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Determination of the map of efficiency of the Jagiellonian Positron Emission Tomograph (J-PET) detector with the GATE package

Abstract: A novel PET detector consisting of strips of polymer scintillators is being developed by the Jagiellonian Positron Emission Tomograph (J-PET) collaboration. The map of efficiency and the map of geometrical acceptance of the two-strip J-PET scanner are presented. The map of efficiency was determined using the Monte Carlo simulation software GEANT4 Application for Tomographic Emission (GATE), which is based on GEANT4. Both maps were compared using a method based on the χ^2-test.

Keywords: GEANT4 Application for Tomographic Emission (GATE); map of efficiency; strip time-of-flight positron emission tomography.

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Introduction

The GEANT4 Application for Tomographic Emission (GATE) represents one of the most advanced specialized software packages for simulations [1] of positron emission tomography (PET) scanners [2]. GEANT4 is a toolkit for simulation of the passage of particles through matter using Monte Carlo methods [3]. Despite its complexity, GATE is easily configurable using script language.

In GATE, there are many tools for designing PET scanners: repeaters that allow to design periodic structures of scanners, the possibility of usage of advanced four-dimensional phantoms, or the ability to simulate time-dependent phenomena (such as breathing or changing of source activity). Owing to its simplicity and configurability, the GATE package is used in many disciplines of medical physics to simulate complex devices or therapies. It can also be successfully used in the simulations of the Jagiellonian Positron Emission Tomograph (J-PET) device.

The J-PET [4–6] device is a prototype PET scanner that uses plastic scintillators. Its main advantage, in comparison to known solutions, is the possibility of scanning a three-dimensional (3D) region of the patient, not only a two-dimensional (2D) slice. It will be also much cheaper than existing scanners.

The prototype scanner is planned to be made of detectors placed on the lateral area of the cylinder with a diameter of 70 cm. The axis of each detector is parallel to the axis of the cylinder. Each detector is made of one strip of plastic scintillator and two photomultipliers attached to its ends (more details about the structure of the J-PET device in ref. [4]).

The aim of this work was to determine the 3D map of efficiency of the two-strip J-PET system and to prepare a tool for computing the map of efficiency for systems made of more than two detectors. However, it is important to stress that because of the axial symmetry of the J-PET scanner, a two-strip module should reflect the main features of the full detector setup.

The map of efficiency is important for determining the maximum spatial resolution that could be achieved in the J-PET scanner. It will also help in understanding some of the effects related with the physical limitations of the spatial resolution in the J-PET scanner. In general, the efficiency map is instrumental for the optimization of the detector's performance.

Map of efficiency

Assume that the points of annihilation (points of generation of back-to-back γ quanta) are generated uniformly in the region of the cylinder with length Z_0 and radius R_0. This cylinder represents the inside of the PET scanner. The inner space of this cylinder is virtually discretized into voxels with size dx×dy×dz (where dx=dy=dz=0.5 cm and dx×dy is the fragment of the cross section of the cylinder). The 3D map of efficiency is defined as

$$f_{\text{eff}}(x,y,z)=\frac{N_{\text{det}}(x,y,z)}{N_{\text{gen}}(x,y,z)}, \tag{1}$$

where (x, y, z) are the spatial coordinates of the center of the voxel, N_{gen} is the number of all annihilations generated in the voxel, and N_{det} is the number of annihilations that could be classified as events (scintillations were detected in two detectors – voltage signals occurred in four photomultipliers attached to two different scintillators).

For the two-strip J-PET system (Figure 1), we simplify the definition above. The points of annihilation must be generated only in the rectangular region between the two walls of both scintillators. The annihilation generated outside this region cannot be detected. There may also be some angular cuts for the directions of the generated back-to-back γ quanta. These directions should ensure that at least one of the quanta will hit one of the scintillators.

The 3D voxels may be replaced with the 2D pixels (with size dx×dz) of the plane that passes through both scintillators.

