are detected in, in order to study the influence of depth of interaction (DOI) on the image resolution. To estimate the resolution on reconstructed images a 3-D maximum likelihood expectation maximization (MLEM) algorithm [15] is used. However, no correction for normalization has been applied yet, though this should be tolerable for point sources.

III. Results

A. Multiring Versus Multihead Design Simulation

1) Octahedron versus Ring Design: In the question of multiring versus multihead design the simulations of the system's peak sensitivity show a clear significant increase from 2.9% for the octahedron to 3.7% for the ring design. The fact that the

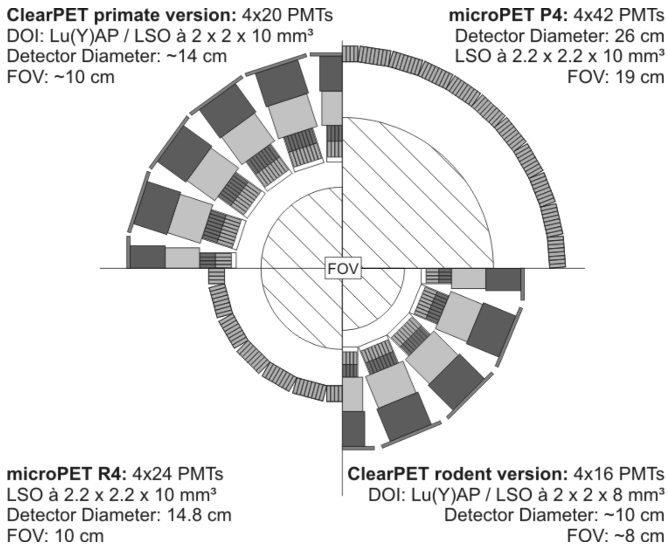

Fig. 4. Scale drawing of the proportions of the two four-ring ClearPET versions for primates (4 × 20 PMTs) and rodents (4 × 16 PMTs) compared to the two microPET systems R4 and P4.

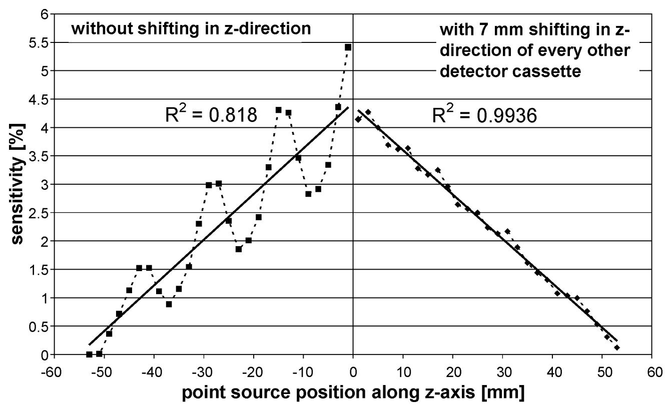

Fig. 5. Axial sensitivity profile of the nonshifted 4 × 20 PMT ClearPET ring design using an energy threshold of 350 keV. High fluctuation caused by the axial gaps (left). Linearized profile using a 7 mm axial shifting of every other detector cassette (right).

sensitivity of a ring design is about 25% higher than in an octahedron design with the same number of PMTs is the decisive factor for constructing the PMT-ClearPETs in a ring geometry.

2) Shifting in Axial Direction: All four-ring designs have a very nonlinear axial sensitivity profile with high fluctuation caused by the axial gaps (Fig. 5 left). The regression coefficient of the best fit straight line is, in the nonshifted case, 0.818. By shifting every other detector cassette by a quarter of the PMT center-to-center distance in axial direction the sensitivity profiles of the scanners can be improved considerably. Fig. 6 shows the change of the regression coefficient depending on the axial shifting. The best results can be achieved by a shift of 7 mm corresponding to 0.993 in the regression coefficient shown in Fig. 5 right.

B. Comparison With Existing Concorde MicroPET Designs

1) Sensitivity: The 20 PMT-ClearPET design for primates is a compromise between the increase of the system's peak sensitivity (3.0% to 4.2% at the CFOV with 350 keV energy threshold) and the reduction of the FOV diameter from 12 cm

