ISSN 2462-2052 | eISSN 2600-8718
DOI: https://doi.org/10.37134/jsml.vol13.2.7.2025

Journal of Science and Mathematics Letters
Volume 13, Issue 2, 87-106, 2025

Research Article

Development and Evaluation of a Miniature Scintillation Gamma Spectrometer for Environmental Radiation Monitoring

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Received: 1 July 2025; **Accepted:** 15 September 2025; **Published:** 21 September 2025

ABSTRACT

Developing a compact gamma spectrometer for radiation monitoring in critical zones, such as nuclear power plants and the Chernobyl Exclusion Zone, is vital for ensuring high sensitivity and accurate measurements amid geopolitical instability and military aggression. The aim of the study was to demonstrate the feasibility of a miniature scintillation spectrometer using a lutetium-yttrium oxyorthosilicate crystal (LYSO) and a silicon photomultiplier (SiPM) or multi-pixel photon counter (MPPC), and to compare it with an existing compact photomultiplier tube (PMT) R7400U assembly with a thallium-doped caesium iodide crystal (CsI(Tl)). The first stage involved preparing a prototype board for the R7400U PMT and analyzing its spectrometric characteristics. Next, an experimental setup using the LYSO crystal, SiPM photodiode, preamplifier electronics, and a spectrum analyzer was assembled, while gamma radiation interaction was modeled with GEANT4. Experimental measurements with a Cesium-137 (137Cs) source (661.7 keV) showed that the spectrometer could register and analyse gamma spectra with moderate resolution. The SiPM signal remained stable with optimal electronics and a 400 V DC-DC converter, providing low noise. Experimental data matched Monte Carlo simulations, and the SiPM's large pixel count ensured better response linearity at high light intensity. As a result, the design proved stable and effective for long-term measurements. The proposed approach demonstrated the possibility of such miniaturisation of spectrometric systems without significant degradation of performance. The study demonstrated the feasibility of a miniature scintillation spectrometer with LYSO and SiPM/MPPC, performing similarly to the PMT-based system. This compact design offers a viable solution for portable radiation monitoring in critical environments.

Keywords: scintillation detector, photomultiplier tube, multi-pixel photon counter, energy resolution, voltage divider, digital signal processing, nuclear safety, detector calibration.

1. INTRODUCTION

In the current conditions of geopolitical instability and military aggression against Ukraine, an important task was to ensure radiation monitoring in critical zones, such as nuclear power plants (NPPs) and the Chernobyl Exclusion Zone. Compact gamma spectrometers played a key role in detecting sources of ionising radiation, which was of great importance for both civilian use and military security. The main challenge in the development of compact gamma spectrometers was to ensure high sensitivity and measurement accuracy while maintaining the small size of the device. The use of a CsI(Tl) scintillation crystal in combination with a PMT provided sufficiently high gamma radiation detection efficiency, although such systems required careful calibration and parameter optimisation to reduce noise levels and improve energy resolution. In the study by Tarancón et al. (2022), the efficiency of different scintillation materials in combination with SiPM for gamma radiation detection was analysed. The experimental results showed that detectors based on CsI(Tl) and thallium-doped sodium iodide (NaI(Tl)) demonstrated better energy resolution, whereas bismuth germanate (BGO) provided higher efficiency for detecting high-energy gamma quanta. The authors emphasised that the choice of scintillation material should be made considering the specific detection requirements and operating conditions. The study by Kim et al. (2022) was dedicated to the development of a low-resolution gamma spectrometer for monitoring radioactivity levels in wastewater. The proposed system allowed the specific activity of radionuclides to be determined quickly and efficiently before the discharge of wastewater, significantly reducing analysis time and increasing control accuracy. Thus, the developed spectrometer was an important tool for the safe management of liquid radioactive waste.

