TOMSK POLYTECHNIC UNIVERSITY ТОМСКИЙ ПОЛИТЕХНИЧЕСКИЙ УНИВЕРСИТЕТ

Министерство науки и высшего образования Российской Федерации
федеральное государственное автономное
образовательное учреждение высшего образования
«Национальный исследовательский Томский политехнический университет» (ТПУ)

Инженерная школа ядерных технологий
Направление подготовки 14.04.02 Ядерные физика и технологии
Отделение ядерно-топливного цикла

МАГИСТЕРСКАЯ ДИССЕРТАЦИЯ

Тема работы
Разработка детектора для доклинической томографии на основе монолитного кристалла с разреженной матрицей кремниевых фотоумножителей

УДК **539.1.074:616-07:621.383.292**

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Томск – 2022 г.

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«Национальный исследовательский Томский политехнический университет» (ТПУ)

School of Nuclear Science & Engineering
Field of training (specialty): 14.04.02 Nuclear Science and Technology
Specialization: Nuclear medicine
Nuclear Fuel Cycle Division

MASTER THESIS

Topic of research work
Development of a detector for preclinical tomography based on a monolithic crystal with a sparse matrix of silicon photomultipliers

UDC 539.1.074:61607:621.383.292

Student

Group	Full name	Signature	Date
0AM0M	Mubanga Edward		

Scientific supervisor

Position	Full name	Academic degree, academic rank	Signature	Date
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ADVISORS:

Section “Financial Management, Resource Efficiency and Resource Saving”

Position	Full name	Academic degree, academic rank	Signature	Date
Associate Professor	Luibov Y. Spicyna	PhD		

Section “Social Responsibility”

Position	Full name	Academic degree, academic rank	Signature	Date
Associate Professor	Perederin Yuri Vladimirovich	PhD		

ADMITTED TO DEFENSE:

Programme Director	Full name	Academic degree, academic rank	Signature	Date
Nuclear medicine	Vera V. Verkhoturova	PhD		

Tomsk – 2022

LEARNING OUTCOMES

Competence code	Competence name
	Universal competences
UC(U)-1	Ability to make critical analysis of problem-based situations using the systems analysis approach, and generate decisions and action plans.
UC(U)-2	Ability to run a project at all life-cycle stages.
UC(U)-3	Ability to organize and lead the teamwork and generate a team strategy to achieve the target goal.
UC(U)-4	Ability to use modern communication technologies to realize academic and professional interaction.
UC(U)-5	Ability to analyze and account for cultural diversity in the process of intercultural interaction.
UC(U)-6	Ability to set and pursue individual and professional activity priorities and ways to modify professional activity based on the self-esteem.
	General professional competences
GPC(U)-1	Ability to formulate goals and objectives of the research study, select assessment criteria, identify priorities for solving problems.
GPC(U)-2	Ability to apply modern research methods, evaluate and present the results of the performed research.
GPC(U)-3	Ability to present research outcomes in the form of articles, reports, scientific reports and presentations using computer layout systems and office software packages.
	Professional competences
PC(U)-1	Ability to maintain medical and technical documentation related to medicophysical aspects of radiation therapy, interventional radiology and radionuclide diagnostics and therapy.
PC(U)-2	Ability to ensure radiation safety of personnel, public, and the environment, to carry out monitoring of radiation exposure levels of patients, personnel, public, and the environment.
PC(U)-3	Ability to operate and maintain equipment and tools applied for the medical use of radiation.
PC(U)-4	Ability to manage the quality of physical and technical aspects within radiation therapy, diagnostics, interventional radiology and radionuclide diagnostics and therapy departments in accordance with the specific equipment requirements, regulatory requirements and staffing of a medical organization.
PC(U)-5	Ability to conduct and organize dosimetry planning, clinical dosimetry, quality assurance procedures for radiotherapy, interventional radiology, and radionuclide diagnostics and therapy.
PC(U)-6	Ability to apply knowledge of natural sciences, fundamental laws in the field of nuclear physics and technology, clinical and radiation standards, hygienic measures in nuclear medicine, which is sufficient to study issues associated with medical physics using modern equipment and information technology relying on the latest Russian and international experience.
PC(U)-7	Ability to develop reference books, tables and software containing data for clinical use in dosimetric planning of radiation therapy, radionuclide diagnostics and therapy.

Competence code	Competence name
PC(U)-8	Ability to take part in the design and physical and technical equipment development for radiation therapy, diagnostics, interventional radiology and radionuclide diagnostics and therapy, and radiation safety divisions.
PC(U)-9	Ability to conduct training sessions and develop instructional materials for the training courses within the cycle of professional training programs (bachelor degree programs).

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School of Nuclear Science & Engineering
Field of training (specialty): 14.04.02 Nuclear Science and Technology
Specialization: Nuclear medicine
Nuclear Fuel Cycle Division

APPROVED BY:
Program Director
_____________ Verkhoturova V.V.
«____» ____________ 2021

ASSIGNMENT for the Graduation Thesis completion

In the form:

Master's thesis

For a student:

Group	Full name
0AM0M	Mubanga Edward

Topic of research work:

Development of a detector for preclinical tomography based on a monolithic crystal with a sparse matrix of silicon photomultipliers	
Approved by the order of the Director of School of Nuclear Science & Engineering (date, number):	№ 104-43/c dated April 14, 2022

Deadline for completion of Master Thesis:	08.06.2022

TERMS OF REFERENCE:

Initial date for research work: *(the name of the object of research or design; performance or load; mode of operation (continuous, periodic, cyclic, etc.); type of raw material or material of the product; requirements for the product, product or process; special requirements to the features of the operation of the object or product in terms of operational safety, environmental impact, energy costs; economic analysis, etc.)*	. Spatial resolution – under 1mm. . Maximum number of electronic channels – 1024 . Simulation toolkit – Geant4
List of the issues to be investigated, designed and developed *(analytical review of literary sources with the purpose to study global scientific and technological achievements in the target field, formulation of the research purpose, design, construction, determination of the procedure for research, design, and construction, discussion of the research work results, formulation of additional sections to be developed; conclusions).*	1. Analytical review of existing small-animal PET scanners 2. Implementation of physics for PET simulation 3. Evaluation of performance characteristics of simulated PET and SPECT scanner 4. Conclusions about simulated PET and SPECT data

List of graphic material *(with an exact indication of mandatory drawings)*	Presentation
Advisors to the sections of the Master Thesis *(with indication of sections)*	

Section	Advisor
Social responsibility	Perederin Yuri Vladimirovich
Financial Management, Resource Efficiency and Resource Saving	Luibov Y. Spicyna

Date of issuance of the assignment for Master Thesis completion according to the schedule	15.03.2022

Assignment issued by a scientific supervisor / advisor (if any):

Position	Full name	Academic degree, academic status	Signature	Date
Director of RSP	Gogolev Aleksey Sergeevich	PhD		

Assignment accepted for execution by a student

Group	Full name	Signature	Date
0AM0M	Mubanga Edward		

ASSIGNMENT FOR THR DIPLOMA PROJECT SECTION
«FINANCIAL MANAGEMENT, RESOURCE EFFICIENCY AND RESOURCE SAVING»

Student:

Group	**Name**
0AM0M	Mubanga Edward

School	**Educational level**	**Department**	**Specialization**
School of Nuclear Science & Engineering	Master	Division for Nuclear-Fuel Cycle	14.04.02 Nuclear Science and Technology

Initial data for the section "Financial Management, Resource Efficiency and Resource Saving":	
The cost of scientific research resources: material, technical, energy, financial, informational and human	*Budget of research is 593,401 rub.*
2 Norms and standards for spending resources	*Supervisor' salary – 72698 rub, student (researcher) salary – 148629 rub, Engineer – 1000 rub.*
The system of taxation used, tax rates, volumes of payments, discounts and loans	*Coefficient of incentive bonuses 30%, coefficient of incentives for the manager for conscientious work activity 25 %; contributions for social funds are 30 % totally*
Problems to research, calculate and describe:	
Assessment of the commercial potential of engineering solutions	*Analysis of alternative ways of conducting research*
Planning of research and constructing process and making schedule for all periods of the project	*The work consist of:* *SWOT – analysis;* *Determination of the complexity of work.*
** Budgeting an engineering project*	*Scientific and technical research budget consist of:* - *calculation of costs for purchasing equipment;* - *calculation of the basic and additional salary of the performers;* - *social contributions;* - *Formation of the budget of costs.*
Calculation of resource, financial, social, budgetary efficiency of an engineering project and potential risks	*Evaluation of efficiency is provided through:* *integral financial indicator;* *-integral resource efficiency indicator;* *- integral efficiency indicator;* - *comparative project efficiency.*
Graphic materials	
1 Competitive power of the project *2 SWOT matrix* *3 Plan of investments.* *4 The budget for scientific and technical research* *5 Project Efficiency indicators*	

Assignment date	15.03.2022

Consultant:

Position	**Name**	**Academic degree**	**Signature**	**Date**
Associate Professor	Luibov Yurievna Spicyna	PhD		

Student:

Group	**Name**	**Signature**	**Date**
0AM0M	Mubanga Edward		

ASSIGNMENT FOR THR DIPLOMA PROJECT SECTION
«SOCIAL RESPONSIBILITY»

Student:

Group	Name
0AM0M	Mubanga Edward

School	Educational level	Department	Specialization
School of Nuclear Science & Engineering	Master	Division for Nuclear-Fuel Cycle	14.04.02 Nuclear Science and Technology

Title of graduation thesis

Development of a detector for preclinical tomography based on a monolithic crystal with a sparse matrix of silicon photomultipliers

Initial data for the section "Social responsibility":	
1. Information about object of investigation (matter, material, device, algorithm, procedure, workplace) and area of its application	Positron and photon emission tomography. Application area: Positron and photon emission tomography of small animals
List of items to be investigated and to be developed:	
. Legal and organizational issues to provide safety: – Special (specific for operation of objects of investigation, designed workplace) legal rules of labor legislation; – Organizational activities for layout of workplace.	– Labour code of Russian Federation #197 from 30/12/2001 GOST 12.2.032-78 SSBT – Sanitary Rules 2.2.2/2.4.1340-03. Hygienic requirements for PC and work with it
Work Safety: 2.1. Analysis of identified harmful and dangerous factors 2.2. Justification of measures to reduce probability of harmful and dangerous factors	– Enhanced electromagnetic radiation level – Insufficient illumination of workplace – Excessive noise – Deviation of microclimate indicators – Electric shock
3. Ecological safety:	– Indicate impact of radionuclides production on hydrosphere, atmosphere and lithosphere
4. Safety in emergency situations:	– Fire safety

Assignment date	15.03.2022

Consultant:

Position	Name	Academic degree	Signature	Date
Associate Professor	Perederin Yuri Vladimirovich	PhD		

Student:

Group	Name	Signature	Date
0AM0M	Mubanga Edward		

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School of Nuclear Science & Engineering
Field of training (specialty): 14.04.02 Nuclear Science and Technology
Specialization: Nuclear medicine
Level of education: Master degree program
Nuclear Fuel Cycle Division
Period of completion: spring semester 2021/2022 academic year

Form of presenting the work:

Master Thesis

SCHEDULED ASSESSMENT CALENDAR
for the Master Thesis completion

Deadline for completion of Master's Graduation Thesis:	05.06.2022

Assessment date	**Title of section (module) / type of work (research)**	**Maximum score for the section (module)**
15.03.2022	*Drawing up the technical assignment*	
20.03.2022	*Calendar planning*	
30.03.2022	*Literature review*	
29.04.2022	*Choosing of scanner configuration*	
3.05.2022	*Implementation of necessary physics in Geant4*	
4.05.2022	*Simulation of detector's unit*	
5.05.2022	*Evaluation of unit's charactristics*	
6.05.2022	*Analisys of resolution properties of simulated data*	
10.05.2022	*Summarizing*	
06.06.2022	*Drawing up a final report*	
25.06.2022	*Masters's Thesis defense*	

COMPILED BY: Scientific supervisor

Position	**Full name**	**Academic degree, academic status**	**Signature**	**Date**
Director of RSP	Gogolev A. Sergeevich	PhD		

APPROVED BY:

Program Director	**Full name**	**Academic degree, academic status**	**Signature**	**Date**
Nuclear medicine	Vera V. Verkhoturova	PhD		

ABSTRACT

The modalities involved in our study are positron emission tomography and single photon emission tomography. When combined together to produce a detector, both produced a higher sensitivity and resolution in space. As a result, it will necessitate reactions towards high radiation, reduce on time of scanning, and know the distribution of various radiopharmaceutical. It will also help us understand how various mechanisms of diseases develop and implore the appropriate theurapetical strategies.

The goal of our work was to simulate multimodality PET/SPECT detector supported monolithic crystal (lutetium yttrium oxyorthosilicate, LYSO) with silicon photomultipliers (SiPMs) array.

In this work, a joint detector for each SPECT and PET was developed. The Monte Carlo method as a result of the software's use, Geant4 to arrive at the goal. The general procedure involved building of cumbersome phantoms, i.e., Nema Nu 2008, and micro derenzo phantoms. The simulation and building of the joint detector based on monolithic crystal, LYSO was done thereafter.

In comparison with other scanners made from a variety of literature, the PET/SPECT detector appeared to have performed better and that fuelled research on this subject.

Key words: Single emission tomography, positron emission tomography, tiny animal, monolithic scintillator, Geant4, lutetium yttrium oxyorthosilicate, NEMA- Nu 2008 phantom, micro derenzo phantom, Monte-Carlo simulation

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Introduction

SPECT and PET are isotope-based techniques that dissent in the main within the radioisotope used and therefore the modalities for generating signal and detection of photon [1]. SPECT imaging distinction agents are labelled with γ-emitting radioisotopes such as technetium-99m, indium-111, and iodine-123 while for PET tracers are labelled with positron-emitting radioisotopes such as oxygen-15, nitrogen-13, carbon-11 and fluorine-18 [2]. The initial cluster produces gamma radiation of various energies, which permit the SPECT camera to detect them through lead collimators.

Positron-emitting radioisotopes via annihilation events (figure 1.1) produce the signal, in which each antilepton collides with a nearby lepton to produce two 511 keV gamma radiation 180 degrees apart [3]. The annihilation results in the release of gamma radiation, which can be detected by a Detector by chance. High-energy gamma rays are capable of penetrating the body, allowing these strategies to be used on both small animals and people. One of the most notable advantages of PET as well as SPECT is their great sensitivity, which allows for the use of small, non-pharmacological dosages (nanograms) for imaging purposes [4]. As a result, the radiotracer is used in such a little amount that it has no effect on the living process. There are a variety of diagnosis experiments to trace radioisotope-labelled cells in illness models and even clinical trials, thanks to the presence of various FDA-regulated distinction agents (e.g. 2-[F-18]-fluoro-2-deoxy-D-glucose for PET, [In-111] oxine for SPECT) [5]. Blocklet et colleagues, for example, used PET and SPECT to monitor myocardial-labeled CD34+ cell orientation during intracoronary implantation in patients with acute myocardial infarction [6].

The goal

The aim of this research is to simulate multimodality PET/SPECT detector based on monolithic crystal (lutetium yttrium oxyorthosilicate, LYSO) with Silicon Photomultipliers (SiPMs) array.

Objectives of this research are:

- Reviewing of existing joint detectors for PET and SPECT
- Analysis of LYSO monolithic scintillator with SiPMs matrix as gamma cameras for PET and SPECT
- Reviewing of preclinical performance measure of mouse phantoms for PET/SPECT
- Building of phantoms in Geant4
- Simulation of PET/SPECT Detector

Research Relevance:

The establishment or development of a new detector sensitive to high radiation on patient, and on both modalities (PET/SPECT) can reduce time of scanning, and the distribution of new radiopharmaceutical. Similarly, we can also attribute its relevance to its applications in nuclear medicine.

1. Literature review

1.1. PET/SPECT detection principle

PET:

A scanner measures a radionuclide injected in an animal, its concentration within the tissues. It is very sensitive enough to sight even a tiny low quantity of the composition of radioactive. During the radioactive decay, the nucleus is excited by charge. To come on stable condition, a radioactive substance antielectron emission happens.

An antielectron transfers with some tiny vary and collides with lepton of medium (usually water).

During this moment antielectron, extinguish with lepton and outline energy of particles changes to two photons. Annihilation photons have energy every 511 keV and opposite directions.

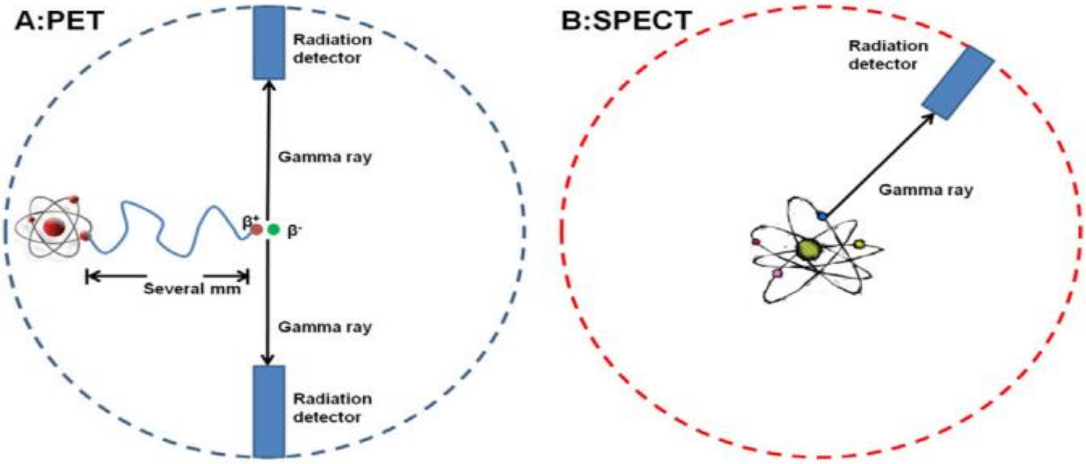
As a result, when annihilation gamma particles form a line, it is known as the line of response (LOR). The detector system that records two photon occurrences at the same time, as well as the energy of constituent photons in a given energy frame. Scintillators are used in PET detectors, and the period between language and registration is extremely short.