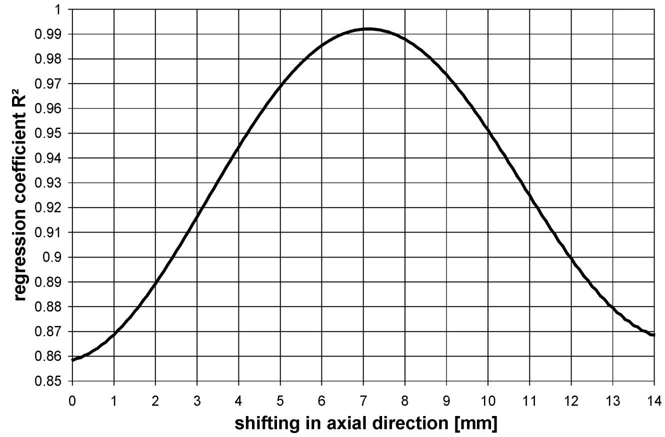

Fig. 6. The regression coefficient for the best linear fit as a function of the axial shifting. Best linearity is reached at a shifting of 7 mm, where the regression coefficient has its maximum of 0.993.

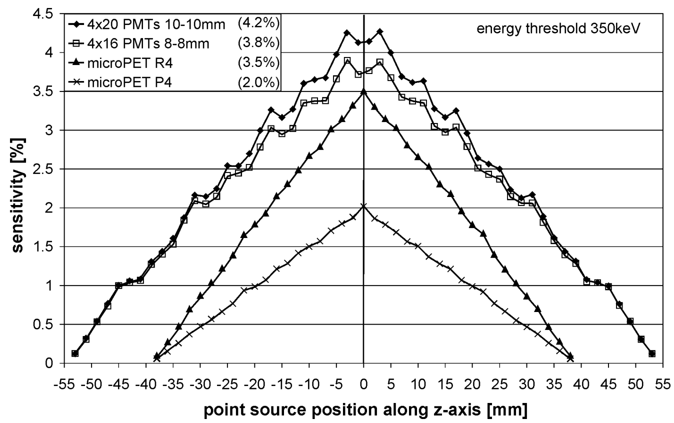

Fig. 7. Axial sensitivity profile of the shifted 4 × 20 and 4 × 16 PMT ClearPET ring designs in comparison to the axial sensitivity profiles of the two microPET designs R4 and P4 using an energy threshold of 350 keV.

to 10 cm compared to the originally planed 24 PMT design. For larger objects the FOV can be enlarged (see below). In the case of 12 cm FOV the system's peak sensitivity is still 2.7%.

Fig. 7 shows the axial sensitivity profiles of the two microPETs and the two four-ring PMT-ClearPETs. It is obvious that the microPET curves are more linear than the PMT-ClearPET curves, because of the higher crystal packaging density in axial direction. The longer crystals more than compensate for the lack of crystal packaging in the PMT-ClearPET systems. The absolute values of the system's peak sensitivity for the different designs are shown in Table I. In addition to this the ClearPET FOV's axial length (112 mm) is nearly a factor of 1.5 longer than that of the microPETs (78 mm).

2) Resolution: To determine the transaxial image resolution the uncorrected simulated list mode data are reconstructed with a 3-D MLEM reconstruction tool [6] using an energy threshold of 350 keV. A Gaussian is fit to the 2-D plots of every reconstructed point source and the full width at half maximum (FWHM) indicates the transaxial image resolution (Fig. 8).

Fig. 8 shows two reconstructed slices with six point sources in air. To study the effect of using DOI information two data sets are generated. In the radial profile a significant improvement up to 20 mm in radial distance from the center could be seen in the

TABLE I
SIMULATED SENSITIVITY OF A POINT SOURCE IN THE CFOV

	energy threshold		
4 rings à	0 keV	250 keV	350 keV
16 PMTs (8/8)	9.8 %	4.8 %	3.8 %
20 PMTs (10/10)	10.1 %	5.2 %	4.2 %
MicroPET			
R4 24 PMTs (10)	8.8 %	4.3 %	3.5 %
P4 42 PMTs (10)	5.0 %	2.5 %	2.0 %

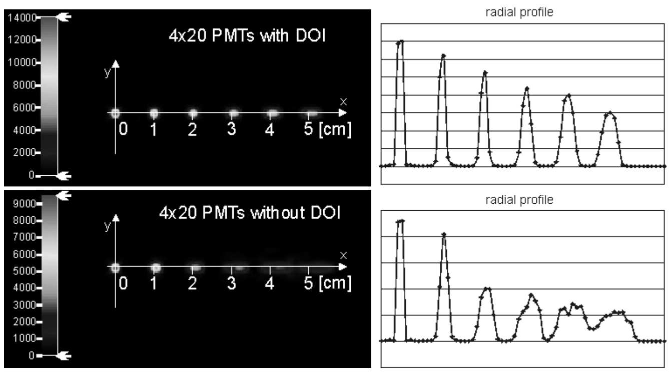

Fig. 8. Reconstructed images of the six point sources with distances of 10 mm with and without using the DOI information and their profiles.

images. In Fig. 9 the radial image resolution of the four scanners is shown as well as the resolution of the 4 $\times$ 20 PMT design using 20 mm crystals instead of evaluating DOI.