The team of Mrdja et al. (2024) presented a compact gamma spectrometer for monitoring radiation background in the environment. The conducted tests confirmed that the device effectively tracked changes in radiation levels in real time, making it a promising solution for environmental monitoring. The work of Carminati et al. (2022) focused on the development of a portable gamma spectrometer compatible with magnetic materials. The main task of the device was radiation safety control and scrap metal inspection. Testing showed that the developed spectrometer ensured rapid and accurate detection of radioactive materials, making it useful for environmental monitoring and industrial applications. In the study by Srivastava et al. (2022), the potential of using SiPM in combination with a gadolinium gallium aluminium garnet crystal doped with cerium and boron (GGAG:Ce,B) for gamma radiation monitoring was analysed. The results obtained indicated that the detector had high linearity in the range of 3.5-300 μGy/h and a sensitivity of 2.44 cps/μGy/h. In addition, the researchers noted its compactness, energy efficiency, and suitability for use in environmental monitoring systems. Kim et al. (2024) considered a condenser air removal system that played a key role in radiation monitoring at NPPs. The main focus was on detecting potential leaks of radioactive materials from the primary to the secondary coolant circuit. The data obtained confirmed the effectiveness of the proposed optimisation method and showed that the calculated values of the k coefficient matched the reference parameters, which allowed minimisation of the need for physical measurements in hazardous conditions. In the work, Mishra and Kumar (2022) investigated methods for measuring radiation levels and radioisotope concentrations in the environment. The authors analysed various types of detectors, including gas-filled ionisation chambers (Geiger-Müller tubes (GM tubes)), scintillation detectors (liquid scintillation counter (LSC), NaI(Tl), silver-activated zinc sulphide (ZnS(Ag)), and semiconductor detectors (high-purity germanium (HPGe), passivated implanted planar silicon detector (PIPS)). The main conclusion was that to ensure measurement accuracy and traceability, regular calibration of instruments was required, which allowed compliance with international radiation safety standards. The study by Stránský et al. (2022) concerned the development of an electromagnetic calorimeter for spectrometry in radiation fields generated by high-power lasers. To test the device, calibration was performed using ^{137}Cs and Cobalt-60 (^{60}Co) sources. The measurements showed that the calorimeter could determine the energy of the incident radiation with an error of about 10%, confirming its effectiveness for use in high-intensity laser experiments.

The aim of this study was to describe the assembly of a scintillation spectrometer based on a LYSO scintillator crystal combined with a SiPM, also known as an MPPC. The task of this

ISSN 2462-2052 | eISSN 2600-8718
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Journal of Science and Mathematics Letters
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study was to create a miniature scintillation spectrometer based on a LYSO crystal and SiPM/MPPC, and to compare this assembly with an existing compact spectrometer based on the PMT R7400U.

2. MATERIALS AND METHODS

2.1. Study Overview and Research Objective

This study employed a comprehensive approach combining the development, assembly, experimental testing, and computer modelling of a scintillation spectrometer using a modern silicon photodetector. The goal was to assess the suitability of the SiPM as a compact and reliable alternative to traditional PMTs for the creation of miniature spectrometers.

2.2. Prototype Development and Testing

The first stage of the study involved the preparation of a prototype board and spectrometric chain for the compact PMT R7400U, followed by testing the resulting detector. The results of this stage served as reference values for miniaturization (Figure 1).

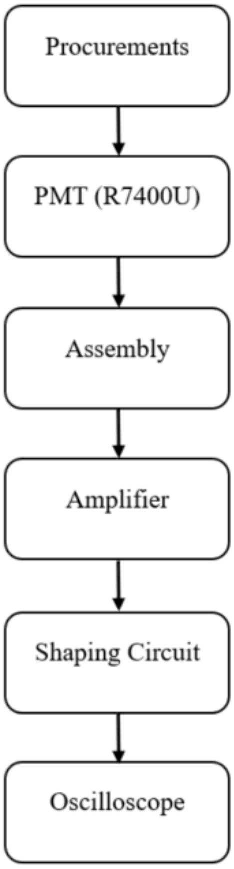


Figure 1. Prototype development and testing diagram

Figure 1 illustrates the key stages involved in the development and testing of the prototype, providing a clear overview of the process. It visually represents the flow from the procurement of components, through assembly, to the final testing and analysis stages. This diagram helps to simplify the complex sequence of operations, making it easier to understand the steps taken to miniaturize the spectrometric system based on the PMT R7400U.