SPECT:

A gamma camera is used to gather several 2-D images (also known as projections) from various angles for SPECT imaging. A computer using a tomographic reconstruction technique, resulting in a 3-D data set, then processes the various projections. This data set can then be processed to reveal thin slices of the body along any desired axis, similar to those acquired using other tomographic techniques such as MRI, X-ray computed tomography (X-ray CT), and positron emission tomography are some of the imaging techniques used (PET). [5]

In that it uses radioactive tracer material and detects gamma rays, SPECT is comparable to PET. SPECT tracers, unlike PET tracers, release gamma radiation that may be directly measured, whereas PET tracers emit positrons that annihilate with electrons.

The primary principle of detection is illustrated in Figure 1.1.



PET and SPECT are depicted in this illustration. (A) Antielectron annihilation in PET: the emitted antielectron from the atom travels via tissue for a short distance (usually less than one millimeter, depending on the isotope), during which time it loses motion, until it slows towards the point where it will act with a negatron. When a negatron and an antielectron collide, they produce two-gamma radiation that go in opposite directions. These emissions 'coincide' within time, which is detected by multi-headed gamma cameras. (B) The isotope produces a gamma light, which can be sensed by a simple gamma camera.

Figure 1.1 – Primary principle of PET/SPECT of detecting photon

In most detector systems, scintillators with SiPM or photomultiplier tubes are employed. Commercial variants now supply largely SiPM variants to attain optimal resolution because to the much lower size of SiPM pixel.

1.2. PET/SPECT reconstruction

Data from scanning represents set of registered LORs. Normally such facts named as sinogram. LORs may be garage in several layout. Import part of mental image systems is to provide the local and extensive used instance of mastering item. Reconstruction is that the solution of this drawback. Reconstruction might be a way of transferring of uncooked LORs information to extent in 3-D or 2-D region of distribution of radioactive atom in body.

Mathematically system of acquisition could be expressed as:

$$P = H * f + d \qquad (1.1)$$

Where p – obtained data (set of LORs);

H – Model of system, commonly matrix of chances of voxel to supply and discover LORs;

f – Unknown volume, for PET distribution of unique pastime in body.

d – Blunders of measurements, distinction between "true" photograph and reconstructed one.

In scenario, once d is zero and system will be determined simply through pure mathematics downside of reconstruction may well be resolved analytically. Such transition from f to p, from purpose of arithmetic named as transformation of Random. Therefore, transition of reverse from p to f is known inverse transformation of Random.

Anyway, if d is supposed as settled range or matrix of numbers the matter of reconstruction will be resolved analytically. There are a unit very different ways of analytical answer. The foremost fashionable one is filtered-back projection (FBP).

FBP enabled a back projection step in which volume was packed on LOR using scalar intensity equal to gathering data at the same LOR price. The filtering stage takes into account the non-uniformity spacing of LOR in volume and allows for the removal of oversampling of lines on the downside and sounds at certain frequencies. The Ram-Lak, Hann, and Sheep-Logan filters are next. Analytical ways give definite image, however does not embody some physical specialties and dependence of noise. Hence, FBP will show droning pictures. However, FBP is still one amongst preferred ways of reconstruction thanks to high computation speed and low laptop needs.

More real assumption to suppose error d, as random price. For answer of such downside repetitious ways, are used [7].

There are tons of repetitious ways counting on the standards of best image and objective operate. The foremost fashionable ways are:

- Expectation maximization: this includes Maximum likelihood and ordered subset [8, 9, 10]
- Algebraic reconstruction technique
    - This includes ART and Simultaneous ART (SART) [11-14]
- Bayesian reconstruction: This includes maximum a posteriori and ordered subsets maximum a posteriori using one step [15-18]

Iterative algorithms generate for the inclusion of disturbance in the process in order as well as the provision of more detailed model and physical features. The computing time, on the other hand, could be tremendous, significantly beyond the time necessary for FBP reconstructions.

When PET is combined with computerized tomography (CT) as well as magnetic resonance (MRI), several approaches for integrating findings and applying corrections such as attenuation [19], scatter [20, 21], random [22], detector efficiency [23, 24], and dead time [25] are often utilized (MRI).

Furthermore, modern technology allows for the use of a time-of-flight (TOF) technique [26, 27], although due to their tiny size, this strategy is not ideal for small animals [28].

1.3 Existing PET scanners for small animals

All scanners have a mean spatial resolution around 1.52 millimeters. Bruker Company's Albira Si scanner has the best value of 0.89 millimeters. It has no value. The Bruker scanner features a monolithic LYSO crystalline, which enables the adoption of something like a depth-of-interaction (DOI) technique to improve LOR estimation and, as a result, resolution. Furthermore, Sofie's scanning G8 [31] has a submillimetre resolution. Nonetheless, a little amount of information about Group of seven setup can be accessed via free access. Furthermore, it is feasible to see that iterative reconstruction techniques are normally used mostly for higher qualities [30].

The average absolute sensitivity is around 5%. There seem to be, nonetheless, devices having reasonably high sensitivity, such as UCLA's PETBox4 [42] (18.1 percent), Sofie's G8 [41] (17.8 percent), and Molecubes' -cubes [32]. Throughout most cases, sensitivity is achieved by increasing the solid angle from the point of geometry. In addition, scintillators with high stopping power and/or thickness can be employed to provide high sensitivity [30].

Maximum resolution is among the most significant features. Maximum energy refers to the capacity to distinguish photons based upon their energy. Imaging systems have an average resolution of 18 percent. Imaging systems provide the greatest bargain: Mediso's LFER 150 [33], while scanners provide the worst results: Sedecal's Argus [36] (26 percent), Raytest GmbH's ClearPET [34] (25 percent), and Gamma Medica's LabPET12 [35] (20 percent).

1.3.1 Material for scintillators

PET scans requires certain characteristics out from individual to the photon detector inside the detector. First, always foremost, due to the high energy of photons, the scintillator should have a strong stopping power. Higher stopping power translates to a thinner scintillator, which reduces the impact of optical phenomena while increasing sensitivity. Moreover, lightweight yield reduces energy resolution while boosting system sensitivity. Because PET works on the coincidence principle, helpful events are required for sensing. Lastly, the decay time is taken into account while selecting a scintillator since this isotope's activity may be strong, and time delay must always be eliminated. Furthermore, spectrum emission and alternative parameters should be considered when perceiving the detecting system as a whole with a photomultiplier tube (PMT) or SiPM.

Below is a table containing the most frequent scintillator characteristics.

Table 1.1 – The most important characteristics are regularly deployed PET photodetectors.

	LSO	LYSO	MLS	GSO	BGO	CWO	LGSO
Illumination yield, ph/keV	31.00	33.20	23.56	7.60	8.5	27.3	23.56
Maximum emission, nm	420	420	420	430	480	475	425
Degradation time, ns	40-47	36	36-39	30-60	300	14500	40
Index of refraction	1.82	1.81	18.83	1.85	2.15	2.20	1.81
Density, g/cm^3	7.4	7.1	7.3	6.71	7.13	7.9	6.5

1.3.2 Detectors electronic

The radiation from the photon detector should be gathered using an electrical device, photomultiplier tube (PMT). Position sensitive PMT (PSPMT), multichannel PMT (MCPMT), avalanche photodiode (APD), and SiPM techniques control measures all options.

The most basic PMT works by multiplication of photoelectrons produced by hitting the cathode with optical photons. MCPMT is a better form of PMT in terms of impact. Small tubes covered with dynode substance are used in MCPMT. Coating produces secondary electrons. This arrangement enhances electronic time resolution.

MSPMT commutation single with array of tiny anodes is different from MCPMT commutation single (multiple anode). This modification enables the position of fundamental lightweight to be defined. The resolution of the system is improved by using electronic devices, but the expense is also increased.

Because of the physical phenomenon influence, APDs are sensitive semiconductor devices that convert light into an electrical signal. They will be viewed as photodetectors that provide intrinsic amplifying via the avalanche amplification effect. Some approaches show that high-resolution PET can be used in a cost-effective manner. APD performs well in terms of time and quantum potency [39].

The SiPM solution combines the advantages of PMT and APD. SiPM features a high gain and time resolution, as well as a small size. However, the cost of such equipment prevents it from being used everywhere. SiPM (solid photodetector with microcells) is a solid photodetector with a collection of tiny integrated single-photon avalanche diodes (microcells) [40]. SiPMs are divided into two types: analog SiPMs (a-SiPM) and digital SiPMs (d-SiPM) (d-SiPM). Freelance cells are used in a-SiPM, but they are coupled to a normal readout electronic.

Although this design has good sensitivity and detecting power, it is not able to count photons several times. Freelance cells with freelance electronic and readout are available in d-SiPm. Such device allows for the induction of further full data about lightweight pulse. As a result, singular gauge particle sensitivity is great in d-SiPMs.

1.4. Monte-Carlo simulation

1.4.1. General features of scanner

The following configuration was proposed based on observed variants, existing techniques, and accessible streams number, as indicated in Table 1.1.

Table 1.2 – Simulated PET general features

Features	Solution
Scintillator compound	LYSO
Electronic	d-SiPM
Performance accent	Spatial resolution
DOI assessment	Monolithic scintillator
Channels in the plate	64
Total number of channels	1024

Because of its simplicity and inability to broaden the spectrum of SiPMs, the monolithic photodetector technique was chosen. In addition, there are currently available PET systems (Albira Si) that enable a monolithic scintillator method with impressive performance. Based on the options, the checkboard order of the following detector and thin plates were directed. Figure 2.1 depicts the current value of the checkboard detector plate.

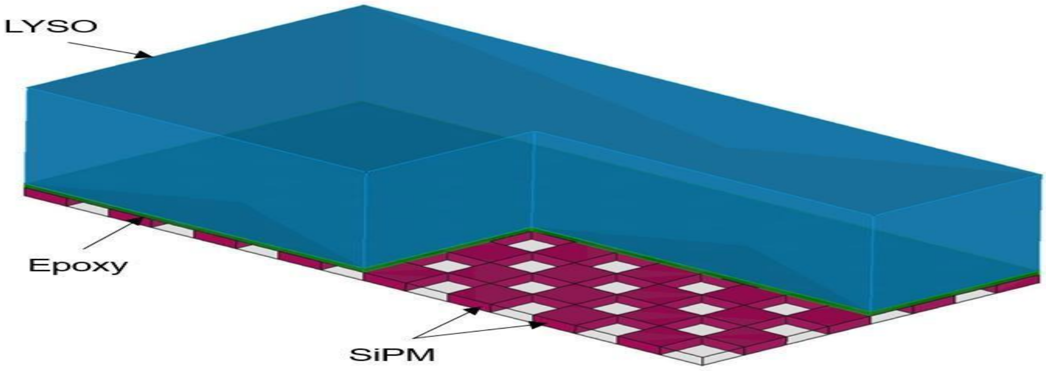


Figure 1.2. – Isometric read on the detector plate with checkboard order

SiPM cells are six cm by six cm in dimension. SiPMs come in sixteen different lengths and eight different widths. The amount of SiPMS are the ones from variation of the same dense array, resulting in a quantity of SiPMs of 16*8/2 = sixty-four, which is excellent in terms of channel count. As a result, length and breadth of plate can be urged using a variety of SiPM. The length is 16*6 = 96 millimetres, while the width is 8*6 = 48 millimetres. There are insensitive sections due to empty spaces in the array. Obviously, for photon detection over an empty area, the neighboring pixels should get some light. Internal reflection limits the amount of light in the room. The pure mathematics of reflection is shown in Figure 1.3.

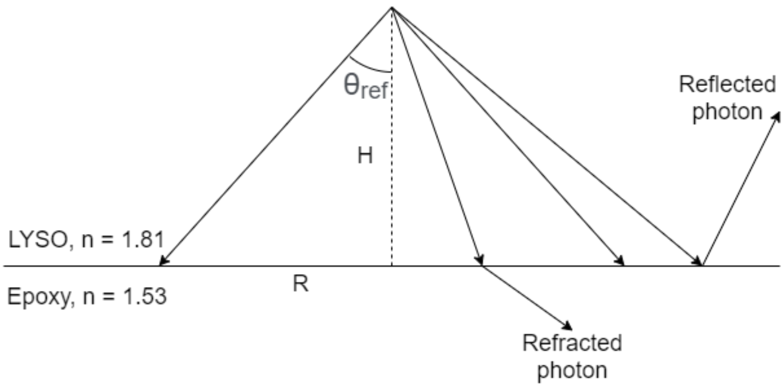


Figure 1.3 – **Internal reflection on scintillator – epoxy border**

Based on the geometry it is possible to get easy equation:

$$H = R * ctg(\theta) = R * \frac{\cos(\theta)_{ref}}{\sin(\theta)_{ref}} = R * \frac{\sqrt{1-sin^2(\theta)_{ref}}}{\sin(\theta)_{ref}}, \qquad (1.2)$$

Where R – radius of area for corresponding height H, where inherent photon are not reflected;

$(\theta)_{ref}$ – Total internal reflection angle for LYSO-Epoxy (scintillator- light guide).

With known refraction indexes the coefficient between radius and height is:

$$H = R * \frac{\sqrt{1-sin^2(\theta)_{ref}}}{\sin(\theta)_{ref}};\ \sin(\theta)_{ref} = \frac{n_{Epoxy}}{n_{LYSO}} => \mathrm{H} = \mathrm{R} * \frac{\sqrt{n_{LYSO}^2 - n_{Epoxy}^2}}{n_{Epoxy}} = 0.632 * R$$

Where, n_{Epoxy} – epoxy refractive index (1.53);

n_{LYSO} – LYSO refractive index (1.81);

Total internal refraction angle is 57.7 °C, and proportional index is 0.632, as shown in the formula.

Insensitive space radius selection is based on two principles: direct sensitivity and sensitivity uniformity. Because of an original demand, the greatest insensitive space is created when photons of light are emitted precisely on top of the vacant spot's centre. The radius of space is three millimetres since the vacant place is square and has a six-millimetre aspect length. As a result, according to the proportional index, height is one.9 mm. It appears that a few of millimetres above the LYSO/epoxy surface is insensitive. Nevertheless, when examining at the XY location of interaction, this height homogeneity would not be the same. While not looking at the XY positioning as much as possible, insensitive space should be closed sufficiently to contain sensitive one.

Homogeneity inside a given area is defined by the size relationship between vacant spots and SiPMs. In fact, due to the limited sizes of the array, the radius should be kept to a minimum, in our instance up to 48 millimeters. As a result, all calculations are constrained by the minimal space requirement and the majority of space sizes.

Choosing an unnecessary elevation is an enhancement negative when the following settings are used: sensitivity area – increased (sensitivity); fill issue (ratio of sensitive to all or any areas) – freelance to XY shifting; radius – reduced. The final attribute was chosen due to pricing potency and spatial resolution considerations. The problem of intersecting a circle with a grid has a sophisticated analytical solution thanks to discretization.

The Monte-Carlo method is often used as a solution to the intersection space issue because to its ease of implementation. Once a new sensitive area is enclosed, the main alteration of fill enormous issue occurs. As a result, it is logical to assume that the sites of fixing the monotone aras are on the node or spots where empty spots meet empty spots, and opposite, where the distance between nodes is greatest. Of course, such concerns do not ensure the chance of parameter locations and so on (Gauss circle downside [41]), but they do obliviously set issue limits to 05, and every difference to the present aim decreases as the radius increases. The prompt formula, on the other hand, covers all critical alternatives due to the lack of infinitive exactness. The example of estimated positions and fill dependencies on radii is shown in Figure 1.4.

The results of Monte-Carlo calculations can be seen to be extremely non-monotonic. For starters, it could be due to poor measurement statistics (107 per radius) or severe non-linearity in the Gauss circle problem. It is worth noting, however, that the order of difference is critical for our task. According to the figure, the difference does not surpass the value of 0.0005, which is significantly less than the desired fill factor of 0.5. Because of the calculations, it is reasonable to conclude that the impact of uniformity is small.

Following homogeneity, the sole criterion that must be considered is sensitivity; for minimal sensitivity, four minimal cells in a grid of 3x3 are recommended. The minimal radius for this design is around 8 mm. As a result, the height for has a coefficient of 0.632 is five millimetres.

After all, of the calculations, the usable thickness is estimated to be around 5 mm. As LYSO has a 12 mm attenuation length, thicknesses of 12 mm, 24 mm, and 36 mm were chosen for comparison, with the 24 mm thick being most ideal.

