HIGH RESOLUTION 3D BRAIN PET WITH HYBRID PHOTON DETECTORS

M. CHAMIZO LLATAS
Université de Genève, 24 Quai E. Ansermet, CH-1211 Genève 4, Switzerland
E-mail: Maria.Chamizo@cern.ch

A. BRAEM, E. CHESI, C. JORAM, S. MATHOT, J. SEGUINOT, P. WEILHAMMER
CERN, CH-1211 Genève 23, Switzerland

F. GARIBALDI
ISS, Rome, Italy

E. NAPPI
INFN-Bari, Italy

F. SCHOENAHL, H. ZAIDI
HUG, CH-1211 Genève, Switzerland

The design of a high resolution 3 dimensional brain PET is presented. Thanks to its novel geometry a 3D measurement of the gamma interaction point in the detector is possible. Each 3D PET camera module consists of a matrix of long scintillation crystals, axially oriented, readout on both sides by Hybrid Photon Detectors. This concept leads to an image reconstruction free of parallax error and provides a uniform spatial and energy resolution over the whole sensitive volume. Furthermore it allows to enhance sensitivity by reconstructing a substantial fraction of the gamma quanta that underwent Compton scattering in the detectors.

1. Introduction

Positron Emission Tomography (PET) is a non invasive diagnosis technique to measure the metabolic activity of cells inside the human body. The patient is injected a radio-pharmaceutical compound (FDG, water, ammonia) labeled with a β^+ emitting radio-nuclide (^{18}F, ^{11}C, ^{13}N, ^{15}O, ...). The positron annihilates with a nearby electron creating two 511 KeV photons flying in opposite directions. From the signals collected in the detector the β^+ emission point is reconstructed using computed tomography. During the past years an increasing effort has been done to improve the sensitivity and resolution of such scanners[1]. In this perspective we propose a novel and innovative 3 dimensional brain PET that allows an image reconstruction free of any parallax error and provides a uniform resolution over the whole sensitive volume.

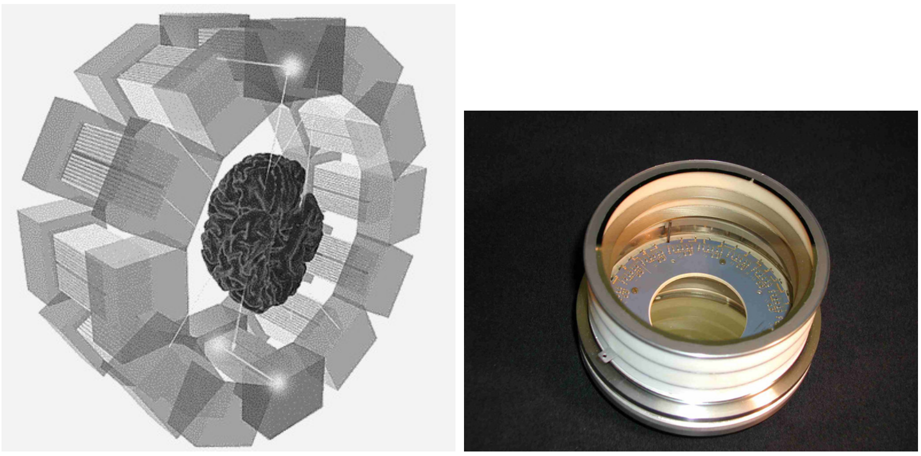

Figure 1. Left: axial view of the 3D HPD brain PET. Right: Hybrid Photon Detector, 5 inch diameter, built at CERN. At the top there is the entrance window and at the bottom one can see the electronics

2. 3D axial PET

Current PET scanners consist of rings of scintillating crystal (BGO, LSO, GSO) radially oriented and readout on the backside by standard photomultiplier tubes. The Depth Of Interaction (DOI) is not measured and gives rise to intrinsic parallax errors in the image reconstruction. To reduce this effect the radial length of the crystal is kept small compromising strongly the detection efficiency. The latest solutions overcome this problem by using the *phoswich* approach[2].

Our 3D axial PET[a] is composed of a ring arrangement of detector modules axially oriented as shown in figure 1. Each module consists of a matrix

[a]Patent applied CERN PCT/EP 02/07967

of scintillating crystals (13×16 crystals) of dimensions $3.2 \times 3.2 \times 100\,\mathrm{mm}^3$, readout on both sides by Hybrid Photon Detectors[3] (HPD). According to the crystal choice the number of rows of the matrix can be adjusted to maximize the gamma absorption (typically 2 or 3 gamma attenuation lengths) without affecting the trans-axial resolution. The photon interaction point in the (x,y) plane is obtained from the address of the crystal hit and the z coordinate is calculated using the ratio of the charges collected in each HPD using the following relation:

$$z = \frac{1}{2}\left(L + \kappa_g \lambda_a log(Q_R/Q_L)\right) \tag{1}$$

$$\kappa_g = \left\langle \frac{z_{eff}}{z} \right\rangle \approx 0.8 \tag{2}$$

where κ_g is a geometrical factor, λ_a is the light absorption length of the crystal, L the crystal dimension along the z direction, and Q_R and Q_L are the charges collected in each of the HPDs.

The highly segmented geometry and the good energy resolution of the HPDs allows the reconstruction of multiple interactions. The possibility of recovering events that underwent Compton scattering in the crystal matrix may increase the detection probability by a factor two.