2.3. Assembly of Experimental Spectrometer Prototype

The second stage focused on the physical assembly of an experimental spectrometer prototype using an MPPC. For this, a lutetium-yttrium oxyorthosilicate crystal doped with cerium (LYSO(Ce)) was selected. LYSO(Ce) was chosen for its high light output (approximately 75% of NaI(Tl)) and an energy resolution of about 8% at 661.7 keV. The dimensions of the crystal were (4×4×26) mm, and its end face was optically coupled with a SiPM model S14160-3010PS from Hamamatsu Photonics, which has an active area of (3×3) mm and contains approximately 90,000 micropixels. This setup ensured good signal linearity, even with numerous scintillation photons typical in gamma radiation detection. It is important to highlight that the successful assembly of the experimental spectrometer prototype, utilizing the LYSO(Ce) crystal and SiPM, represents a critical step in the development of a compact, high-performance radiation detection system (Figure 2). The integration of these components ensures efficient gamma radiation detection with reliable signal linearity, laying the foundation for further testing and optimization in subsequent stages of the study.

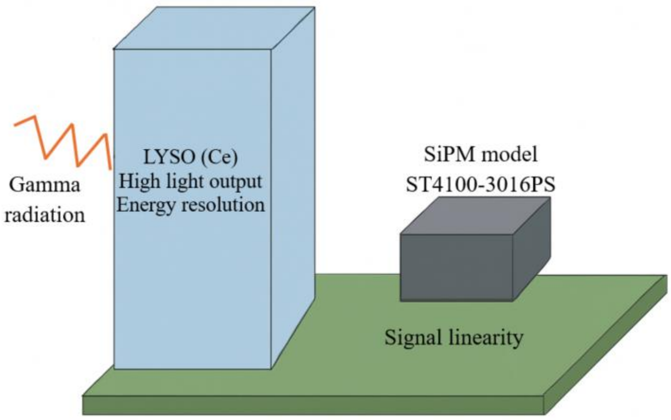


Figure 2. Assembly of experimental spectrometer prototype diagram

2.4. Light Collection and Optical Coupling

To ensure effective light collection, aluminium foil was attached to the surface of the crystal to act as a reflective layer. The optical contact between the crystal and photodiode was established with minimal light loss, ensuring optimal signal collection efficiency.

2.5. Front-End Electronics and Power Supply

The main signal readout component was a charge-sensitive preamplifier CR-113-R2.1, mounted on a test board CR-150-R6 from Cremat Inc., assembled in Configuration 3, which optimally read pulses from the SiPM. This configuration provided correct amplification of the SiPM avalanche discharge current signal into a voltage signal (transimpedance amplification). Additionally, the study compared three reverse voltage source options for powering the SiPM: a laboratory power supply, a 400-watt DC-DC converter, and a 1,200-watt DC-DC converter. It was found that the 400-watt converter generated the least electrical noise and provided the most stable background for accurate signal amplitude measurements.

2.6. Signal Measurement and Calibration

After stabilizing the circuit, signal measurements were taken using an oscilloscope. Spectrum formation and energy resolution were evaluated using a CANBERRA DCA1000 analyser. The isotope 137Cs, emitting gamma quanta at 661.7 keV, was used as the calibration radiation source for testing. This allowed for the characterization of the spectrometer's performance.

2.7. Theoretical Modelling and Simulation

In addition to experimental testing, significant attention was given to the theoretical modelling of processes within the spectrometer. The Monte Carlo method was applied using the GEANT4 toolkit, which allowed for the modelling of photon transport, optical processes, and light detection statistics in the SiPM. Spectra were modeled taking into account photon collection, and the smearing caused by the operation of the spectrometric chain was evaluated.