Geometrical acceptance

Geometrical acceptance does not include any physical effects such as interaction of the γ quanta with the material of the scintillators. The 2D map of geometrical acceptance of the two-strip J-PET scanner was simulated independently of the GATE software using a dedicated program based on the Monte Carlo method and written by the authors.

Inside the rectangular region with a size of 70×50 cm, the point of annihilation was chosen randomly. After which, the direction of the back-to-back γ quanta was randomized. If the line with the chosen direction crossing the point of annihilation was also crossing both the shorter edges of the rectangle (corresponding to the scintillators), this case was treated as an event and was added to a histogram. The method of calculating geometrical acceptance is illustrated in Figure 2.

The 2D map of geometrical acceptance may be defined as

$$f_{\text{acc}}(x,z)=\frac{N_{\text{acc}}(x,z)}{N_{\text{gen}}(x,z)}, \tag{2}$$

where (x, z) are the spatial coordinates of the center of the pixel (y=0), N_{gen} is the number of all the annihilations generated in the pixel, and N_{acc} is the number of all events caused by the annihilations from the pixel.

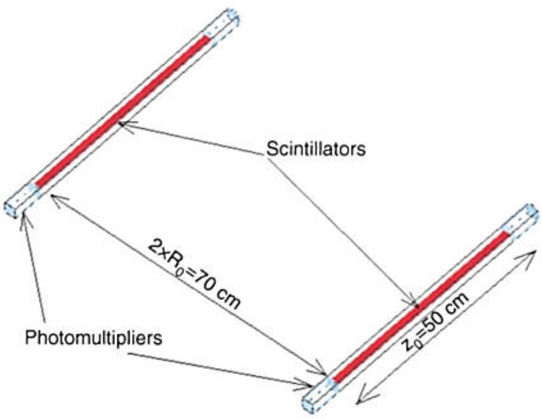

Figure 1 Visualization of the two-strip J-PET system.

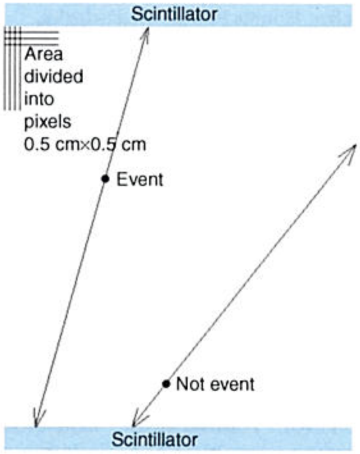

Figure 2 Method of estimating geometrical acceptance.

Table 1 Features of the EJ230 material [7].

Feature	Value
State	Solid
Density	1.023 g/cm³
Scintillation yield	10,240 MeV⁻¹
Refractive index	1.58
Absorption length	110 cm

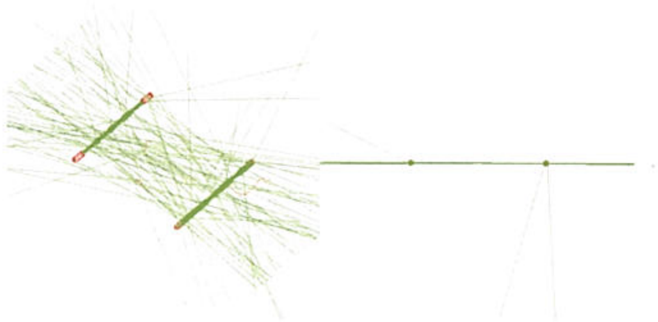

Figure 4 Visualization of the simulation of the two-strip J-PET system using the GATE software.
Lines represent the back-to-back γ quanta. Some of the γ quanta underwent scattering in the detector. (Left) Perspective view of the two-strip system. (Right) Cross section in the plane perpendicular to the tomograph axis.

Description of the simulation setup in the GATE software

In simulations, a substance called EJ230 was used as a material of the scintillators. The approximate chemical composition of this hydrocarbon polymer is $C_{10}H_{11}$. Some of its features are presented in Table 1.