Hybrid Photon Detectors

The photon detectors planed to be used in this prototype PET camera were originally developed for HEP experiments. They combine the high sensitivity of standard photo-multipliers and the excellent spatial and energy resolution of a Silicon sensor. HPDs are made of a ceramic vacuum tube, capped with a transparent front window[b] of 1.8 mm thick on which a photocathode has been deposited by evaporation at the inner side. Following the absorption of a photon an electron from the photo-cathode is emitted. Two focusing electrodes create a uniform electric field (∼12 KeV) that accelerates the electron toward a silicon sensor. The electron is stopped in the depleted silicon creating ∼3000 electron-hole pairs that allow an excellent energy resolution. The silicon sensor is segmented to match exactly the scintillating crystal matrix. For our 3D PET module we are planning to use 208 silicon pads of $4x4$ mm^2 together with a self-triggering chip that should have a dynamic range of 300 fC (1.2 pC) for YAP ($LaBr_3$) crystals.

[b]The entrance window should have a refraction index similar to the PET crystals. A sapphire entrance window for YAP crystals is the best option.

The characterization of the first ceramic HPD has been done using a silicon pad detector with 2048 pads of dimensions 1×1 mm^2. The quantum efficiency using a bi-alkali photo-cathode is $\sim$ 22% and a perfect 1:1 correspondence is observed between the silicon and the photo-cathode coordinates.

2.1. *Scintillating crystals*

To build a fast and sensitive PET it is also necessary to have crystals with high light yield, high photo-fraction and fast decay time. The properties of several candidates are listed in table 1. YAP is good for proof of principle although it suffers from low photo-fraction. $LaBr_3$ and LSO have also been studied but they were not available at the time of writing this paper.

Table 1. Characteristics of YAP, LSO, $LaBr_3$ and LuAP crystals.

	YAP	LSO	LuAP	$LaBr_3$
Density ρ (g/cm^3)	5.55	7.4	8.34	5.3
Effective atomic charge Z	32	66	65	46.9
Scintillation light output (photons/MeV)	18000	23000	10000	61000
Wavelength of max. emission (nm)	370	420	370	356
Refractive index n at wavelength of max. emission	1.94	1.82	1.95	1.88
Bulk light absorption length λ_a (cm) at 370 nm	$\sim$14	$\sim$20		
Principal decay time	27	40	38	30$\pm$5
Mean γ attenuation length at 511 KeV (mm)	22.4	11.5	10.5	$\sim$20
Photo-fraction at 511 KeV (%)	4.5	32.5	30.5	15
Energy resolution at 663 KeV	4.5	8		2.9

3. Performance estimates of the 3D axial PET

The performances of the 3D axial PET have been estimated using analytical calculations and Monte Carlo simulation (GEANT4 and EGS4). All the results presented in table 2 have been estimated using YAP crystals and a sapphire entrance window for the HPD. The energy resolution is $\sim$ 7% FWHM and the spatial resolution in the trans-axial and axial plane are 1.5-2.2 m and 4.5 mm FWHM respectively. These are very promising results and will certainly be improved when using the best choice of scintillating crystals.

Table 2. Performance estimates of the 3D HPD-PET.

	Expected performance using YAP
Detected photo-electrons per HPD	540-625
Energy resolution (FWHM)	7-7.5%
Spatial resolution trans-axial plane (FWHM)	1.5-2.2 mm
Spatial resolution axial plane (FWHM)	4.5 mm
Coincidence interval	$\sim$5 ns
Compton gain	$\sim$ 2
Sensitivity (10 cm AFOV)	3-4 cps/kBq
NEC	130 kcps

4. Characterization of YAP crystals

A set of YAP crystals of dimensions $3.2\times3.2\times100$ mm^3 has been fabricated by the Czech enterprise Crytur. The characterization of their optical properties has started using ^{137}Cs and two Hamamatsu R1535 photo-multipliers as readout. The measured energy resolution for E_γ=662 KeV is 10.6% FWHM, in agreement with the expectations for such a experimental set-up. The measured light absorption length is 27.9 cm, a factor two higher than the values reported in the literature[4]. This would lead to a higher light yield and therefore an improved energy resolution when using the HPD with sapphire entrance window. On the other hand the z charge asymmetry decreases and results in a degraded z resolution of $\sim$ 11 mm FWHM. Possible solutions to make YAP crystals less transparent are under investigation.

5. Conclusions

A new 3D PET scanner free of parallax error is proposed providing a uniform spatial resolution in all dimensions. The 3D axial concept overcomes the resolution versus sensitivity dilemma, inherent to conventional PET designs. Moreover Compton enhancement can be used to increase sensitivity by a factor two. The first characterization of the crystals and Hybrid Photon Detectors looks very promising.

References

1. A. Chatziioannou *et al Nucl. Med.* ***38*** *1164-75 (1999); G. Di Domenico et al Nucl. Inst. Meth.* ***A 447****505 (2002).*
2. *K. Wienhard et al IEEE Trans. Nucl. Sci.* ***49*** *104-10 (2002)*
3. *A. Braem et al Nucl. Instr. Meth. Phys. Res.* ***A497*** *202 (2003)*
4. *S. Baccaro et al Nucl. Instr. Meth.* ***A406*** *479 (1998)*