3. RESULTS AND DISCUSSION

Gamma spectrometry was one of the main methods for analysing ionising radiation, enabling the identification of radioactive isotopes by the characteristic gamma lines. This method was widely used in nuclear physics, environmental monitoring, radiation control, and the detection of illicit trafficking of radioactive materials. The operating principle of gamma spectrometers was based on the registration of gamma quanta by detectors, which converted the energy into electrical signals that were then analysed to obtain the radiation spectrum (Luxium Solutions, 2023; Choi et al., 2025). The main types of detectors used in gamma spectrometers were scintillation detectors, semiconductor detectors, and gas-filled counters (Chierici et al., 2021; Pak et al., 2018). Scintillation detectors, such as NaI(Tl) and CsI(Tl) crystals, were among the most common due to the high radiation detection efficiency, compactness, and availability. NaI(Tl) provided high light output but had high hygroscopicity, which complicated its use in portable devices (Loburets et al., 1997). CsI(Tl), which was used in this study in combination with a PMT, had lower hygroscopicity and greater mechanical strength, making it more suitable for mobile gamma spectrometers. Moreover, it demonstrated high light output and efficiency in the low-energy range.

PMTs were key components of scintillation detectors, as PMTs provided the conversion of light pulses generated in the crystal by gamma quanta into electrical signals. The operating principle of the PMT was based on photoemission of electrons from the photocathode upon interaction with photons, followed by cascade multiplication of electrons on dynodes. This allowed the signal to be significantly amplified and further analysed (Lee et al., 2023; Pekur et al., 2023). In this study, a Hamamatsu R7400U PMT was used, characterised by compact size, high sensitivity to weak light signals, and an operating voltage of 1,000 V. Stable PMT operation depended on the quality implementation of the voltage divider, which ensured uniform potential distribution between the dynodes. Voltage divider circuits typically included resistive chains that allowed control of the voltage at each stage of the PMT (Pino et al., 2021; Azarov et al., 2022). In this study, the voltage divider consisted of nine resistors with a total resistance of 2.8 MΩ and capacitors that improved the linearity of the output signal. Additionally, R-C filters were used to reduce noise influence and stabilise the output signal.

The power supply of the spectrometer played an important role in ensuring stable PMT operation (Sergiyenko et al., 2011; Qawaqzeh et al., 2020). The use of high-voltage DC-DC converters significantly reduced the size of the device, but could also cause electromagnetic interference (Verbelen et al., 2021; Shchurov, 2022). Therefore, special attention was given to the use of filters and shielding to reduce noise levels. In this study, a 3V→950V DC-DC converter was implemented, making the spectrometer more portable compared to traditional counterparts requiring an external high-voltage power source. During the experiments, the performance of the compact gamma spectrometer was tested by registering gamma quanta from various radiation sources. The focus was on analysing the detector's output signal, its stability, signal-to-noise ratio, and correctness of energy spectrum construction. The spectrometer output signal consisted of electrical pulses generated by the PMT during the interaction of the scintillation crystal with gamma quanta. Each pulse corresponded to a separate radiation detection event and was characterised by an amplitude directly proportional to the energy of the absorbed gamma quantum. Analysis of these pulses formed the basis for constructing the radiation energy spectrum and identifying radioactive isotopes (Han et al., 2022; Mikhailova et al., 2025).

To test the detector's operation, a series of experiments with different gamma radiation sources was conducted. The primary radiation source used was the isotope ^{137}Cs, which emitted gamma quanta with an energy of 662 keV. This was one of the most common radiation sources widely used for calibrating spectrometric systems. During signal registration, pulses of different amplitudes corresponding to the radiation source’s energy levels were recorded. It was determined that the maximum signal amplitude correlated with the expected photon energy, and the pulse shape retained a characteristic exponential decay. The dynode signal was an intermediate electrical pulse formed at the output stages of the PMT. Its analysis allowed for assessment of the internal dynamics of PMT operation, as well as the influence of the voltage divider and the signal amplification efficiency (Melnychuk et al., 2023; Naik et al., 2024). During the experiments, the signal was taken from the eighth dynode of the PMT, which allowed a sequence of pulses to be obtained, each corresponding to the interaction event of a gamma quantum with the scintillation crystal. Measurements were carried out using a high-resolution digital oscilloscope. The analysis of the obtained oscillograms showed that the average dynode signal amplitude was about 25-30 mV, and the pulse rise time did not exceed 10 ns. This matched the expected parameters of PMT operation and indicated high-speed performance of the amplification system. Comparison of the obtained data with the theoretical model showed that the amplitude-time characteristics of the signal corresponded to calculated values. This confirmed the correctness of the voltage divider circuit and the efficiency of potential stabilisation between dynodes.