Each scintillator is cuboid, with length of 50 cm and a rectangular cross section of 5×19 mm. The center of the scintillator was placed in the zero of the *x*-axis, and the scintillator was parallel to the *z*-axis of the coordinate system (Figure 3).

In the simulation, the photomultipliers are modeled as dielectric-metal interfaces. All optical photons hitting these surfaces are assumed to be detected. The distance between two detectors (each detector consists of one scintillator and two photomultipliers) was 70 cm.

The source of the back-to-back γ quanta was a rectangular region stretched between two scintillators (walls 5 mm×50 cm). Its size was 70 cm×50 cm×5 mm, and the γ quanta had energy of 511 keV (source illustrated in Figure 4). To speed the simulation, some limitations on the direction of the generated γ quanta were used.

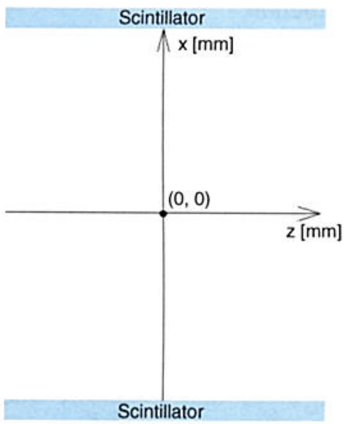

Figure 3 System of the two-detector scanner in GATE coordinate system.

The following physical processes were simulated: Compton effect, electron ionization, multiple electron scattering, fluorescence, optical absorption, scintillation, and boundary effects.

The simulation was performed using computing cluster at Świerk Computing Centre Project (CIŚ) at the National Centre for Nuclear Research.

Owing to the analysis of the ROOT [8] output, which was obtained with GATE software (version 6.2), the map of efficiency was calculated using specialized tools developed in Python and C++. Furthermore, some additional properties of the studied system could be checked such as wavelength spectrum of photons that were detected by dielectric-metal surfaces (Figure 5). This exercise showed

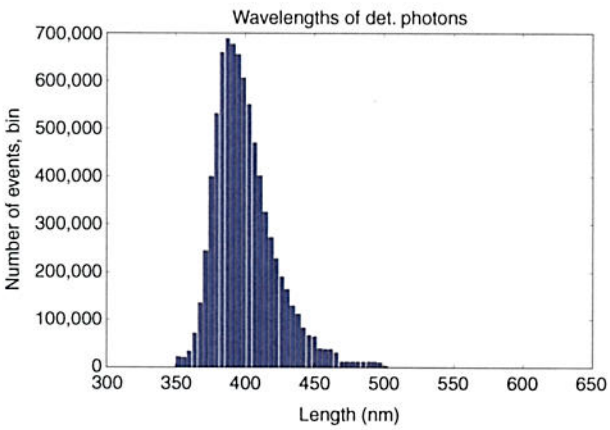

Figure 5 Distribution of wavelengths of photons detected by dielectric-metal surfaces (photomultipliers) using the GATE software: histogram of 8 mln of photons.
Wavelengths accepted by photomultipliers R4998 range between 300 and 650 nm.

that the wavelengths of the generated photons are consistent with the wavelength accepted by photomultipliers used in the prototype J-PET device (Hamamatsu R4998 [9]). Furthermore, the emission spectrum of scintillator simulated in GATE software is in accordance with the spectrum obtained in the experiment.

Results and discussion

The map of geometrical acceptance was calculated using 100 mln generated points of annihilation. The rectangle was divided into 14,000 bins with a size of 0.5×0.5 cm, which corresponds to about 7×10^3 points generated in each bin. The normalized (by the maximum value) map of geometrical acceptance is presented in Figure 6.

The map of efficiency was calculated using much poorer statistics. The modesty of the event sample was due to the long simulation time. The presented map of efficiency (Figure 7) consists of about 210,000 points of annihilation.