The 3-D MLEM reconstruction of a point source shows the enormous improvement in resolution using a double crystal layer for DOI detection (3.1 mm at 40 mm from CFOV) instead of a 20 mm single layer (7.1 mm).

C. Design: PMT-ClearPET Primate Version

The diameter of the detector ring can be varied between 130 and 300 mm (see Fig. 10). The gantry allows rotation of the detector modules around the field of view as well as tilting up to 90°. This design is essential for the measurement of nonhuman primates sitting in an upright position.

IV. DISCUSSION AND CONCLUSION

The simulation has shown that all PMT designs with inhomogeneous axial coverage obviously have a very nonlinear corresponding axial sensitivity profile. By shifting every other detector module by a quarter of a PMT length in axial direction the sampling of the FOVs became more homogeneous. Applying an energy threshold of 350 keV the regression coefficient increases from 0.818 for the nonshifted to 0.993 for the shifted design.

Depending on crystal length and energy threshold there are significant differences in sensitivity between the individual designs. Simulation of a point source centered in the FOV resulted in a 25% higher sensitivity for a ring design compared to an octahedron with the same number of PMTs per "ring." These results show a preference for a circular design of detector modules. The 3-D MLEM reconstruction of the point sources shows the enormous improvement in resolution using a double crystal layer for DOI detection instead of a 20 mm single layer.

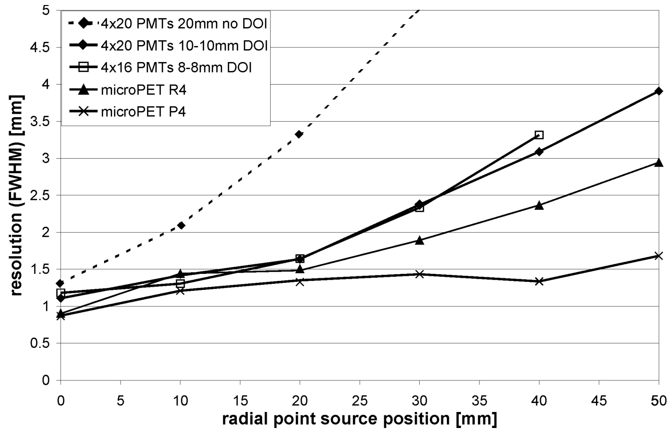

Fig. 9. Radial image resolution of the two ClearPET versions compared to the microPET designs. Furthermore the resolution of a 4 $\times$ 20 PMT ring design with 20 mm crystals instead of a dual layer with 10 and 10 mm and using DOI is shown.

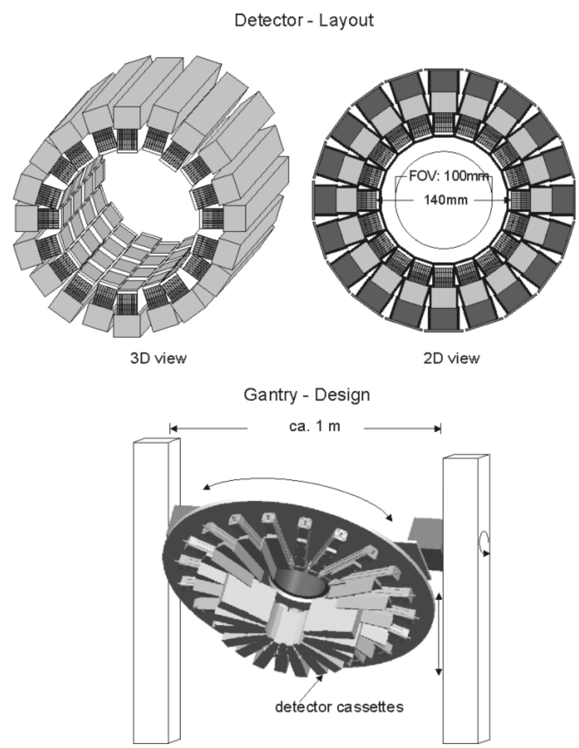

Fig. 10. Design of the PMT-ClearPET primate version. 3-D view of the shifting in axial direction, 2-D view of the layout including the front-end electronics, and a 3-D view of the flexible gantry.

Some of the design calculations have also been performed based on the GEANT4 package and were consistent with those above.

On the basis of simulation studies with GEANT3, we have successfully improved the axial sensitivity curves. These results are used for design decision in the PrimatePET project.

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