The anode signal was the final output pulse of the spectrometer, which was fed into an analogue-to-digital converter (ADC) for further processing. Its shape and amplitude characteristics determined the accuracy of spectrometric measurements and the possibility of gamma line identification (Menush Dilka, 2025; Zakharova et al., 2025). Oscillographic analysis of the anode signal showed that its maximum amplitude for ^{137}Cs gamma quanta reached 300-350 mV, which corresponded to the energy level of 662 keV. It was found that the average pulse width at 50% amplitude was 200 ns, which was optimal for registering high-frequency events. Some amplitude fluctuations within 5-7% were noted, which were explained by fluctuations in the process of secondary electron emission in the PMT. This was a standard effect for PMTs, which could be compensated by additional digital signal processing. Based on the obtained anode signals, the gamma radiation spectrum of the ^{137}Cs source was constructed. For this, digital filtering algorithms and amplitude-based pulse distribution were used.

Spectrum analysis showed a clearly defined peak at 662 keV, which corresponded to the main gamma line of ^{137}Cs. In addition to the main peak, a number of low-energy events were recorded, which could be associated with Compton scattering of photons in detector materials and the surrounding environment. To assess the spectrometer’s resolution, full width at half maximum (FWHM) measurements were conducted. It was found that the peak width was 63 keV, which corresponded to an energy resolution of approximately 9.5% at 662 keV. This value was typical for scintillation spectrometers with CsI(Tl) and confirmed the suitability for basic gamma radiation analysis. The device’s operational stability under different temperature conditions was also assessed. Measurements were carried out within a temperature range of 10-35°C to detect possible temperature dependencies in detector operation. The results showed that with each 10°C increase, the signal amplitude decreased by approximately 2-3%. This was explained by the temperature dependence of the scintillation crystal and variations in the PMT gain factor. At the same time, the 662 keV spectral line remained stable, indicating sufficient temperature resistance of the device. To compensate for the temperature influence, automatic adjustment of the energy scale based on control radiation lines could be used. The obtained results confirmed the effectiveness of the developed spectrometer for gamma radiation registration. It was determined that the device correctly identified gamma lines of radioactive isotopes, had sufficient energy resolution, and stable operation. The identified shortcomings related to parasitic noise and temperature dependence could be resolved through further optimisation of the electronic circuit and signal processing software.

Following the initial experiments with ^{137}Cs, a series of additional measurements with other radioactive sources was conducted to assess the spectrometer's sensitivity and resolution. In particular, sources of ^{60}Co and Americium-241 (^{241}Am) were investigated, which had characteristic gamma lines and allowed for assessment of the spectrometer's capability to identify different isotopes. During the measurement of ^{60}Co radiation, two main peaks were obtained at 1,173 keV and 1,332 keV, which corresponded to the gamma radiation of this isotope. Despite the high photon energies, the CsI(Tl) scintillation detector maintained sensitivity in this range. However, the peak width was significantly greater than for ^{137}Cs, indicating a decrease in detector resolution as radiation energy increased (Figure 3).