All annihilations that caused coincidences (scintillations occurred in both scintillators at the same time) were treated as events. Both processes, the interaction of the γ quantum in the scintillator material and the transport of photons inside the scintillator, were simulated. However, a number of photons produced in the process of the scintillation were accounted. This means that some of the annihilations counted as an event in the real world would not be detected because of the very small number of photons reaching the photomultipliers (signals at photomultipliers could have very small amplitudes). If there would be an amplitude filter, the event sample would be smaller.

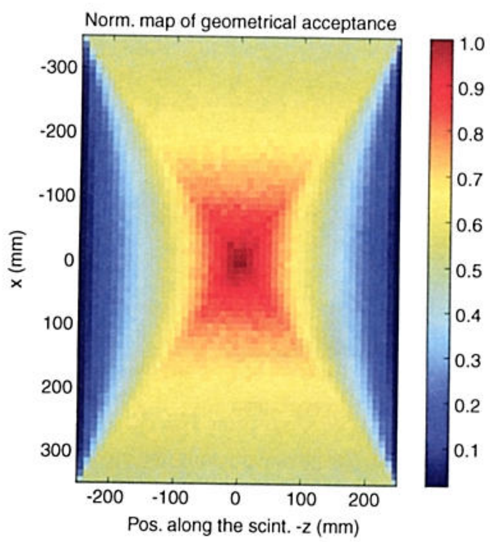

Figure 6 Map of geometrical acceptance.

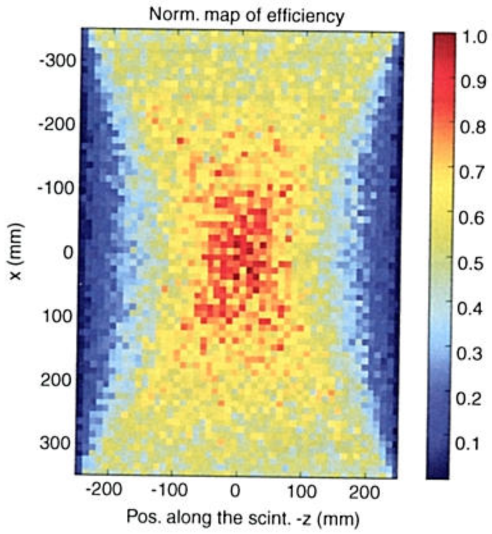

Figure 7 Map of efficiency calculated using the GATE software.

The map of efficiency (normalized by the maximum value), computed using GATE software and dedicated tools, is presented in Figure 7. The maximum number of events per bin was about 120.

Comparison: χ^2-test

The corresponding values of pixels of the two maps (Figures 6 and 7) were treated as random variables with the Poisson distribution. After the normalization of the map of geometrical acceptance, it was possible to show the statistical dependencies between both maps. In the calculations, it was assumed that if the number of counts was >10 [10], the Poisson distribution could be approximated with the normal distribution.

Each pair of pixels was analyzed independently (with the assumption that the values of pixels in each map were independent) and their values were compared using χ^2-test [Eq. (3)]. The value of the χ^2-test between the two pixels located in the same position (i, j) in the two maps (x and y) can be defined as

$$\forall_{i,j}\ \chi^2_{i,j}=\frac{e^2_{ij}}{E_{ij}}, \tag{3}$$

where $e_{i,j}=x_{i,j}-\frac{y_{i,j}}{k}$, $E_{i,j}=x_{i,j}+\frac{y_{i,j}}{k^2}$, and $k=\frac{\sum x_{i,j}}{\sum y_{i,j}}$. The calculated map of the value of the χ^2-test is presented in Figure 8.

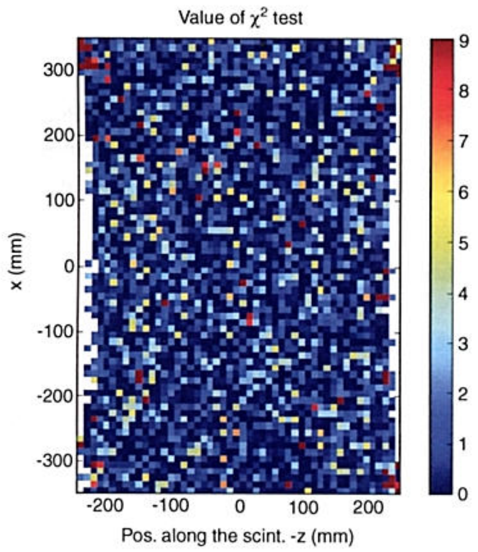

Figure 8 The map of the value of χ^2-test.