The sparse array of SiPMs is the second plate configuration. Fig.1.4 depicts the scarce structure of SiPMs.

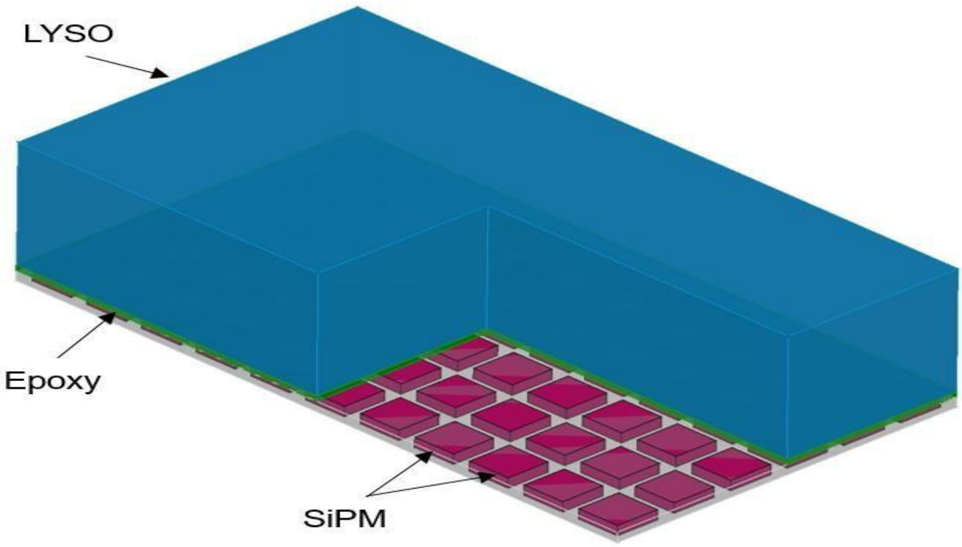


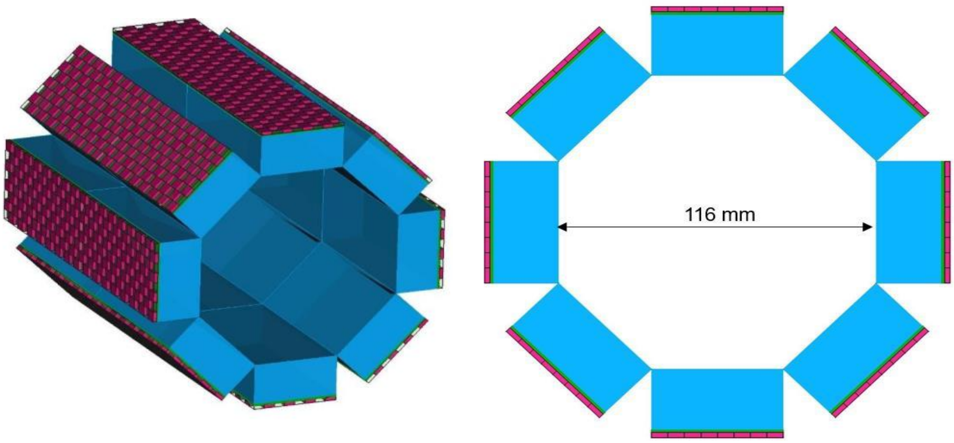
Figure 1.4 – **Isometric view of a detector's plate with sparse order.**

There are Eleven SiPMs all along length and six along the width. The amount was chosen for two reasons: the ratio of axial to transaxial FOV is close to two, and the dimension of the entire array is comparable to the checkboard option. Because a sparse array contains a variable fill factor, the size of the entire plate can be changed by adjusting the pitch (distance between pixels). The arrays with such a fill factor of 0.5 was chosen to correspond to the checkboard variant in the first technique. The pitch (P) can be calculated using the cell size (c) and fill factor (φ) as follows:

$$P = \frac{c}{\sqrt{\varphi}} \qquad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots.. (1.3)$$

Because the pixels in SiPM are 6 mm in size, the assessed pitch is 8.5 mm. Sparse plate sizes with known pitch are 11x8.5=93.5 mm in length and 6x8.5 = 51 mm in width. In general, the arrangement was chosen to provide the best contrast between checkboard and sparse configurations. The thickness of the scintillator was decided to be 24 mm for the checkboard variant.

The complete detector consists of eight plates arranged in rings, with the number of rings varying, but the most common variety having two rings. Figure 1.5 depicts the typical detector design.



Isometric view of the detector Frontal image of the detector

Figure 1.5 – **A clear view of the detector**

1.5. Physics simulation of the simulation

The Geant4 [42] was used to create a simulation the PET device. Geant4 is a software tools for simulating particle interactions in matter. Geant4 is indeed an ASCII text file that is a well-known and widely utilized physics-modelling programme. One of Geant4's most advantageous features is its complete physics construction and flexible physics registering mechanism. The most important procedures for detector unit are magnetism and optical simulation.

1.5.1 Processes of electromagnetic

Physics packages have been created by Geant4. The G4EmStandardPhysics option4 [43] construct is used as a physics foundation. In the case of photons, the following magnetic force mechanisms are involved:

1. The photoelectric effect
2. Compton scattering
3. Lord Rayleigh's scattering

Therefore, because intensity of photons does not surpass the remaining energy of electron, couple formation of negatron/positron is ruled out. The Monarsh University model [44] is used for Arthur Holly Compton scattering in G4EmStandardPhysics option4. The Livermore models are used for photoelectrical impact and Lord Rayleigh scattering [45].

Following magnetic force operations square measure includes for electrons:

1. Production of electrons and ionization
2. Bremsstrahlung
3. Scattering in multiple directions
4. The annihilation of a positron into two emitted photons

For huge angle scatterings, the Goudsmit-Sounderson model [46], based on one Coulomb scattering model, is employed to enforce multiple scattering. Use For multiple scattering, safety and step limitation with an error-free technique close to pure mathematics boundaries are used. The vary issue has a value of 0.08.

The eBremSB enforces Bremsstrahlung. The Moller-Bhabha formulation models ionization, while the eplus2gg model enforces antilepton annihilation. Appendix B contains cross-sections for magnetic force gauge boson interaction processes as ancient as LYSO and its compartment components.

1.5.2 Optical processes

These mechanisms are included in the simulation of optical photons:

1. Synthesis of visual light
   - Scintillation
   - Cerenkov
2. Optical photons interaction
   - Absorption
   - Rayleigh scattering
   - Boundary

In Geant4, the transition from elevated photons to optical photons is not seamless. Furthermore, classic boundary optical phenomena like reflection, refraction, and absorption are included in Geant4. All of the required characteristics for lightweight, such as energy resolution, spectrum, lightweight output, decay time, absorption length, and medium index of refraction, should be outlined. Appendix C contains the optical parameters for LYSO, epoxy, and air.

With 511 keV photons, the mean variety of created optical photons is 0.511x33200 = 16965. The high lightweight yield means that a single Geant4 event produced roughly 17,000 particles. This data demonstrates that optical procedures are relatively expensive in terms of calculating time. Some "tricks" will be utilized to reduce analysis time.

The datasheet [47] explains SiPM's detection efficiency. As a result, taking the detection potency of SiPM into account when generating optical photons is a method of lowering created optical photons. It is suggested that the wavelength LYSO emission value be multiplied by SiPM potency. Although the scintillation lightweight yield can scale down on SIPM potency constant, such a fresh updated spectrum can already encompass SiPM attributes. The typical effectiveness of the SiPM J series is around fifty nothing.

The amount of radiation produced may have decreased. However, such a method should take into account the need to recalculate some attributes as well as the impossibility to employ data for multiple SiPMs.

Coincidentally, the index of SiPM's surface is 1.53, and the index of epoxy is constant. As a result, the epoxy/SiPM border can be determined as a swish transition of one material. As there are approaches for changing reflection and refraction properties with wraps or coatings [48, 49], the Geant4 gives a reasonable surface on which these properties can be defined manually rather than material properties. Except for the basic iteration of labor, Snell's law employed the classical border.The physics guide of Geant4 [50] has more detailed information on mandated physical models.

1.5.3 Validation of PET simulation physics

The simulation experiment was simulated to confirm the selected simulation physics. The light coating of LYSO is bombarded with 551 keV photons, which stores all of the energy of all deposited particles. Figure 1.6 shows the outcome of the spectrum.

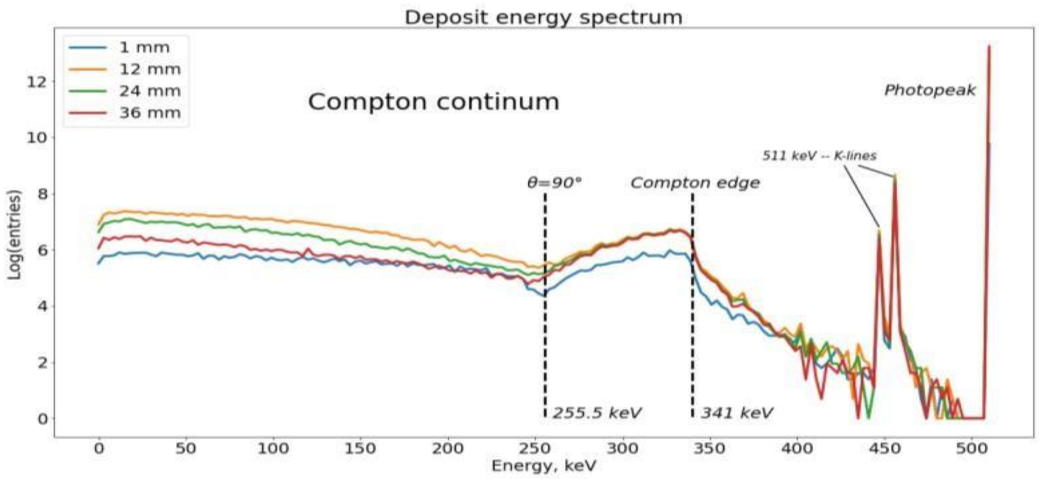


Figure 1.6 – **LYSO energy spectrum deposition**

In a scintillator, the spectrum has all of the characteristics of a photon spectrum. The Compton continuum is first observed from 0 to 341 keV. The Compton boundary, which leads to the increased energy with a dispersed angle of 180 degrees, can be determined using the following equation:

$$E_{comp} = E_O * \left(1 - \frac{1}{1 + \frac{2 * E_0}{m_e * c^2}}\right) \quad \text{(1.4)}$$

where E_0 – the energy of photon before collision, in our case 511 keV;

$m_e c^2$ – rest energy of electron, 511 keV.

The calculated Compton boundary has a value of 340.7 keV. It is possible to observe how the boundary corresponds to theory in Figure 1.6. Furthermore, the spectrum of Compton scattering conforms to the Klein-Nishina distribution

[51], which is a distribution by angle (the energy and angles are unambiguously interrelated). The idea that the Compton lowest dispersion is at scattering angle = 90 degrees corresponds to the traditional spectrum.

2.4. Conclusion

One of most important aspects of small-animal PET scanners, such as spatial resolution, energy resolution, sensitivity, and axial and transaxial FOV, were investigated. The following primary patterns may be seen in the dynamics of characteristics from older to newer scanners: growing axial FOV, decreasing transaxial FOV, and action of spatial resolution below one millimeter. The following main simulated scanning choices were determined: LYSO is the scintillator element; monolithic scintillators allow for executive division research; and d-SiPM is the electronic. SiPMs are presented as a checkboarded pattern with 6x6 millimeter sensitive cells. One detector unit is ninety-six millimeters long and forty-eight millimeters wide. The scintillator has a thickness of twenty-four millimetres, which doubles the attenuation distance for 511 keV photons.

Finally, the detection unit was simulated. The most important physical magnetic attraction and optical processes have been identified. For such investigations, cross-sections and deposition curves match to traditional shapes. The optical parameters of the scintillator were imposed for calculations using supported technical documents. The reduction in energy resolution due to the LYSO spectrum is explained.

Finally, several of the detector's performance parameters were measured. Individual simulations reveal that the distance between scatterings has a significant impact on the sex chromosomal determination error.

There were no exciting inquiries covered in this study, such as executive department, performance computation, enhancing spatial resolution regarding unit fringes, and the effect of coating on performance.

2.0 MATERIALS AND METHODS

On this stage, the following methods were used to arrive at the targeted objective:

- Installing an operating system (OS), Linux.
- Download and install the software, Geant4 [52]
- Learn the basic commands i.e. C++
- Build the PET/SPECT Phantoms in Geant4 i.e. Nema PET/SPECT Phantom (NU 4-2008), Micro-derenzo phantom.
- Simulate the PET/SPECT detector and phantoms in Geant4
- PET/SPECT detector

2.1. NEMA PET Small Animal Phantom (NU 4-2008)

2.1.1 Main Features

• Designed in accordance with the recommendations by the National Electrical Manufacturers Association (NEMA) to standardize the measurements of performance of PET for animal imaging.*

Fig. 2.1. NEMA PET small animal phantom (NU 4-2008)

2.1.2. Main Applications

• Hot Rod measurements indicative of special resolution

• Uniform region for evaluation of signal to noise ratio

• Uniformity for evaluation of attenuation and scatter correction performance

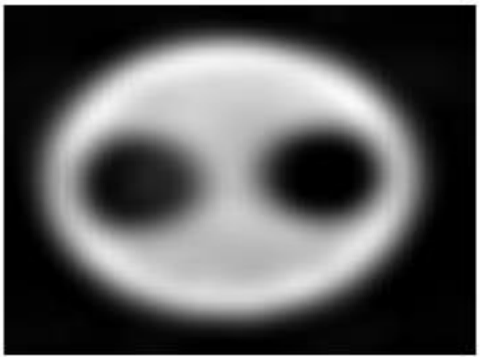


Fig. 2.2. Chambers of NEMA PET Small Animal Phantom (NU 4-2008)

2.1.3. Specifications

Table 2.1 Specifications

Parameter	value
Outside Diameter	33 mm
Cylinder Length	63 mm
Fillable Chamber Inside Diameter	30 mm
Fillable Chamber Length	1.5 mm
Sidewall Thickness	1.5 mm
Fillable Chamber Inside Diameter	8 mm
Fillable Chamber Inside Length	14 mm
Fillable Chamber Wall Thickness	1 mm
Hot Spot Dimensions	
Length	20 mm
Diameters	1, 2, 3, 4, and 5 mm

2.1.4. NEMA PET Phantom in Geant4

The phantom was built in Geant4 according to the above specification in Table 2.1. The simulation was done according to C++ commands. The specifications in table 2.1 were applied during the building of the phantom.

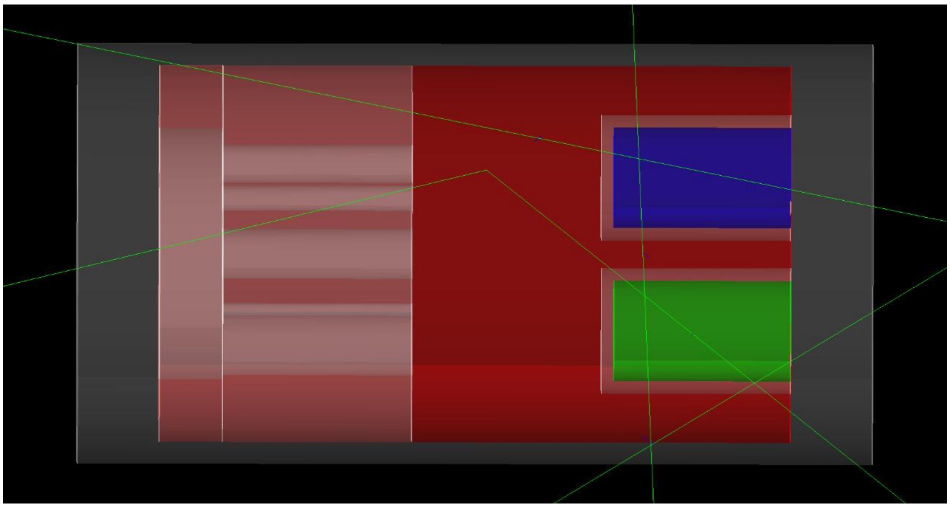


Figure 2.3. NEMA PET Phantom

The points below should be noted:

- Green lines are lines of response (LOR): They have photon annihilation of 511 keV.
- The scattering curve is a false line of response (non-straight LOR)

A (sodium-22) ^{22}Na point source can used to measure the energy resolution, spatial resolution, and sensitivity of the scanner. Scatter fractions (SF) and noise equivalent count rates (NECR) were measured using mouse- and rat-like phantoms. The image quality (IQ) phantom can also be used to measure the scanner's quality characteristics.

2.2. Micro derenzo phantom

2.2.1. Specifications

Table 2.2. Specifications

Parameter	value
Base material	PMMA
Outside Diameter	35 mm
Cylinder Length	70 mm
Hot Rod insert	
Length	20 mm
Diameter	29 mm
Rod diameters	0.6, 0.8, 1.0, 1.2, 1.5, 2.0 mm
Height	12 mm
Center to center distance	2 x diameter

The small Derenzo phantom, with rod diameters of zero.5, 0.6, 0.7, 0.8, 0.9, and 1.0 mm, can be used for activity of abstraction resolution of the PET system. The center-to-center distance between adjacent rods is doubly the rod diameter. Figure 2.4 shows the image of small Derenzo phantom. 18F-FDG mixed with saline will be injected into the phantom, and placed upright on the scanning bed to stay the central axis of the phantom perpendicular to the central axis of the detector to judge the tangential resolution. For the small Derenzo phantom experiment, Ioverol 350™ will mixed with the radiation within the phantom to more appraise PET/CT image quality.