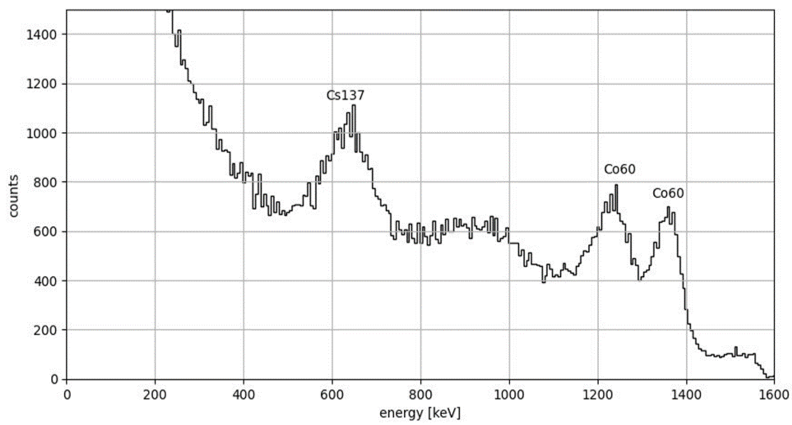


Figure 3. Gamma spectrum of ^{137}Cs, ^{60}Co

These measurements confirmed that the spectrometer could be used to analyse a wide range of gamma radiation energies, although the accuracy of isotope identification decreased at high energies due to the increased width of the peaks. Another important factor was the influence of data accumulation time on the quality of spectral analysis (van der Veeke et al., 2021; Wójcik et al., 2022). During the study, measurements of the ^{137}Cs spectrum were carried out with different exposure times: 30 seconds, 60 seconds, 120 seconds, and 300 seconds. At short exposure time (30 seconds), a significant statistical error was obtained, which made it difficult to accurately determine the 662 keV peak. Increasing the time to 120 seconds allowed a clearer spectrum with an improved signal-to-noise ratio to be obtained. An optimal time of 300 seconds was identified, at which the obtained spectra had the lowest statistical error and the peak was determined with high accuracy. The level of natural background in laboratory conditions was also assessed. In the absence of a radioactive source, the measurements showed a low-energy background composed mainly of gamma quanta from natural radionuclides, including Potassium-40 (^{40}K-40, 1,460 keV) and radon decay products. This confirmed the sensitivity of the spectrometer even without the use of strong radiation sources. Since the operating voltage of the PMT had a critical impact on the characteristics of the output signal, a series of experiments was conducted by varying the supply voltage within the range of 850-1,000 V (Sun et al., 2021; Irtyshcheva et al., 2022). At 850 V, a significant decrease in pulse amplitude and a deterioration in spectral resolution were recorded. This was due to insufficient acceleration of electrons in the PMT, which reduced the signal gain factor. Optimal results were obtained at 950 V, which corresponded to the recommended parameters for the Hamamatsu R7400U. At this value, the signal had a stable amplitude, and the peak resolution remained within 9-10%. When the voltage was increased to 1,000 V, a slight improvement in signal amplitude was observed, but additional noise appeared, which could negatively affect the quality of spectral analysis. This confirmed the need for precise adjustment of the supply voltage to achieve optimal spectrometer performance. One of the important characteristics of the spectrometer was its stability and repeatability of results (Wu et al., 2025; Ilderbayeva et al., 2024). A series of 10 measurements of the ^{137}Cs spectrum was carried out, each lasting 120 seconds.

Statistical analysis of the obtained spectra showed that the deviation in the position of the 662 keV peak did not exceed ±2%, which indicated high measurement accuracy. The relative intensity of the peaks varied within 5%, which was acceptable for scintillation detectors. The developed gamma spectrometer was designed to identify radioactive isotopes by analysing characteristic gamma lines. It was based on the use of a CsI(Tl) scintillation crystal in combination with the Hamamatsu R7400U PMT, which operated at 1,000 V and had a signal gain factor of 7×10^5. The main task of this study was to verify the operability of the spectrometer, assess the quality of the obtained signals, evaluate the stability of the device, and measure the accuracy of gamma radiation identification. Since gamma spectrometers are widely used in radiation monitoring and nuclear physics, it was important to confirm that the characteristics of the developed device matched the expected parameters (Marques et al., 2021; Luniov et al., 2019). A key component of the spectrometer's electronics was the voltage divider, which ensured uniform voltage distribution between the PMT stages, providing correct detector operation. The divider consisted of 9 resistors (R1-R8=330 kΩ, R9=160 kΩ) with a total resistance of 2.8 MΩ and three capacitors (C1=C2=C3=1μF/200V) which acted as decoupling components, improving the output linearity of the signal when the PMT operated in pulse mode.