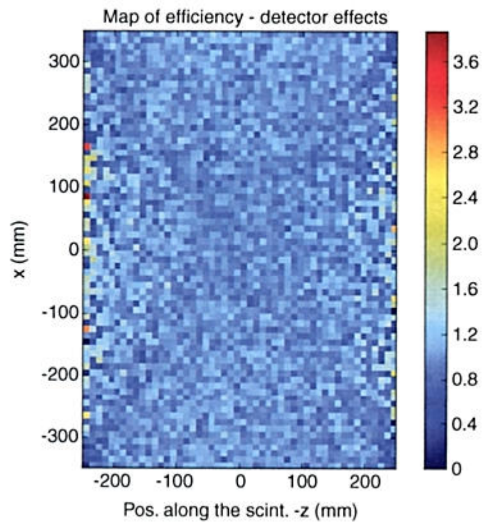

Figure 9 Map of efficiency.
Only detector effects are included.

The values of the χ^2-test were calculated for pixels, where the number of counts in corresponding pixels of the map of efficiency (from GATE software) was >10. In the opposite situation, as it is seen in side areas of the picture, the values of the χ^2-test were not calculated (in white).

Detector effects

To separate the detector effects from geometrical acceptance, the map of efficiency f_{eff} was divided (pixel by pixel) by the map of geometrical acceptance f_{acc}. Before calculating the new map, the map of geometrical acceptance was normalized (divided) by the factor k

$$k=\frac{S_x}{S_y}, \tag{4}$$

where S_x is number of all events in the map of geometrical acceptance and S_y is the number of events in the map of efficiency. The calculated map is presented in Figure 9.

As one can see, most of the central area of the map showing detector effects is homogeneous and has value of ~1. It means that influence of the detector effects on the map of efficiency is much less than the influence of geometrical acceptance. In the boundary regions of the scanner, the values of the pixels from the map of efficiency are even three times bigger than the corresponding values of the map of geometrical acceptance. It may mean that in these regions, physical phenomena have significant influence on the efficiency of the scanner. When other physical effects such as amplitudes of voltage signals will be included in analysis, this effect will be studied more accurately.

It may be also observed that, on the diagonals, the efficiency is less than in other regions. This effect may be caused by the fact that the γ quanta generated in these areas with maximum angle, which may lead to coincidence, have smaller paths in the scintillators, and it is less probable that they will cause scintillations.

Discussion of results

At first sight, the map of geometrical acceptance and the map of efficiency calculated using GATE look very similar. The chosen method of comparison showed that there are no statistically significant differences between the two compared maps (Figures 6 and 7). For the majority of pixels, the χ^2 are in three-σ interval. It is noteworthy that there is no structure visible in Figure 8. It shows that the map of efficiency is strongly dominated by the geometrical properties of the system, and the detector effects are not clearly visible. However, the map of efficiency, including only detector effects, showed that these effects influence the final efficiency of the scanner.

The results of performed calculations will be the subject of further studies. The map of efficiency with more statistically significant data will be computed. Other methods of comparison, e.g., based on correlation coefficient, will be performed.

Conclusions

The simulation of the two-strip J-PET detector was performed using GATE software. The map of efficiency was determined using the obtained results and was compared with the map of geometrical acceptance.

The efficiency of our detector depends on many geometrical and physical factors. The simulations presented in this article indicate that the map of the total detection efficiency is strongly correlated with the detector geometry. A more detailed study of the influence of each of the physical processes is underway.

The GATE software and its configuration on the CIŚ cluster (e.g., configuration of output obtained with GATE software) must be optimized for shortening the time of simulations.

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Conflict of interest statement

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