2.2.2. Micro derenzo phantom in Geant4

The phantom was built in Geant4 according to the above specification in Table 2.2. The simulation was done according to C++ commands. The specifications in table 2.2 were applied during the building of the phantom.

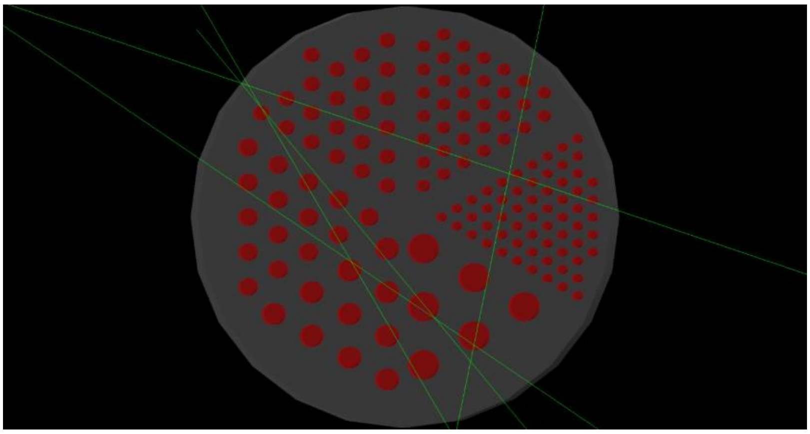


Figure 2.4. Micro derenzo phantom

The points below should be noted:

- Green lines are lines of response (LOR): They have photon annihilation of 511 keV
- The scattering curve is a false line of response (non-straight LOR)

The phantom can selected for testing PET/SPECT tomographic systems because it is simple to complete, established for a PET session, and can be used to assess tomographic uniformity, spatial resolution, and the detectability to "hot" lesions. The researchers can observe rather modest variances in system performance due to the range of quality and "hot" parts.

Using the same methodology as a conventional clinical whole-body scan, get the best possible images on your system. Each and every configuration should be recorded. Rebuild the whole phantom as if it were for clinical trials.

3.0. Results

3.1. PET/SPECT detector

In figure 4.1, gives us a clear view of a joint detector based on a monolithic crystal with Silicon photomultiplier (SiPMs), and incorporated with a Nema NU-2008 phantom in Geant4.

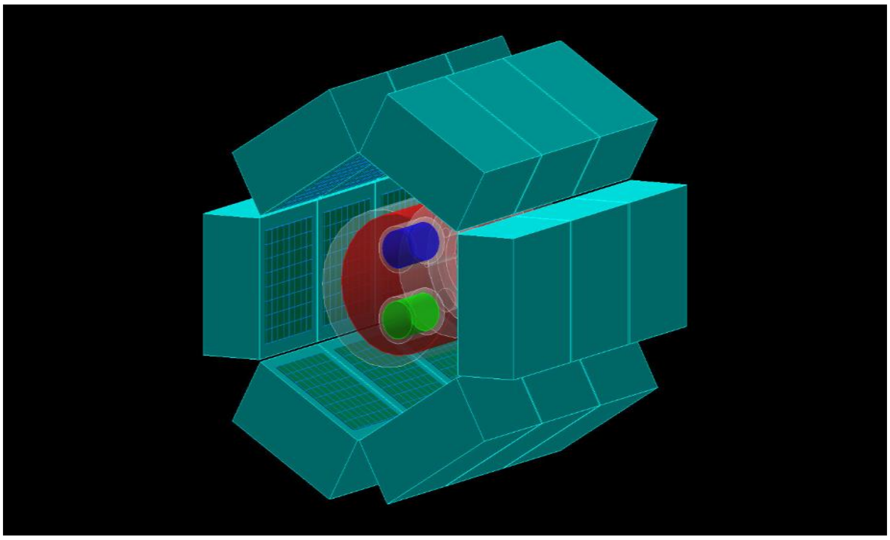


Fig. 3.1 PET/SPECT Detector

The following were the features of the detector, which were built in Geant4:

- Multimodal
- monolithic
- Silicon photomultiplier (SiPMs)
- FSR (Front side read-out)
- Plastic light guide
- Low density

Geant4 phantoms implemented:

- NEMA-NU 2008
- Derenzo

It is worth noting that the above detector in figure 3.1 only shows a Nema –Nu 2008 phantom with identifiable features. However, the derenzo phantom can also be put in to the same detector.

3.1.2. Attenuation lengths

We shall consider determining the attenuation length of one gamma camera for multimodality PET at 511 keV and SPECT at 140 keV. For PET and SPECT, we could consider one common gamma camera, meaning a scintillator is attached to a photodetector (as for PET). Both PET and SPECT modalities can be combined.

One of main difference from detection points of view is different isotopes used for modalities: for PET it mainly (fluorodeoxyglucose) ^{18}FDG, for SPECT its technetium-99m (Tc99m). For PET we could register 511 keV photons 140 keV for SPECT. For example, let us take LYSO scintillator.

We need to understand how big differences will be in attenuation lengths between the two modalities and shall consider properties of LYSO from table 3.1.

Table 3.1. Properties of scintillation crystal (LYSO)

Density, (g/cm^3)	7.2
Attenuation coefficient, μ (cm^{-1}) @ 511 Kev	0.86
Attenuation coefficient, μ (cm^{-1}) @ 140 Kev	6.4

From the table,

$\mu = 0.86\ cm^{-1}$,

Lambda, $\lambda = 1/\ \mu = (1/0.86\ cm^{-1}) = 1.16cm = 11.6mm$

For PET at 511 keV, LYSO scintillation detector has an attenuation length of 1.16 cm or 11.6 mm.

μ= 6.4 cm^{-1},

Lambda, $\lambda = 1/\mu = (1/6.4\ cm^{-1}) = 0.16cm = 1.6$ mm,

For SPECT at 140 KeV, LYSO scintillation detector has an attenuation length of 0.16 cm or 1.6mm.

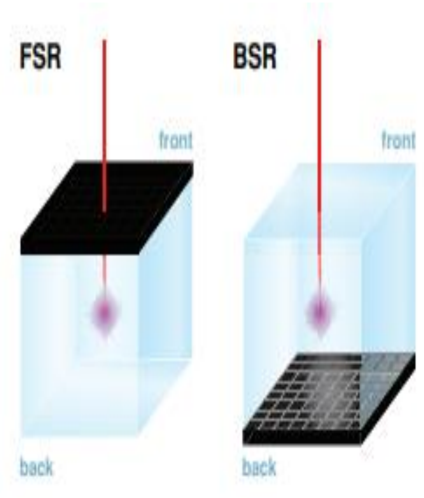
Difference:

The difference in attenuation length of 511 keV and 140 keV photons in LYSO is 10 mm approximately.

Small Animal PET is used for imaging low energy γ-emitting isotopes (^{99m}Tc, ^{111}In, ^{123}I, and ^{131}I). Different radiolabels with their characteristic photon energies (^{111}In [171, 245 keV], ^{125}I [27–35 keV], ^{131}I [364 keV], and ^{99m}Tc [140 keV]) can be attached to molecules of interest. A chelating moiety is required for radiolabeling with ^{99m}Tc and ^{111}In. The type of molecular probe (in the nanogram range) used can be directly or indirectly radiolabeled. Upon injection into the small animals, most of these tracers circulate from the intravascular to the extravascular compartments and emit γ-rays at their specific energies in different directions upon decay [56].

3.1.3. Front side read out (FSR) versus back side read out (BSR)

A SiPM array based can be placed on the front surface of the crystal without significantly disturbing the annihilation photon beam. Front side read out (FSR) performs better than backside read out (BSR) because sixty percent of the annihilation photons are absorbed in the front half of the crystal. Events occurring closer to the SiPM array result in more sharply peaked light distributions that vary more strongly with the position of interaction.



(a) (b)

Fig. 3.2. Schematic representation of geometries: (a) front side read-out (b) backside read-out

For photon detection efficiency, it is necessary to use the FSR on the LYSO scintillator unlike BSR because the front side registers a greater amount of photons on one pixels of SiPMs. The following points to be taken note of:

- ❖ We need to put the SiPMs with front side readout and not back side readout (BSR) because of small attenuation length of photons for SPECT modality.
- ❖ Due to close interaction point to SiPMs matrix, the resolution will degrade to one pixel (3 mm) because of internal reflection to shift absorption distribution in depth. We recommend putting light guide (1mm).
- ❖ Plastic light guide gives low attenuation.

3.1.4 Sensitivity

The absolute peak sensitivity of the system is half 6.8% and most sensitivity is 0.062 counts per second/Becquerel (cps/Bq) with the energy window of 350–750 keV at the middle of FOV, whereas absolutely the peak sensitivity price is 7.7% and most sensitivity is zero.070 cps/Bq with the energy window of 200–750 keV. Figure 3.7 shows the sensitivity profiles measured on the system axially victimization the 22Na beginning. (See Appendix B, Fig. B3)

3.2. Discussion

Single photons released by the radioactive substance are identified by SPECT using arrays of detectors, regardless of their orientation. Tracers containing positron-emitting isotopes are required for detection in a PET scanning. There are a variety of decay modes for these isotopes. Positrons are released in a small percentage of these decays. When a positron collides with an electron, it will go a certain distance, which is determined by its energy and the surrounding matter. The annihilation event generates two 511 keV photons that fly in opposing directions at almost exactly 180 degrees. PET scanner detectors record all events in a ring of detectors around the radiation source, but only analyze those that happen at the same moment within a specific timeframe.

The monolithic scintillator method was selected because it is simple to manufacture and does not require a rise in the amount of SiPMs. There are already current PET systems (Albira Si) that have excellent performance due to their monolithic scintillator method.

Geant4 has created physics packages. The G4EmStandardPhysics option4 [81] constructor is used for the physics basis. The following electromagnetic processes are included in photon:

- Compton scattering
- Rayleigh scattering
- Photo-electric effect

For PET at 511 keV, LYSO scintillation detector has an attenuation length of 1.16 cm while at 140 keV, LYSO scintillation detector has an attenuation length of 0.16 cm. Small Animal PET is used for imaging low energy γ-emitting isotopes (^{99m}Tc, ^{111}In, ^{123}I, and ^{131}I) and florodeoxyglucose (FDG) for SPECT.

3.3. Conclusion

A joint detector based on a monolithic crystal with Silicon photomultiplier (SiPMs) was developed and possessed the following features:

- Multimodal; monolithic; Silicon photomultiplier (SiPMs); FSR (Front side read-out); Plastic light guide; Low density.

Since PET has an attenuation length of 1.16 cm whereas SPECT has 0.16 cm, we have a tendency to use front side read-out (FSR) of SiPMs on the LSYO detector and not back facet read-out because of the tiny attenuation length on SPECT. These primary simulated scanner options were determined to be supported: LYSO is the scintillator substance; monolithic scintillators allow for executive department analysis; and d-SiPM is the electronic. SiPMs have a checkboarded layout with sensitive cells that are 6x6 millimeters in size. One detector unit has a length of 96 metric linear units and a width of 48 metric linear units. The scintillator has a thickness of twenty-four millimetres, which doubles the attenuation length for 511 keV photons.

The detector unit was simulated. The fundamental physical magnetism and optical processes have been identified. For such investigations, cross-sections and deposition curves match to traditional shapes. The optical parameters of the scintillator were imposed for calculations using supported technical documents. The reduction in energy resolution due to the LYSO spectrum is explained.

Small-animal PET will be accustomed image benign and malignant tumors, particularly to determine models of tumors and metastases in vivo to guage the expansion processes of and varied therapeutic effects on tumors. high-resolution PET supported latest chemical element photomultiplier (SiPM) technology will clearly establish the brain structure of tiny rodents for cerebral anaemia assessment, presenile dementia, degenerative disorder, epilepsy, and alternative diseases.

4. Financial management, resource efficiency and resource saving

Introduction

Nuclear medicine imaging methods such as single photon emission computed tomography (SPECT) and positron emission tomography (PET) provide metabolic and functional information. Fluorodeoxyglucose (FDG) for PET and technetium-99 for SPECT are two examples of radionuclides.
The purpose of this study was to simulate a multimodality PET/SPECT detector using Silicon Photomultipliers and a monolithic crystal (lutetium yttrium oxyorthosilicate, LYSO) (SiPMs).

The research methodology comprised a review of existing PET and SPECT joint detectors:

- Analysis of LYSO monolithic scintillator with SiPMs matrix as PET and SPECT gamma cameras
- Review of preclinical performance measures of mice phantoms for PET/SPECT Detection phantom simulation in geant4 and PET/SPECT Detector
- Building a full detector with a National Electrical Manufacturers Association (Nema)-Nu 2008 phantom as a result of this research
- Attenuation lengths for PET/SPECT LYSO scintillators were determined.

The project budget was 593,401 rubles, with costs of procuring equipment totaling 274,016 rubles and a supervisor's compensation of 87,239 rubles.

4.1. Pre-research Analysis

People who might be interested in the research findings. It is vital to split the market in order to assess research results customers.

Clients interested in the study results who would buy the good/service associated with the student's investigation make up the target market. The national research polytechnic university (TPU), medical scientific centers, and medical equipment manufacturers are all included in this case.

The grouping of purchasers into groups of similar, each of which may require a specific product, is known as segmentation (service). For segmenting the consumer market, you can use geographic, demographic, behavioral, and other factors, as well as their combinations, such as age, gender, nationality, education, favored professions, lifestyle, social connectivity, career, and level of income.

Appropriate segmentation criteria must be employed depending on the kind of consumer (commercial entities, individuals). For commercial businesses, segmentation criteria could include things like location, industry, manufactured products, size, and so on.

Age, sex, country, school, economic level, sense of belonging, career, and other factors could be used to segment persons.

You must choose the two most important criteria for the market from the list. A market segments is created based on these factors.

4.2. Competitiveness analysis of technical solutions

Analysis of competitive technical solutions in terms of resource efficiency and resource saving allows to evaluate the comparative effectiveness of scientific development. This analysis is advisable to carry out using an evaluation card.

Technical performance of project strongly depends on CPU power. For this work, three configurations were selected: *CPU Ryzen 9 5950X*, *CPU Ryzen 7 5800X and real detector*.

The position of the development and competitors is assessed for each indicator by an expert method on a five-point scale: 1 – the weakest position, 5 – the strongest.

The weights of the indicators, determined by expert judgment, should add up to one.

The analysis of competitive technical solutions is determined by the equation:

$$C = \sum_i P * W_i \qquad (4.1)$$

Where, C – the competitiveness of research or a competitor;

W_i – criterion weight;

P_i – point of i-th criteria.

The Table 4.1 shows comparison of three solutions: index *f* means Ryzen 9 5950X, *i1* – Ryzen 7 5800X, *i2* – real detector.

By comparison, Ryzen 9 5950X shows the best results but Ryzen 7 5800X has close results and same orders of values. Real detector has much lower results due to concept of project and importance of mutability of configuration in development step.

Table 4.1 – Evaluation card for comparison of competitive technical solutions

Evaluation criteria	Criterion weight	Points			Competitiveness		
		P_f	P_{i1}	P_{i2}	C_f	C_{i1}	C_{i2}
1	2	3	4	5	6	7	8
Technical criteria for evaluating resource efficiency							
1. Growth in User' productivity	0.4	5	4	1	2.00	1.60	0.4
2. Energy efficiency	0.05	5	5	1	0.25	0.25	0.05
3. Ability to connect to a computer network	0.05	3	2	5	0.15	0.10	0.25
4. Ease of operation	0.1	3	3	5	0.30	0.30	0.50
5.Functional capacity	0.05	5	5	3	0.25	0.25	0.15
6. Safety	0.01	5	5	4	0.05	0.05	0.04
7. Ease of operation	0.03	2	3	4	0.06	0.09	0.12
8. Convenience in operation (meets the requirements of consumers)	0.1	3	3	4	0.3	0.3	0.4
Economic criteria for performance evaluation							
1.Development cost	0.1	5	5	1	0.50	0.50	0.10
2.Price	0.2	4	5	1	0.80	1.00	0.02
3. Expected lifecycle	0.04	5	5	5	0.20	0.20	0.2
After-sales service	0.04	4	5	2	0.16	0.2	0.08
Estimated life-time	0.1	5	5	5	0.5	0.5	0.5
Market penetration rate	0.2	5	2	3	1	0.4	0.6
Total	1	59	57	44	6.25	5.74	3.41

The above information indicates the comparison of technical solution. The evaluation card shows the development of competitive advantages that will help the created product gain the trust of buyers by offering goods that are noticeably different either by a high level of quality with a standard set of parameters defining it, or by non-standard set properties of interest to the buyer.

4.2.2 SWOT analysis

Complex analysis solution with the greatest competitiveness is carried out with the method of the SWOT analysis: Strengths, Weaknesses, Opportunities and Threats. Table 4.2 presents the final SWOT-analysis matrix.

Analysis of SWOT matrix shows that combination of working on opportunities with weaknesses has more reliable options. In addition, strength features of project works with opportunities and threats as well. The lowest number of variants with combination of weaknesses and threats.