Figure 4 shows the schematic diagram of the voltage divider. Before the coaxial connector used for signal transmission, a decoupling capacitor C4=0.01μF/200V was installed to protect the output signal from high voltage influence. Additionally, an R-C filter was provided at the anode output to help minimise parasitic voltage oscillations and stabilise pulse amplitude (Hamamatsu Photonics, 2024; Ahmadov et al., 2022).

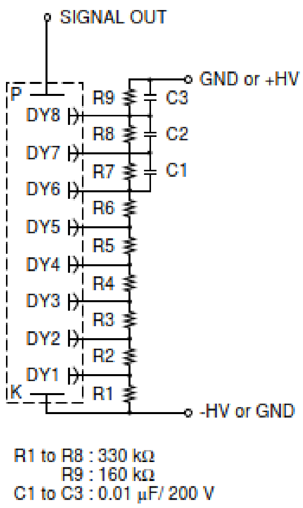


Figure 4. Voltage divider circuit for PMT R7400U

The spectrometer design was optimised for compactness, so the main electronic components were made in Surface-Mount Device (SMD) format. This significantly reduced the dimensions of the board compared to conventional THT components and also improved the signal characteristics by reducing parasitic inductances (van der Veeke et al., 2021; Huseynzada et al., 2023). XH-type "female" connectors with a pin width of 1.2 mm were used to connect the PMT, which simplified assembly and ensured reliable contact between detector elements. A photograph of the finished detector with PMT and voltage divider is presented. The device was powered by a 3V→950V DC-DC converter, which significantly reduced the instrument size compared to classical counterparts using bulky external power supplies. At the same time, the use of a switching converter could cause electromagnetic noise, which potentially affected signal quality (Flyckt and Marmonier, 2002; International Atomic Energy Agency, 2024).

To evaluate the operation of the spectrometer, the output signal was analysed using a digital oscilloscope. The main parameters of the signal were its shape, amplitude, signal-to-noise ratio, and temporal stability. The amplitude of the pulses varied within the range of 25-30 mV, and the average signal rise time was 10 ns. This corresponded with the expected operating parameters of the PMT and confirmed its correct functionality. In Figure 5, the anode signal is shown, which was the main output signal of the spectrometer. Its amplitude for ^{137}Cs gamma quanta reached 300-350 mV, which corresponded to the energy level of 662 keV. The average pulse width at 50% of the amplitude was 200 ns, which was an optimal value for high-speed gamma quantum registration.

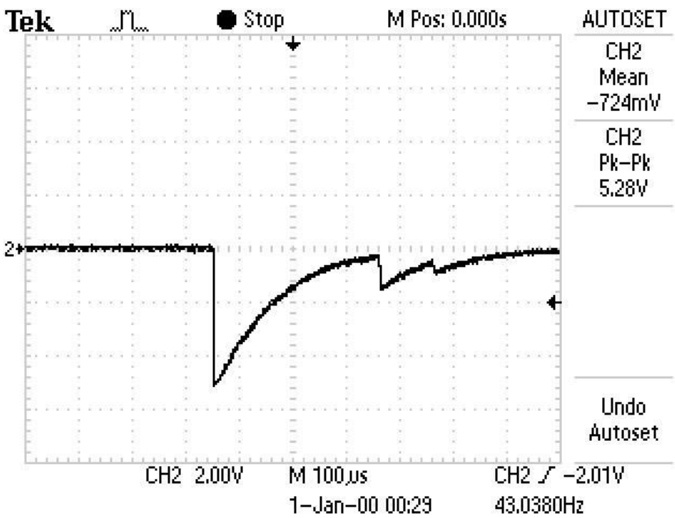


Figure 5. Anodic signal

An equally reliable and reproducible result was obtained when using the SiPM. Avalanche diodes operated under reverse bias voltage high enough for each electron to trigger an electron avalanche. The bias voltage was higher than the breakdown voltage, and taking into account the diode's intrinsic capacitance, the generated charge could be estimated as (1):

$$Q = C_{diode} \times (V_{bias} - V_{breakdown}) \quad (1)$$

where Q – charge, C_{diode} – diode capacitance, V_{bias} – bias voltage (applied voltage), $V_{breakdown}$ – breakdown voltage.