Table 4.2 – SWOT-analysis

	Strengths: S1. Possibility to change configuration. S2. Low cost of one experiment. S3. Low cost of equipment. S4. Portability on other devices. S5. Low preparation time.	Weaknesses: W1. Experiment requires a lot of time. W2. Consistency lower than real. W3. After project, the real detector required anyway.
Opportunities: O1. Accelerating calculation of experiment.	S1O1. Providing of high flexible and fast simulation to reduce number of possible variants of configurations.	W1O1. Using of calculation tricks to speed up experiment time.

O2. Improving of consistency. O3. Improving of equipment.	S4O1. Reducing of transport cost through internet transition of model. S4O3. Using cloud calculation power as equipment.	W2O2. Using some empirical knowledge to improve consistency. W3O3. PC devices can be chosen for next usage as part of detector. W1O3. Improving of CPU can significantly reduce calculation time.
Threats: T1. Calculation time to long. T2. Model will be not enough accurate. T3. Disability to include some real property.	S1T2. Exclude insignificant properties after testing different close configurations. S1T3. Tune configuration using known empirical data. S5T1. Using some tricks before each experiment.	W1T1. Necessary of reducing time performance. W3T3. Combination of simulation knowledge and real detector results.

The results of the SWOT analysis were taken into account when developing the structure of the work performed within the framework of the research project.

4.1 Project initiation

Beginning goals as well as content are defined, as well as initial financial resources. The project's internal and external stakeholders have been identified, and they will communicate and affect the research project's outcome.

4.1.1 Project goals and results

Table 4.3 – Stakeholders of the project

Stakeholders of the project	Stakeholders of the project expectations
Medical research institutes, medical equipment manufacturers, National research Tomsk polytechnic university (TPU)	Experimentation is inexpensive; System for modifying experiments that is flexible; The results are extremely precise.

The upper table contains information about the project's stakeholders, the project's hierarchy of goals, and the criteria for meeting those goals (Table 4.1). The table below shows the hierarchy of project goals and the conditions for meeting those goals.

Table 4.4 – Project goals and results

1	Project goals	The research goal is to simulate multimodality PET/SPECT detector based on monolithic crystal (lutetium yttrium oxyorthosilicate, LYSO) with Silicon PhotoMultipliers (SiPMs).
2	Expected results of the project	Check of simulation physics and optimization of calculation processes Construction of detector's plate
3	Acceptance criteria of the project result	High precision of experiments and enough statistics
4	Requirements to the project results	Project completion on time
		Stability of simulation provided
		The efficiency of the simulation

4.1.2 Organization structure of the project

Table 4.5 – Project Working Group

№	Name	Position	Functions	Hours spent
1	Mubanga .E.	Student	Work on project implementation	800
2	Gogolev A.S.	Superviser	Coordination of work activities and assistance in project implementation	140
3	Filatov Nikolay Aleksandrovich	Engineer	Building of Personal computer equipment	7
Total:				1147

The organizational structure of the project is presented in the Table 4.3. Engineer Filatov Nikolay Aleksandrovich is employer from research unit of TPU "X-Ray Optics International Lab". As all equipment for work belongs to laboratory, the building of PC was done by laboratory specialist.

4.1.3 Assumptions and constraints

Table 4.6 – Limitations and assumptions

Factor	**Limitations/assumptions**
1. Project budget - for PC and design	593401 RUB
1.1 Source of budgeting	Customers
2. Project timeline:	1 Febuary 2022 – 30 May 2022
2.1 Date of approval of the project management plan	05 February 2022

Limitations and assumptions are summarized in the upper table.

As a result, of the initialization of the project, the goals and expected results were formulated; the stakeholders of the project and the financial framework were identified, which is important for the completion of the project and its implementation.

4.1.4 Project planning

Deadlines for the project stages are listed in Table 4.7. In addition, Table 4.8 visualized project schedule in form of bar chart also called Gantt chart.

Table 4.7 – Project timeline

No.	Job title	Duration, working days	Start date	Date of completion	Participants
1	Building Personal computer(PC)	1	01.02.2022	02.02.2022	Engineer
2	Drawing up the technical assignment	4	01.02.2022	05.02.2022	Supervisor
3	Calendar planning	4	06.02.2022	10.02.2022	Supervisor, Student
4	Literature review	13	11.02.2022	24.02.2022	Student
5	Choosing of PET/SPECT configuration	3	25.02.2022	28.02.2022	Supervisor, Student
6	Detector unit Geant4 implementation	20	01.03.2022	21.03.2022	Student
7	Evaluation of detector unit performance	10	21.03.2022	31.03.2022	Student
8	Updating of PET/SPECT configuration	10	01.04.2022	11.04.2022	Supervisor, Student
9	Phantoms Geant4 implementation	11	12.04.2022	23.04.2022	Student
10	PET system Geant4 implementation	15	24.04.2022	09.05.2022	Student
11	Evaluation of PET/SPECT system performance	10	10.05.2022	20.05.2022	Student
12	Summarizing	2	21.05.2022	23.05.2022	Supervisor, Student
13	Drawing up a final report	6	24.05.2022	30.05.2022	Student

A Gantt chart, or harmonogram, is a type of bar chart that illustrates a project schedule. This chart lists the tasks to be performed on the vertical axis, and time intervals on the horizontal axis. The width of the horizontal bars in the graph shows the duration of each activity.

Table 4.8 – Schedule of the project design

№	Activities	Participants	*Tc, days*	Duration of the project															
				February				March				April				May			
				1	2	3	4	1	2	3	4	1	2	3	4	1	2	3	4
1	Building personal computer	Engineer	1																
2	Drawing up the technical assignment	Supervisor	4																
3	Calendar planning	Supervisor, Student	4																
4	Literature review	Student	13																
5	Choosing of PET/SPECT configuration	Supervisor, Student	3																
6	Detector unit Geant4 implementation	Student	20																
7	Evaluation of detector unit performance	Student	10																
8	Updating of PET/SPECT configuration	Supervisor, Student	10																
9	Phantoms Geant4 implementation	Student	11																
10	PET/SPECT system Geant4 implementation	Student	15																

11	Evaluation of PET/SPECT system performance	Student	10
12	Summarizing	Supervisor, Student	2
13	Drawing up a final report	Student	6

* Tc – calendar days

Supervisor | Student | Engineer

Total duration: Mubanga E. (Student) – 104 days, Gogolev A.S. (Supervisor) – 23 days, Engineer – 1 day

4.1.5 Project budgeting

The project budget must display reliable values for all types of costs associated with its implementation. The costs of this project include:

- Costs of purchasing equipment;
- Costs of additional materials;
- Expenses for the main and additional salaries of the theme performers;
- Costs of social security contributions;

4.1.5.1 Costs of purchasing equipment

Due to digital twin concept, only Personal computer equipment required.

Table 4.7 shows needful basic equipment and accessories, and its cost for scientific work.

Table 4.9 – Cost of equipment and accessories for project

Name of equipment	Quantity, units	Price per unit, tsd rub	Total cost for position, tsd rub
CPU	1	95	95
Motherboard	1	30	30
CPU Cooler	1	11	11
Memory module	1	66	66
Power supply	1	15	15
SSD	1	12	12
Computer case	1	4	4
GPU	1	7	7
Monitor	1	25	25
UPS	1	6	6
Electricity			3
Total:			274

All transportation costs already are included in price of equipment. Electricity cost are calculated by formula:

$$C = P_{el} * P * F_{eq}, \qquad (4.1)$$

Where, P_{el} – power rates (5.8 rubles per 1 kWh);

P – power of equipment (0.65 kW);

F_{eq} – equipment usage time, hours. (800 hours);

So, cost of power for project time is about 3016 rubbles.

Depreciation is the gradual transfer of costs incurred to purchase or build property, plant and equipment to the cost of the finished product. With its help, money spent on the construction or purchase of property is compensated. Depreciation deductions are paid during the entire period of property exploitation.

Working time deprecation for PC as an whole was calculated with linear equation:

$$C*T_w / T_{full} * 365 \qquad (4.2)$$

Where,

C – Price of PC (271000 rubles);

T_w – working days (104 days);

T_{full} – life time of equipment (7 years).

Final deprecation for working period according to (3.2) is 11031 rubles. All required software and operation system are open-source, which cost for this no needs to include.

4.1.5.2 Costs of additional materials

Table 5.8 shows needful other materials for scientific work. These costs include office supplies, printing costs and various equipment required for research except specialized equipment.

Table 4.10 – Cost of additional materials for project

Name	Unit of measurement	Number	Price per unit, RUB	Expenses (E_M), RUB
Paper	Pack	1	250	250
Name	Unit of measurement	Number	Price per unit, RUB	Expenses (E_M), RUB
Pens	Unit	2	50	100
Pencils	Unit	1	50	50
Ruler	Unit	1	40	40
Printing	Page	100	2	200
Folder	Unit	2	5	10
Total				425

4.1.5.3 Salary

The quantity of earnings paid to employees is calculated using the amount of labour required of the services done as well as the current salary and customs tariff system.

The sector pay system is used to calculate the basic remuneration of the head of a research project. At TPU, the division structure of payments comprises the following wage composition:

- The company sets the salary. Salaries at TPU are allocated according on the roles held, such as assistant, art lecturer, associate professor, and professor (see "Regulations on remuneration" given on the website of the Planning and Finance Department of TPU).

- Incentive money - set by department heads for good work, extra responsibilities, and so on.
- Districts coefficient; other payments

Because incentive bonuses, additional payments, and rewards are all dependent on the management's activities, we will employ a 30 percent coefficient for incentive bonuses (kb) and a 25 percent coefficient for incentives for conscientious work (kpr) activity, with a regional coefficient of 1.3.

Average daily salary S_d for a 5-day working week:

$$S^d = S / F_d \tag{4.3}$$

Where S – monthly salary, rub;

F_y – average number of working days in a month;

Monthly salary with bonuses S_M can be calculated using formula:

$$S_M = S_b *(1 *k_{pr} * k *k_b)*K_r \tag{4.4}$$

Where, S_b – basic monthly salary, rub.

Additional monthly salary:

$$S_{add} = k_{extra} *S_M \tag{4.5}$$

Where, k_{extra} – additional salary coefficient (10-15%). For calculation values 10% is used.

Average number of working days in a month F_d was determined as:

$$F_d = D/M = 247/ 12 = 20.58 \tag{4.6}$$

Where, D – number of working days in year (247 days); M – number of months in year (12);

Salary for working period T can be determined through daily salary S^d as:

$$S^W = S * T^d \qquad (4.7)$$

The full salary for working period is:

$$S_{full}^{w} = S_M^W + S_W^{add} \qquad (4.8)$$

Where, S_M^W – salary with bonuses for working period, rub; S_W^{add} – additional salary for working period, rub.

Table 5.9 shows calculated salary values for Supervisor and student. Student was equalized to engineer-researcher. $S_M{}^d$ and $S_{add}{}^d$ are daily corresponding salaries. Engineer in this project has one-time job. Salary for building PC by engineer costed 1000 rubles.

Table 4.11 – Salaries of participants in the project

Participants	S_b, rub	S_M, rub	S_{add}, rub	$S_M{}^d$, rub	S_d^{add}, rub	T, days	S_M^W, rub	S_W^{add}, rub	S_{full}^{w}, rub
Gogolev A.S.	45000	90675	9068	4406	441	18	79308	7931	87239
Mubanga E.	20000	40300	4030	1958	196	69	135117	13512	148629
Engineer									1000
Total:									236868

4.1.5.4 Contributions to social funds

I shall deduct mandatory contributions to the state social insurance bodies (FSS), the pension fund (PF), and medical insurance (FFOMS) from employee earnings in accordance with Russian Federation legislation. The following formula determines the amount of contributions to extra-budgetary funds: $S_{soc} = k_{soc} * S_{full}^{w}$ (4.9)

Where, k_{soc} – contribution rate to extrabudgetary funds.

In accordance with Federal Law № 212-FL of 24.07.2009, the amount of insurance premiums is set at 30 %. Table 3.12 shows contributions to social funds.

Table 3.12 – Contributions to social funds

Participants	*S*, rub	*kexb*	S_{exb}, rub
Gogolev A.S.	87239	30%	26172
Mubanga .E	148629		44589
Engineer	1000		300
Total:			71061

4.1.5.5 Formation of the budget of the costs of a research project

Table 4.13 – The total budget of research

Name	Cost, rub	Cost, %
Costs of purchasing equipment	274016	46.17
Deprecation of equipment	11031	1.86
Costs of additional materials	425	0.07
Supervisor salary costs	87239	14.70
Student (Researcher) salary costs	148629	25.05
Engineer	1000	0.17
Contributions to social funds	71061	11.98
Research budget	593401	100

4.2 Economic model development

4.2.1 Methods of commercialization of the results of scientific and technical research

Due to high price of final PET system (over 150 million rubles), any event of selling vary unique and highly depends on customer and developer. However, for most common situation expertise is preferred as most flexible type for this purpose.

4.3 Evaluation of the comparative efficiency of the scientific research project

Determination of efficiency is based on the calculation of the integral indicator of the effectiveness of scientific research. Its finding is associated with the determination of two weighted averages: financial efficiency and resource efficiency.

Integral financial indicator I_f^p of a scientific research is obtained in the course of assessing the budget of the costs of three (or more) variants of the implementation of a scientific research. For this, the largest integral indicator of the implementation of a technical problem is taken as the calculation base (as the denominator), with which the financial values for all execution options are correlated.

Integral financial indicator I_f^p of current project is determined in the equation:

$$I_f^p = F_{pi} / F_{max} , \qquad (4.11)$$

Where, F_{pi} – price for i-th variant of execution;

F_{max} – maximum cost of execution of a research project (including analogs).

The resulting value of the integral financial indicator of development reflects the corresponding numerical increase in the budget of development costs in times (a value greater than one), or the corresponding numerical reduction in the cost of development in times (a value less than one, but higher than zero).

The integral indicator of the resource efficiency I_m^p,I_m^a of the variants of the object of research can be defined as follows:

$$I_m^a = \sum_{i=1}^{n} a_i * b_i^a \qquad (4.12)$$

$$I_m^p = \sum_{i=1}^{n} a_i * b_i^p \qquad (4.13)$$

Where,

a_i – the weight coefficient of the i[th] parameter;

b b_i^a , $_i^p$ – the score of the i[th] parameter for the analog and development, set by an expert method on the selected rating scale, index a means alternative, p – project;

n – The number of comparison parameters.

For comparative analysis were chosen CPU Ryzen 9 5950X, CPU Ryzen 7 5800X and real detector as in section 4.2.1.

Table 4.14 – Comparative evaluation of the characteristics of the project

Criteria	Weighting factor	Scientific research project (Ryzen 9 5950X)	Alternative 1 (Ryzen 7 5800X)	Alternative 2 (Real detector)
1. Mutability	0.3	5	5	1
2. Execution time	0.2	3	2	5
3.After usability	0.2	5	4	5
4. Workers qualification	0.1	4	4	2
5. Consistency	0.2	3	3	5
Total:	1	20	18	18

An integral efficiency indicator of the scientific research project I_{fin}^{p} and of the analog I_{fin}^{a} are determined according to the formula of the integral basis of the financial integral resource efficiency:

$$I_{fin}^{a} = \frac{I_m^a}{I_f^a} \tag{4.14}$$

$$I_{fin}^{p} = \frac{I_m^p}{I_f^p} \tag{4.15}$$

Comparison of the integral indicator of the efficiency of the current project and analogs will determine the comparative efficiency the project. Comparative project efficiency, E_{av} :

$$E_{av} = \frac{I_{fin}^{p}}{I_{fin}^{a}} \qquad (4.16)$$

All calculated indicators are listed in Table 4.15.

Table 4.15 – Comparative project efficiency

№	Indicator	Project,	Alternative 1	Alternative 2
	Final cost, rub	593401	545401	58632548
1	Integral financial indicator I_{fin}^{p}	0.01	0.009	1
2	Integral resource efficiency indicator I_{m}^{p}, I_{m}^{a}	4.1	3.7	3.5
3	Integral efficiency indicator I_{fin}^{a}, I_{fin}^{p}	408.4	401.2	3.5
4	Comparative evaluation of the project execution variants	Alternative 1: 1.02 Alternative 2: 116.69	Alternative 2: 114.63	Alternative 1: 0.01

Comparison of the integral indicator allows to understand and choose a cheaper option for solving the technical problem in terms of financial and resource efficiency.

As a result, we can conclude that the most optimal option is CPU Ryzen 9 5950X.

4.4 Conclusion

In this financial section, the general organizational and planning stage were determined. For effective time managing of project, the Gantt diagram was constructed.

In addition, the cost required for project were calculated. Summary cost was divided onto such groups as: purchasing equipment, additional materials, salaries, social security contributions. After all calculations, the final budget of project was evaluated as 593401 rubles.

Finally, economic potential of project was observed. Competitive analysis was provided and results show PC with CPU Ryzen 9 5950X as best option for project. For developing of project SWOT matrix was constructed. The most varies way according to SWOT is use opportunities of improvement to reduce weaknesses of project. As final parameter the comparative efficiency was evaluated and shown well results.

5. Social responsibility

5.1 Introduction

In the modern days, the cost of small-animal PET system is high enough (over 100 million rubbles). It is important to know performance and optimize configuration of PET system to exclude overhead on building step. Digital twin one of the solutions of this problem. However, simulation of PET system on the personal computer cost much lower than real detectors. Hence, allows changing configuration fast. The location of this work was in room 042 B, at the 10^{th} building, Lenin Avenue, 2.

5.2 Legal and organizational items in providing safety

Nowadays one of the main ways to radical improvement of all prophylactic work referred to reduce Total Incidents Rate and occupational morbidity is the widespread implementation of an integrated Occupational Safety and Health management system. That means combining isolated activities into a single system of targeted actions at all levels and stages of the production process.

Occupational safety is a system of legislative, socio-economic, organizational, technological, hygienic, therapeutic, and prophylactic measures and tools that ensure the safety, preservation of health and human performance in the work process [52].

According to the Labor Code of the Russian Federation, every employee has the right:

- to have a workplace that meets Occupational safety requirements;
- to have a compulsory social insurance against accidents at manufacturing and occupational diseases;
- to receive reliable information from the employer, relevant government bodies and public organizations on conditions and Occupational safety at the workplace, about the existing risk of damage to health, as well as measures to protect against harmful and (or) hazardous factors;

- to refuse carrying out work in case of danger to his life and health due to violation of Occupational safety requirements;
- be provided with personal and collective protective equipment in compliance with Occupational safety requirements at the expense of the employer;
- for training in safe work methods and techniques at the expense of the employer;
- for personal participation or participation through their representatives in consideration of issues related to ensuring safe working conditions in his workplace, and in the investigation of the accident with him at work or occupational disease;
- for extraordinary medical examination in accordance with medical recommendations with preservation of his place of work (position) and secondary earnings during the passage of the specified medical examination;
- for warranties and compensation established in accordance with this Code, collective agreement, agreement, local regulatory an act, an employment contract, if he is engaged in work with harmful and (or) hazardous working conditions. [55]

The labor code of the Russian Federation states that normal working hours may not exceed 40 hours per week. The employer must keep track of the time worked by each employee.

Rules for labor protection and safety measures are introduced in order to prevent accidents, ensure safe working conditions for workers and are mandatory for workers, managers, engineers and technicians. [55]

5.3. Basic ergonomic requirements for the correct location and arrangement of researcher’s workplace

The location of this work was in room 042 B, at the 10th building, Lenin Avenue, 2.

The workplace when working with a PC should be at least six square meters. The legroom should correspond to the following parameters: the legroom height is at least 600 mm, the seat distance to the lower edge of the working surface is at least 150 mm, and the seat height is 420 mm. It is worth noting that the height of the table should depend on the growth of the operator.

The following requirements are also provided for the organization of the workplace of the PC user:

- The design of the working chair should ensure the maintenance of a rational working posture while working on the PC and allow the posture to be changed in order to reduce the static tension of the neck and shoulder muscles and back to prevent the development of fatigue. [53]
- The type of working chair should be selected taking into account the growth of the user, the nature and duration of work with the PC. The working chair should be lifting and swivel, adjustable in height and angle of inclination of the seat and back, as well as the distance of the back from the front edge of the seat, while the adjustment of each parameter should be independent, easy to carry out and have a secure fit. [53]

5.4. Occupational safety

A dangerous factor or industrial hazard is a factor whose impact under certain conditions leads to trauma or other sudden, severe deterioration of health of the worker. The factors were considered at the location of this work in room 042 B, at the 10th building, Lenin Avenue, 2.

A harmful factor or industrial health hazard is a factor, the effect of which on a worker under certain conditions leads to a disease or a decrease in working capacity. [54]

5.4.1 Analysis of harmful and dangerous factors that can create object of investigation

During PET scanning, the radiopharmaceuticals are implemented. As these drugs, have radioactive isotopes all corresponding harmful and dangerous factors such as:

- Internal exposure to ionizing radiation occurs when radionuclides are inhaled, absorbed or otherwise entered the circulation.
- External radioactive contamination can occur when radioactive material in the air (dust, liquid, aerosols) settles on the skin or clothes.
- External irradiation of human body from different gamma – sources, also lead to DNA damage.

5.4.2 Analysis of harmful and dangerous factors that can arise at workplace during investigation

The working conditions in the workplace (room 042 B, at the 10^{th} building, Lenin Avenue, 2) are characterized by the presence of hazardous and harmful factors, which are classified by groups of elements:

- physical,
- chemical,
- biological,
- Psychophysiological.

The main elements of the production process that form dangerous and harmful factors are presented in Table 5.1.

Table 5.1 – Possible hazardous and harmful factors

Factors (GOST 12.0.0032015)	Work stages			Legal documents
	Development	Manufacture	Exploitation	
1. Deviation of microclimate indicators	+	+	+	Sanitary rules 2.2.2 / 2.4.1340–03. Sanitary and epidemiological rules and regulations "Hygienic requirements for personal electronic computers and work organization." [53] Sanitary rules 2.2.1 /
2. Excessive noise		+	+	
3.Increased level of electromagnetic radiation	+	+	+	
4.Insufficient illumination of the working area		+	+	2.1.1.1278–03.Hygienic requirements for natural, artificial and combined lighting of residential and public buildings [56] Sanitary rules 2.2.4 / 2.1.8.562–96. Noise at workplaces, in premises of residential, public buildings and in the construction area [57]. Sanitary rules 2.2.4.548–96.

				Hygienic requirements for the microclimate of industrial premises[58]
5. Abnormally high voltage value in the circuit, the closure which may occur through the human body	+	+	+	Sanitary rules GOST 12.1.03882 SSBT. Electrical safety. Maximum permissible levels of touch voltages and currents [59].

When carrying out work related to theoretical research, an important role is played by the layout of the workplace. It must comply with the rules of labor protection and meet the requirements of convenience of work, saving energy and time of the engineer.

The main document that defines working conditions when working with a PC is SanPiN 2.2.2/2.4.1340-03 "Hygienic requirements for personal electronic computers and organization of work." The rules specify the basic requirements for premises, microclimate, noise and vibration, lighting of premises and workplaces, organization and equipment of workplaces.

The following factors effect on person working on a computer:

- *Physical, temperature and humidity, noise, static electricity, electromagnetic field of low purity, illumination, presence of radiation; – psychophysiological: physical overload (static, dynamic), mental stress (mental overstrain, monotony of work, emotional overload).*

Deviation of microclimate indicators

The air of the working area (room 042 B, at the 10th building, lenin avenue, 2) (microclimate) is determined by the following parameters:

- Temperature, relative humidity, air speed.

The optimum and permissible values of the microclimate characteristics are established in accordance with [53] and are given in Table 5.2.

Table 5.2 – Optimal and permissible parameters of the microclimate

Period of the year	Temperature, °C	Relative humidity,%	Speed of air movement, m/s
Cold	23-25	40-60	0.1
Warm	23-25	40	0.1

Excessive noise

Noise and vibration were considered at (room 042 B, at the 10th building, Lenin Avenue, 2). This factor worsen working conditions, have a harmful effect on the human body, namely, the organs of hearing and the whole body through the central nervous system. It result in weakened attention, deteriorated memory, decreased response, and increased number of errors in work. Noise can be generated by operating equipment, air conditioning units, daylight illuminating devices, as well as spread from the outside. When working on a PC, the noise level in the workplace should not exceed 50 dB [57].

Increased level of electromagnetic radiation

The screen and system blocks produce electromagnetic radiation. Its main part comes from the system unit and the video cable. According to [53], the intensity of the electromagnetic field at a distance of 50 cm around the screen along the electrical component should be no more than:

- in the frequency range 5 Hz - 2 kHz - 25 V / m;
- in the frequency range 2 kHz - 400 kHz - 2.5 V / m.

The magnetic flux density should be no more than:

- in the frequency range 5 Hz - 2 kHz - 250 nT;
- in the frequency range 2 kHz - 400 kHz - 25 nT.

Abnormally high voltage value in the circuit

Depending on the conditions (room 042 B, at the 10th building, Lenin Avenue, 2), the risk of electric shock to a person increases or decreases. Do not operate the electronic device in conditions of high humidity (relative air humidity exceeds 75% for a long time), high temperature (more than 35 °C), the presence of conductive dust, conductive floors and the possibility of simultaneous contact with metal components connected to the ground and the metal casing of electrical equipment. The operator works with electrical devices: a computer (display, system unit, etc.) and peripheral devices. There is a risk of electric shock in the following cases:

- with direct contact with current-carrying parts during computer repair;
- when touched by non-live parts that are under voltage (in case of violation of insulation of current-carrying parts of the computer);
- when touched with the floor, walls that are under voltage;
- Short-circuited in high-voltage units: power supply and display unit.

Table 5.3 – Upper limits for values of contact current and voltage

	Voltage, V	Current, mA
Alternate, 50 Hz	2	0.3
Alternate, 400 Hz	3	0.4
Direct	8	1.0

Insufficient illumination of the working area

Light sources can be both natural and artificial. The natural source of the light in the room (042 B, at the 10th building, Lenin Avenue, 2) is the sun, artificial light are lamps. With long work in low illumination conditions and in violation of other parameters of the illumination, visual perception decreases, myopia, eye disease develops, and headaches appear.

According to the standard, the illumination on the table surface in the area of the working document should be 300-500 lux. Lighting should not create glare on the surface of the monitor. Illumination of the monitor surface should not be more than 300 lux.

The brightness of the lamps of common light in the area with radiation angles from 50 to 90° should be no more than 200 cd/m, the protective angle of the lamps should be at least 40°. The safety factor for lamps of common light should be assumed 1.4. The ripple coefficient should not exceed 5%.

5.4.3 Justification of measures to reduce the levels of exposure to hazardous and harmful factors on the researcher

Deviation of microclimate indicators

The measures for improving the air environment in the production room (room 042 B, at the 10th building, Lenin Avenue, 2) includes: the correct organization of ventilation and air conditioning, heating of room. Ventilation can be realized naturally and mechanically. In the room, the following volumes of outside air must be delivered:

- at least 30 m^3 per hour per person for the volume of the room up to 20 m^3 per person;
- Natural ventilation is allowed for the volume of the room more than 40 m^3 per person and if there is no emission of harmful substances.

The heating system must provide sufficient, constant and uniform heating of the air. Water heating should be used in rooms with increased requirements for clean air.

The parameters of the microclimate in the laboratory regulated by the central heating system, have the following values: humidity 40%, air speed 0.1 m/s, summer temperature 20-25 °C, in winter 13-15 °C. Natural ventilation is provided in the laboratory. Air enters and leaves through the cracks, windows, doors. The main disadvantage of such ventilation is that the fresh air enters the room without preliminary cleaning and heating [58].

Excessive noise

In research audiences, there are various kinds of noises that are generated by both internal and external noise sources. The internal sources of noise are working equipment, personal computer, printer, ventilation system, as well as computer equipment of other engineers in the audience. If the maximum permissible conditions are exceeded, it is sufficient to use sound-absorbing materials in the room (sound absorbing wall and ceiling cladding, window curtains). To reduce the noise penetrating outside the premises, install seals around the perimeter of the doors and windows [57].

Increased level of electromagnetic radiation

There are the following ways to protect against EMF:

- increase the distance from the source (the screen should be at least 50 cm from the user);
- the use of pre-screen filters, special screens and other personal protective equipment.

When working with a computer, the ionizing radiation source is a display. Under the influence of ionizing radiation in the body, there may be a violation of normal blood coagulability, an increase in the fragility of blood vessels, a decrease in immunity, etc. The dose of irradiation at a distance of 20 cm to the display is 50 μrem/hr. According to the norms [53], the design of the computer should provide the power of the exposure dose of x-rays at any point at a distance of 0.05 m from the screen no more than 100 μR/h [61].

Fatigue of the organs of vision can be associated with both insufficient illumination and excessive illumination, as well as with the wrong direction of light.

Abnormally high voltage value in the circuit

Measures to ensure the electrical safety of electrical installations:

- disconnection of voltage from live parts, on which or near to which work will be carried out, and taking measures to ensure the impossibility of applying voltage to the workplace;
- posting of posters indicating the place of work;
- electrical grounding of the housings of all installations through a neutral wire;
- coating of metal surfaces of tools with reliable insulation;
- Inaccessibility of current-carrying parts of equipment (the conclusion in the case of electroporating elements, the conclusion in the body of current carrying parts) [54].

Insufficient illumination of the working area

Desktops should be placed in such a way that the monitors are oriented sideways to the light openings, so that natural light falls mainly on the left.

In addition, as a means of protection to minimize the impact of the factor, local lighting should be installed due to insufficient lighting, window openings should be equipped with adjustable devices such as blinds, curtains, external visors, etc [56].

5.5 Ecological safety

5.5.1 Analysis of the impact of the research object on the environment

Sources of ionizing radiation used in medicine could be divided into two groups:

- Radioactive substances and radiation generators: The difference is that radiation generators like accelerators and x-ray tubes emit ionizing radiation only when they are turned on.
- In ordinary work with necessary safety precautions, there are insignificant impact of using sources of ionizing radiation on environment. The immediate effect of ionizing radiation is ionization of air in room, but after a specified time the ionization disappears.

The danger of using radioactive materials could occur only in accidents with stealing and loosing these materials due to high toxicity [60].

5.5.2 Analysis of the environmental impact of the research process

Process of investigation itself in the thesis do not have essential effect on environment. One of hazardous waste is fluorescent lamps. Mercury in fluorescent lamps is a hazardous substance and its improper disposal greatly poisons the environment.

Outdated devices goes to an enterprise that has the right to process wastes. It is possible to isolate precious metals with a purity in the range of 99.95–99.99% from computer components. A closed production cycle consists of the following stages:

primary sorting of equipment; the allocation of precious, ferrous and non-ferrous metals and other materials; melting; refining and processing of metals. Thus, there is an effective disposal of computer devices [53].

5.5.3 Justification of environmental protection measures

Pollution reduction is possible due to the improvement of devices that produces electricity, the use of more economical and efficient technologies, the use of new methods for generating electricity and the introduction of modern methods and methods for cleaning and neutralizing industrial waste. In addition, this problem should be solved by efficient and economical use of electricity by consumers themselves. This is the use of more economical devices, as well as efficient regimes of these devices. This also includes compliance with production discipline in the framework of the proper use of electricity.

Simple conclusion is that it is necessary to strive to reduce energy consumption, to develop and implement systems with low energy consumption. In modern computers, modes with reduced power consumption during long-term idle are widely used [53].

5.6 Safety in emergency

5.6.1 Analysis of probable emergencies that may occur at the workplace during research

The safety measure were considered in the room 042 B, 10^{th} building.

Table 5.4 Safety in emergency

No.	Causes of fire	Prevention(s)	Response(s)
1	malfunction of current-carrying parts of installations;	- correct maintenance of buildings and territories (exclusion of the source of ignition - prevention of spontaneous combustion of substances, restriction of fireworks);	-Take measures to eliminate the accident in accordance with the instructions. - call 112
2	work with open electrical equipment	the correct operation of the equipment (proper inclusion of equipment in the electrical supply network, monitoring of heating equipment);	-Take measures to eliminate the accident in accordance with the instructions - Call 112
3	short circuits in the power supply	elimination of the formation of a flammable environment (sealing equipment, control of the air, working and emergency ventilation);	Call the Emergency Service or the Ministry of Emergency, 112

4	non-compliance with fire safety regulations	training of production personnel in fire safety rules the publication of instructions, posters, the existence of an evacuation plan	inform the management (duty officer) Call 112
5	- presence of combustible components: documents, doors, tables, cable insulation, etc.	- use in the construction and decoration of buildings of non-combustible or difficultly combustible materials	- Call the Emergency Service or the Ministry of Emergency Situations - tel. 112; - Take measures to eliminate the accident in accordance with the instructions

Activities on fire prevention are divided into organizational, technical, operational and regime [54].

5.6.2 Substantiation of measures for the prevention of emergencies and the development of procedures in case of emergencies

Organizational measures provide for correct operation of equipment, proper maintenance of buildings and territories, fire instruction for workers and employees, training of production personnel for fire safety rules, issuing instructions, posters, and the existence of an evacuation plan.

The technical measures include compliance with fire regulations, norms for the design of buildings, the installation of electrical wires and equipment, heating, ventilation, lighting, the correct placement of equipment [54].

5.6.3. Illumination of the working area

In room 042B, comfortable light working conditions were put into consideration. These improve visual work conditions, reduces fatigue, improves labour productivity, has a beneficial effect on the working environment, having a positive psychological impact on the worker, increases labor safety and reduces injuries.

Mixed lighting is used in this working room. Natural lighting is provided through a window in the outer wall of the building. As artificial lighting, a general lighting system is used (lighting, the lamps of which illuminate the entire area of \u200b\u200bthe room). Illumination on the surface of the table in the area where the working document is placed should be 300 lux. In this work, we used the "General sanitary and hygienic requirements for the indicators of the microclimate of the working area, which establishes the SanPiN 2.2.4.3359-16 standard."

To organize such lighting, it is better to choose fluorescent lamps 66, as they have a number of advantages over incandescent lamps: their spectrum is closer to natural light; they have greater efficiency (greater light output) and service life (10–12 times longer than incandescent lamps). However, it should be remembered that there are also disadvantages: the operation of lamps of this type is sometimes accompanied by noise; they work worse at low temperatures; such lamps have a low inertia. For a given room in which the information system will be operated, fluorescent lamps are suitable. Currently, the laboratory uses SHOD lamps (fluorescent lamp corresponding to a wide type of luminous intensity curve, belonging to the reflected light class of the lamp in terms of light distribution) [53].

The norms for these works set the required illumination of the workplace E = 300 lux (since the work is of very high accuracy - the smallest size of the object of difference is 0.15–0.3 mm; the category of visual work is G, the background is light, the contrast of the object with the background is large). The illumination value is corrected taking into account the safety factor, because over time due to pollution of fixtures and a decrease in light lamp flow decreases illumination. The value of the safety factor, selected for a room with low dust emission, with fluorescent lamps KZ = 1.5. The location of the fixtures must meet two criteria:

- ensuring high quality lighting, limiting glare and;
- the necessary direction of light to workplaces.

The most economical creation of normalized illumination. Let us place the lamps parallel to the walls. The distance between luminaires calculated by the formula:

$$L = \lambda * h \qquad (5.1)$$

Where, L is the distance between the lamps, m;

h is the height of the lamp suspension above the working surface, 2.5 m.

We find λ = 1.2 (at h = 2.5 m)

From this, it follows that:

$L = \lambda * h = 1.2 * 2.5 = 3$ m.

The distance from the walls of the room to the outer lamps is 1/3·L.

$$F = \frac{E*K*S*Z}{\eta*n}, \qquad (5.2)$$

Where, F is the calculated luminous flux, lm;

E - Normalized minimum illumination, lux (determined by table).

The work of a specialist, in accordance with this table, can be attributed to the category of precise work; therefore, the minimum illumination will be E \u003d 400 lux;

S - is the area of the illuminated room (in our case, S = 48 m^2);

Z -is the ratio of average illumination to minimum (usually taken equal to 1.1-1.2, let Z = 1.1);

K - safety factor, taking into account the decrease in luminous flux lamps as a result of contamination of luminaires during operation (its value depends on the type of premises and the nature of the work carried out in it and in our case K = 1.5);

η - is the utilization factor, (expressed by the ratio of light flow incident on the design surface to the total flow of all lamps and is calculated in fractions of a unit; depends on the characteristics of the lamp, the size of the room, the colour of the walls and ceiling, characterized by reflection coefficients from walls (RS) and ceiling (RP)).

They are evaluated subjectively and determined according to the table. So, for a freshly whitewashed ceiling and with freshly whitewashed windows without curtains PC = 50% and RP = 70%, respectively.

The value of η is determined from the table of utilization factors various lamps. To do this, calculate the room index using the formula:

$$I = \frac{S}{h.(A+B)}, \qquad (5.3)$$

Where, S is the area of the room, S = 45 m^2;

h -is the estimated suspension height, h = 2.3 m;

A -is the width of the room, A = 7 m;

B -is the length of the room, B = 9 m. Substituting the values, we get:

$$I = \frac{45}{23*(7+9)} = 0.122 \qquad (5.4)$$

Knowing the room index I, we find from the table η = 0.6.

When choosing lighting fixtures, we use OD-type fixtures. Each luminaire comes with two lamps. We place the lamps in two rows. Each row can have 3 lamp type ODR. The length of one lamp is 1 m, 69 the width is 0.5 m.

In this case, the gaps between the lamps in a row will be 50 cm. We depict in

scale layout of fixtures on it (Figure 5.1).

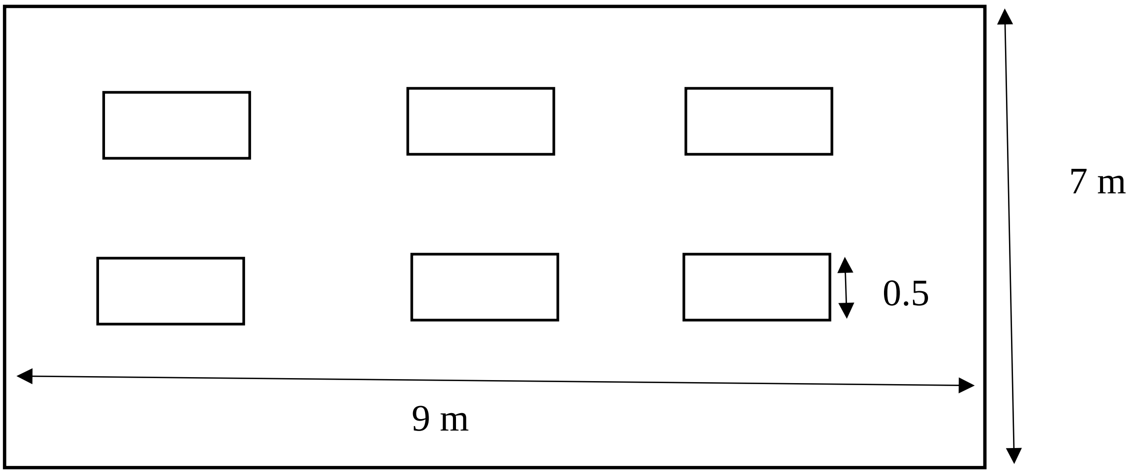


Fig 5.1. Luminaire layout

Let us substitute all the values into the formula for determining the luminous flux

F:

$$F = \frac{400 * 1.5 * 48 * 1.1}{0.6 * 12} = 4400$$

In accordance with the luminous flux, we select a standard LB lamp -80-4 with a flow of 4960 lm. Thus, the lighting system of the laboratory corresponds to norms.

5.6.3. Fire, explosion hazard

A fire in the office, 042B, building 10^{th}, can lead to irreversible consequences (loss of valuable information, damage to property, injury and death of people), therefore it is necessary: to identify and eliminate all causes of fire; to analyse the plan of measures to eliminate the fire in the building; building evacuation plan.

The room 042 B, at the 10th building was classified with room category B4, room zone class П-IIa.

The causes of a fire can be:

- Faulty electrical wiring, sockets and switches, which can lead to a short circuit or insulation breakdown;
- Use of damaged (faulty) electrical appliances;
- Use indoor electric heaters with open heating elements;

- The occurrence of a fire due to lightning entering the building;

- Fire of the building due to external influences;
- Careless handling of fire and non-compliance with fire safety measures [55].

Table 5.5. Maximum allowable values of touch voltages and currents

Type of current	Normalized value	Maximum allowable values, no more, with the duration of current exposure t, s									
		0,01–0,08	0,1	0,2	0,3	0,4	0,5	0,6	0,7	0,8	0,9
Variable 50 Hz	Y, B I, мА	550	340	160	135	120	105	95	85	75	70

Operational measures provide for the correct operation of the equipment and the correct maintenance of the premises that meets the requirements of SNiP 245-71 [62].

As a means of fire extinguishing, fire hydrants located in the corridor, as well as a mobile carbon dioxide fire extinguisher of the OP-1 type, are used. Powder fire extinguisher OP-1 is designed to extinguish the fire of solid, liquid and gaseous substances (class A, B, C or B, C, depending on the type of powder used).

Let us draw the layout of the room in accordance with the initial data, indicate the location of the lamps on it and determine their number.

Let us use the luminous flux utilization factor method. It can be used to calculate both the luminous flux of lamps necessary to create a given illumination of a horizontal surface, taking into account the light reflected by the walls and ceiling, and the illumination with a known flux.

To determine the number of fixtures, we determine the luminous flux incident on the surface according to the formula [55].

5.7 Conclusion

In this section about social responsibility, the hazardous and harmful factors were revealed, and these included:

- Noise [57]
- Microclimate [58]
- Electromagnetic radiation [61]
- Insufficient illumination of the working area [56]
- Abnormally high voltage value in the circuit [59]

The room 042 B, at the 10th building was classified with room category B4, room zone class П-IIa. All necessary safety measures and precaution to minimize probability of accidents and traumas during investigation are given.

Possible negative effect on environment were given in compact form describing main ecological problem of using nuclear energy. It could be stated that with respect to all regulations and standards, investigation itself and object of investigation do not pose special risks to personnel, other equipment and environment. To prevent fire from short circuits, overloads, etc., the following fire safety rules must be observed:

- elimination of the formation of a flammable environment (sealing equipment, control of the air, working and emergency ventilation);

- use in the construction and decoration of buildings of non-combustible or difficultly combustible materials;

In the case of an emergency, it is necessary to:

- inform the management (duty officer);
- Call the Emergency Service or the Ministry of Emergency Situations - tel. 112;
- take measures to eliminate the accident in accordance with the instructions [54,55].

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Table A.1 – Design characteristics of small-animal PET scanners

Scanner	Manufacturer	Scintillator	Cristal dimensions, mm^3	Electronic	Transaxial FOV, mm	Axial FOV, mm
microPET P4	Siemens	LSO (8 x 8)	2.2 x 2.2 x 10	PSPMT	190	78
microPET Focus220	Siemens	LSO (12 x 12)	1.5 x 1.5 x 10	PSPMT	190	76
Inveon-DPET	Siemens	LSO (20 x 20)	1.5 x 1.5 x 10	PSPMT	100	127
Mosaic-HP	Philips	GSO	2 x 2 x 10	PMT	128	119
Argus	Sedecal	LYSO/GSO (13 x 13)/(20 x 20)	1.45 x 1.45 x 7/8	PSPMT	67	48
ClearPET	Raytest GmbH	LYSO/LuYAP (8 x 8)/(8 x 8)	2 x 2 x 10/10	PSPMT	144	110
VrPET	Sedecal	LYSO (30 x 30)	1.4 x 1.4 x 12	PSPMT	86.6	45.6
LabPET12	Gamma Medica	LYSO/LGSO	2 x 2 x 11.9/13.3	APD	100	112.5
X-PET	Gamma Medica	BGO (8 x 8)	2.3 x 2.3 x 9.4	PMT	100	116
NanoPET/CT	Mediso	LYSO (39 x 81)	1.1 x 1.1 x 13	PSPMT	123	94.8
nanoScan (PET82S)	Mediso	LYSO (29 x 29)	1.5 x 1.5 x 10	PSPMT	80	98.6
Albira	Bruker	LYSO (monolithic)	50 x 50 x 10	MAPMT	80	148
Albira Si	Bruker	LYSO (monolithic)	50 x 50 x 10	SiPM	80	148

PETbox4	UCLA	BGO (24 x 50)	1.8 x 1.8 x 7	PSPMT	45	95
G4	Sofie Bioscience	BGO (24 x 50)	1.8 x 1.8 x 7	MAPMT	45	94
G8	Sofie Bioscience	BGO (26 x 26)	1.8 x 1.8 x 7.2	MAPMT	47.44	94.95
GNEXT	Sofie Bioscience	LYSO/BGO (8 x 8)/(8 x 8)	1.01 x 1.01 x 6.1 1.5 x 1.5 x 8.9	Not available	120	104
ClairvivoPET	Shimadzu	LYSO/LYSO (32 x 53)/(32 x 54)	1.3 x 2.7 x 7	PMT	102	151
Scanner	Manufacturer	Scintillator	Cristal dimensions, mm^3	Electronic	Transaxial FOV, mm	Axial FOV, mm
TransPET-LH	Raycan	LYSO	1.9 x 1.9 x 13	PSPMT	130	53
Xtrim-PET	Parto Negar Persia	LYSO (24 x 24)	2.1 x 2.1 x 10	SiPMs	100	50.3
β-cubes	Molecubes	LYSO (monolithic)	25 x 25 x 8	MPPC	72	130
VECTor	MILabs	NaI(Tl) (monolithic)	590 x 470 x 9.5	Not available	48	36
MuPET	University of Texas M.D. Anderson Cancer Center	LYSO (30 x 30)	1.2 x 1.4 x 9.5	PMT	100	116

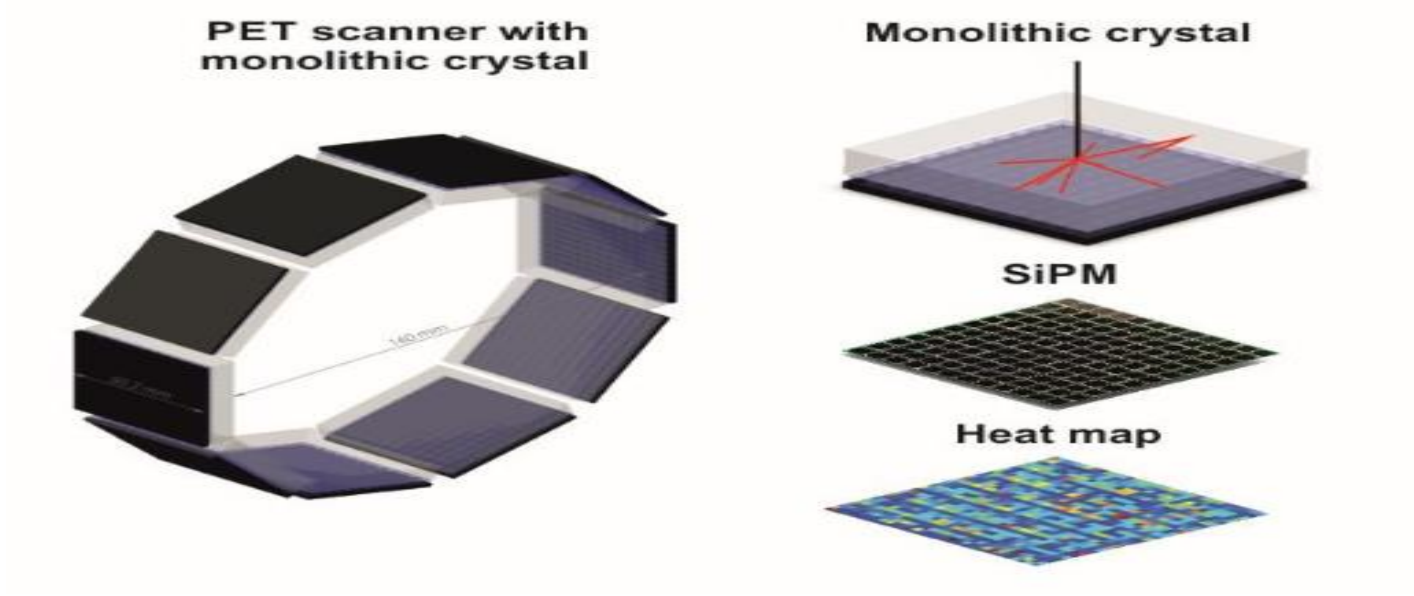

Fig. A1. Detector’s geometry.

Appendix B

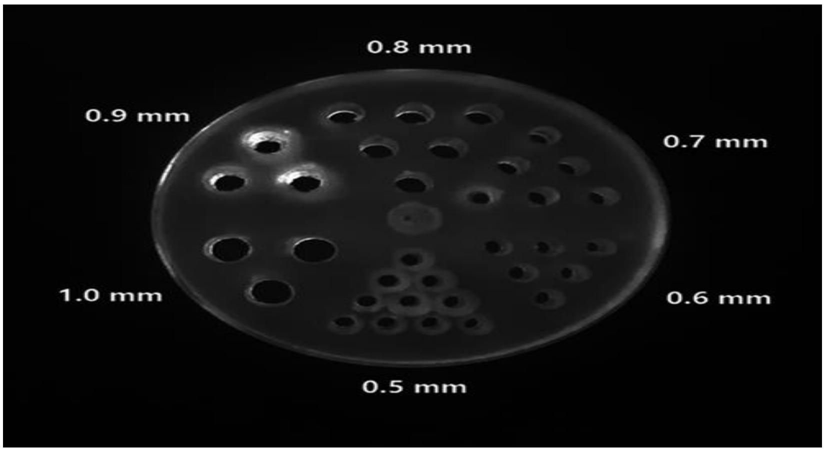

Fig. B1. **Photograph of the micro Derenzo phantom (end view). The center-to-center distance between adjacent rods is twice the rod diameter.**

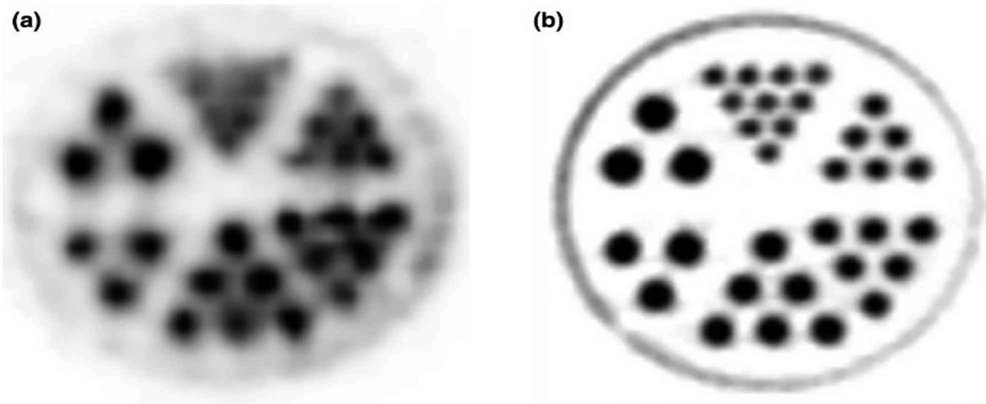

Fig. B2. Micro Derenzo phantom transverse images reconstructed using 3D-OSEM (10 subsets, 5 iterations) and CT image after injecting Ioverol 350 developer. The size of the porous array from small to large are 0.5, 0.6, 0.7, 0.8, 0.9, and 1.0 mm. (a) PET image of the micro Derenzo phantom. (b) CT image of the micro Derenzo phantom

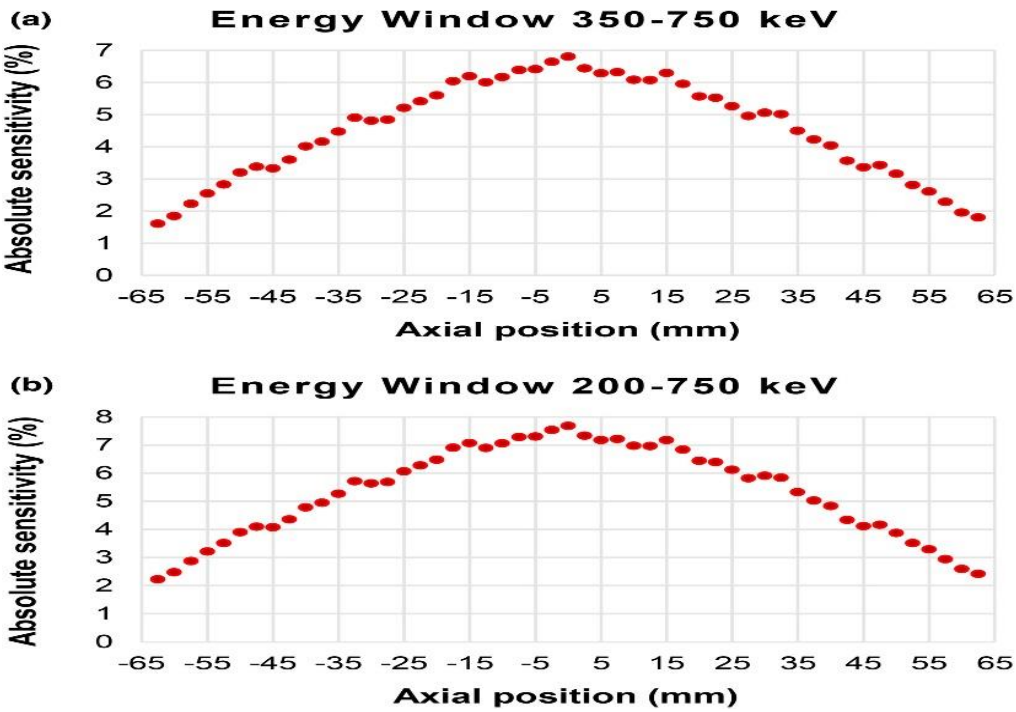

Fig. B3. The axial absolute sensitivity profiles of PET/CT system in the energy window of (a) 350–750 keV and (b) 200–750 keV respectively [Color figure can be viewed at wileyonlinelibrary.com]

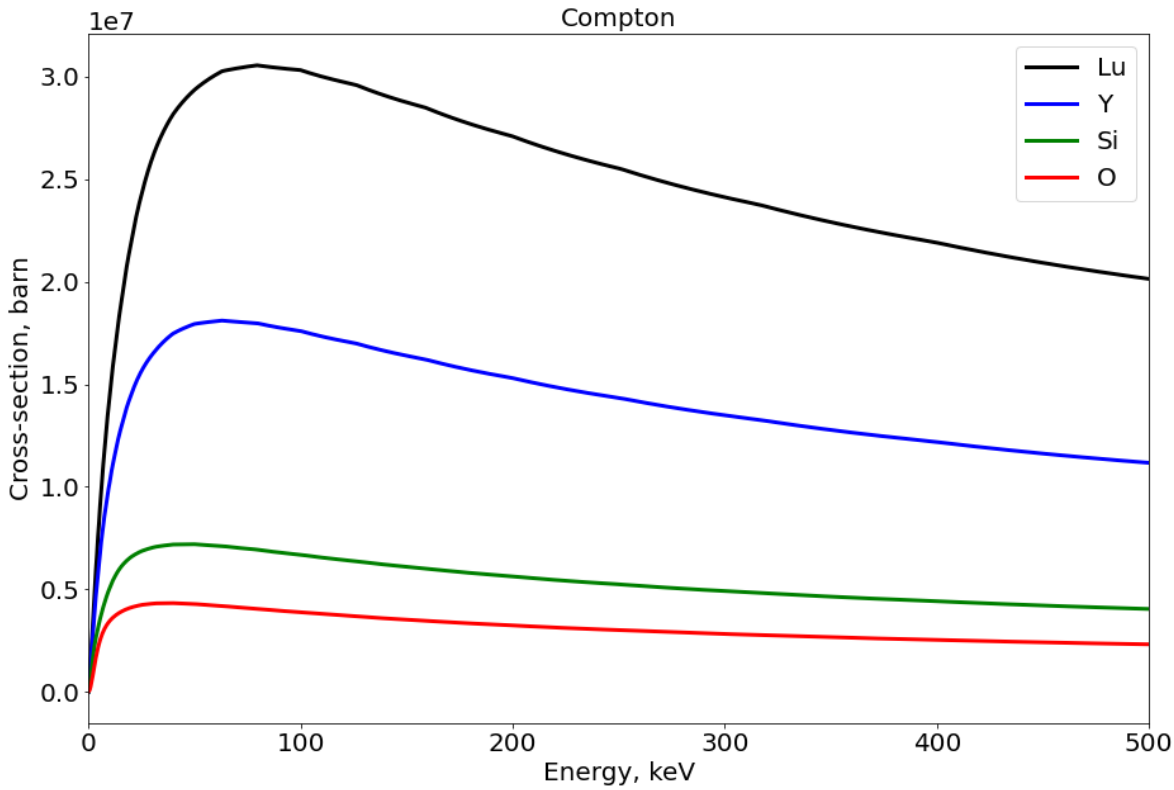

Figure B.4 – Compton scattering cross-sections for different LYSO's elements

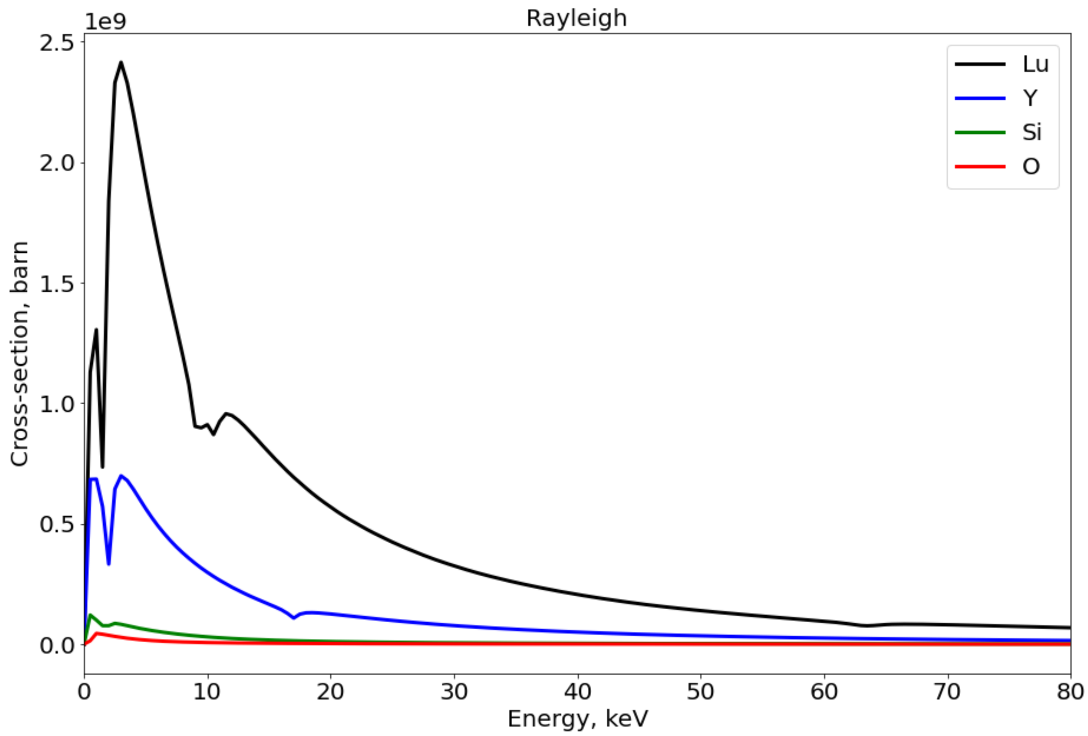

Figure B.5 – Rayleigh scattering cross-sections for different LYSO's elements

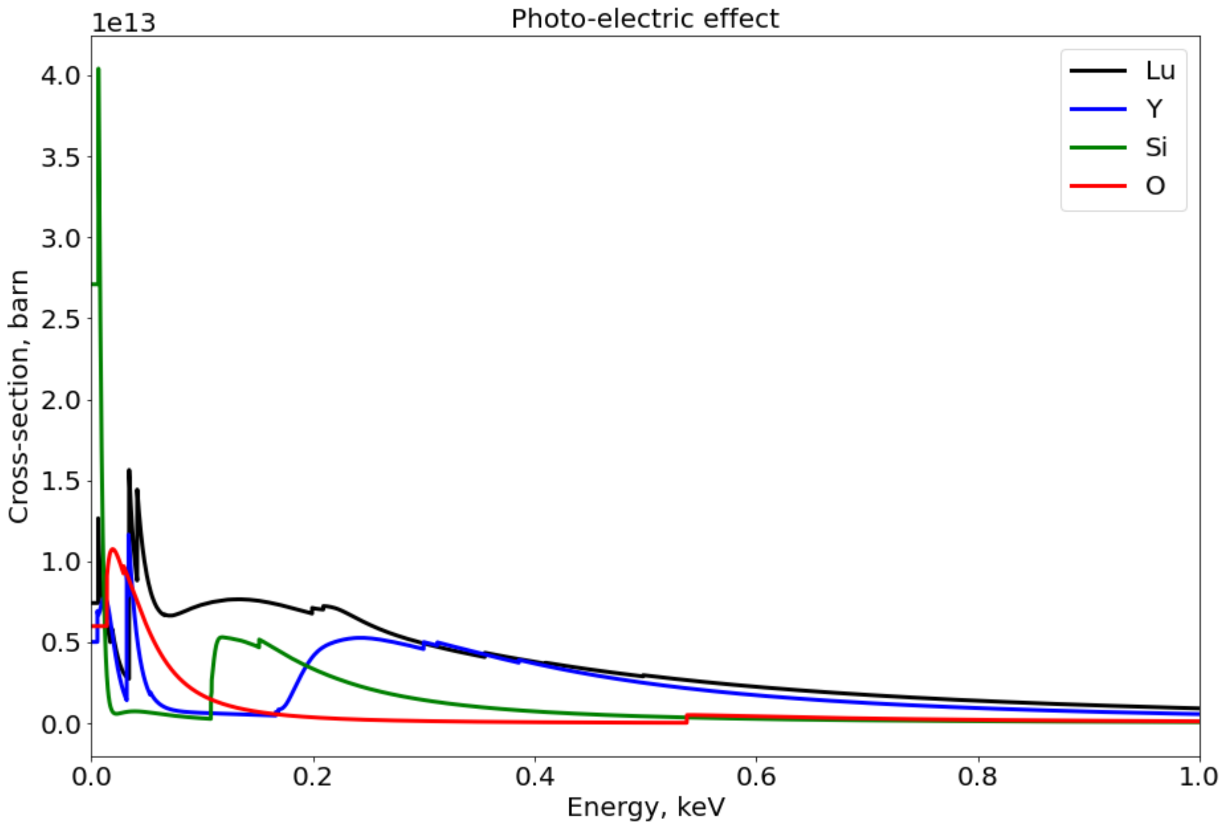

Figure B.6 – Photo-electric effect cross-sections for different LYSO's elements

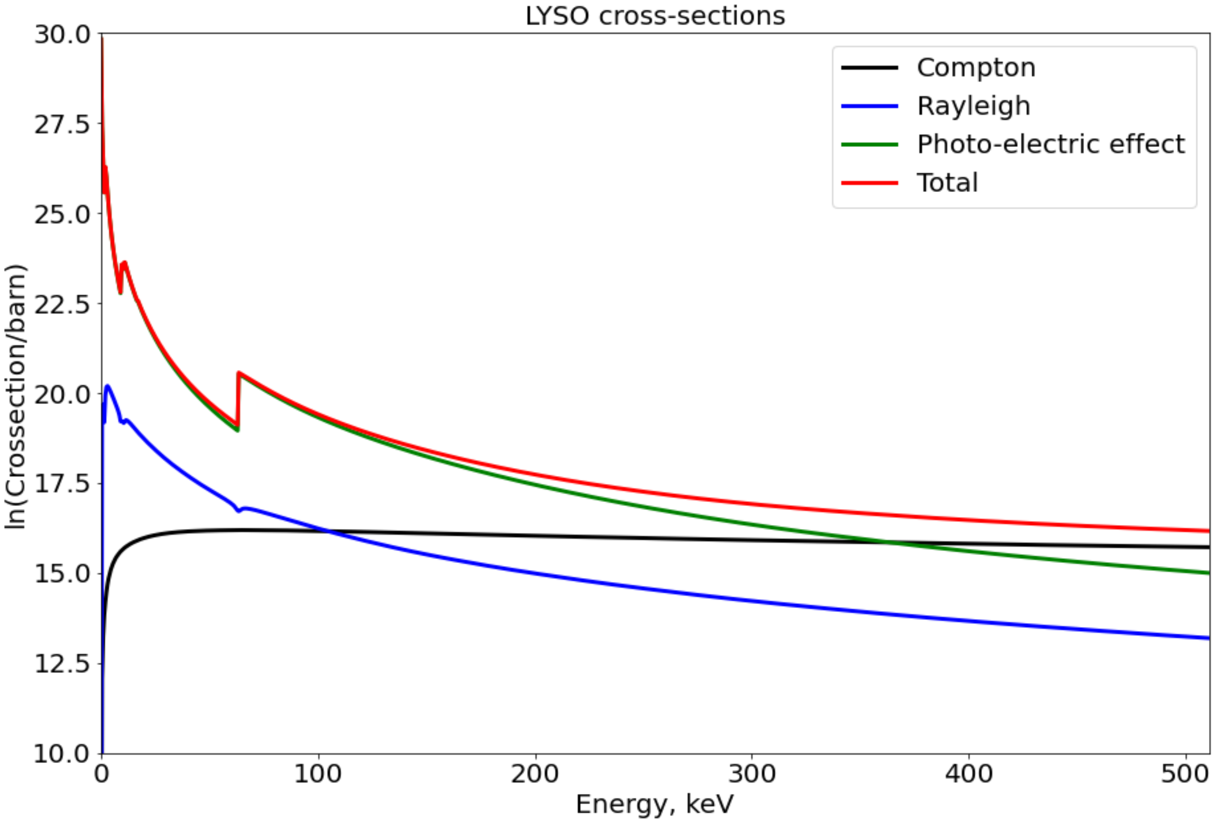

Figure B.7 – Overage LYSO cross-sections of different processes

Appendix C

Table C.1 – Optical properties of detector materials

Material	Density, g/cm^3	Refractive index	Light yield, photons/MeV	Decay time, ns	Absorption length, cm	Rayleigh attenuation lengths, cm
LYSO	7.1000	1.81	33200	36	50	260
Epoxy	1.2000	1.53	-	-	-	-
Air	0.0012	1.00	-	-	-	-

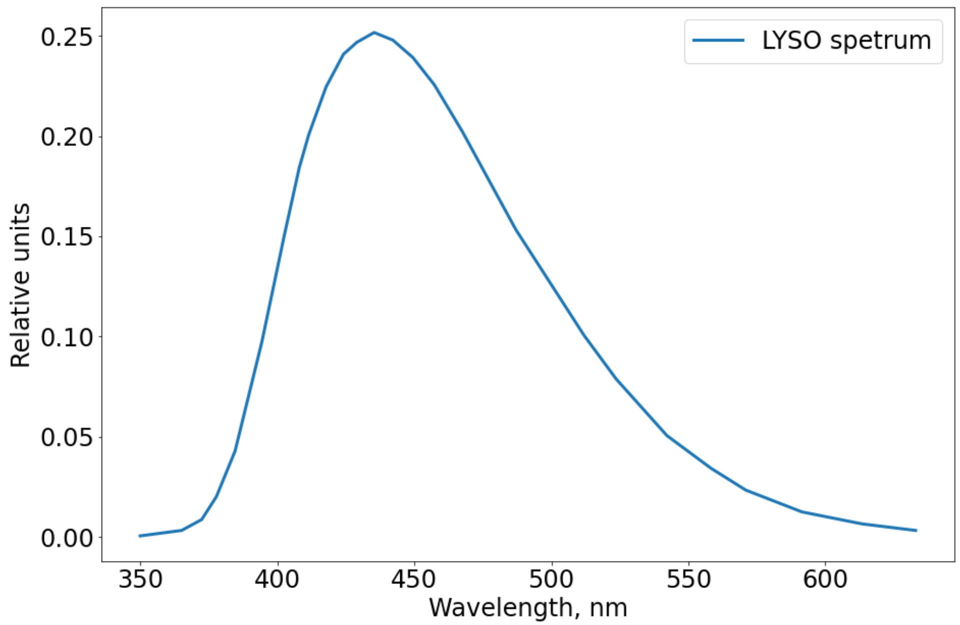

Fig. C1. LYSO Spectrum curve