This was similar to the operating principle of PMTs, but there was no linear dependence of the diode signal on the number of incident photons. Such diodes were often used in counter mode – regardless of the number of photons causing external photoeffect in it simultaneously, the electrical pulse would be of the same amplitude. The idea of SiPM was that the generated light would reach different pixels as individual photons, an ordinary stream of events. It was assumed that the probability of two photons hitting the same diode simultaneously was unlikely and could be neglected. Thus, within the time window (scintillator emission time), the signal would be directly proportional to the number of photons that hit the matrix. And due to electronic avalanches, each individual pulse was a single photoelectron multiplied millions of times in an avalanche process. There existed semi-empirical probabilistic formulas (2) and (3) for calculating the number of detected photons $N_{\gamma det}$ (2) and (3):

$$PDE = QE \times \varepsilon_{geom} \times P_{geiger} \tag{2}$$

where QE was the quantum efficiency, ε_{geom} – the geometric efficiency, P_{geiger} – the Geiger discharge probability, and PDE – the photon detection efficiency.

$$N_{\gamma det} = N_{cells} \times (1 - e^{-N_{\gamma det} \times PDE/N_{cells}}) \tag{3}$$

where $N_{\gamma det}$ was the number of detected photons, N_{cells} the number of pixels. From this formula, it was evident that to preserve the linearity of detected photons relative to incident photons, the number of pixels had to exceed the number of photons in the brightest flashes in the scintillator. This requirement arises from the consideration of expanding the exponential into a series (Tavernier, 2009; Hamamatsu Photonics, 2024).

According to documentation to S14160-3010PS SiPM, the time of single charge avalanche in diode was τ_{det}≈100ns (Figure 6). The total number of scintillation photons was exponentially distributed with decay time τ (900 ns for CsI(Tl), for example). To evaluate the number of photons which illuminated the MPPC in the lifetime, it was possible to integrate the photons over time distribution in range of detector time window. For example, it was worth taking CsI(Tl) with 900 ns decay time and light yield N=54photons/keV, the actual number of photons in first 100 ns is $N_{inc}=N*(e^{0}-e^{-100/900})$≈6ph/keV. For incident gamma-particle of ^{137}Cs, with energy 661.7 keV, the total number of photons was 3,5731 but N_{inc}=3,757. When the scintillator decay time was less than dead time of the diode: for example, a lot of organic scintillators with couple ns, or, inorganic LYSO crystal with decay time of around 40 ns – the total incident photons of event counts in the range of single avalanche lifetime.

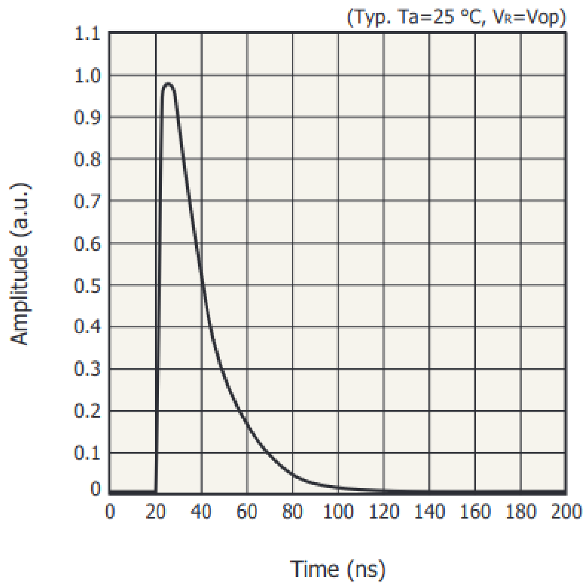
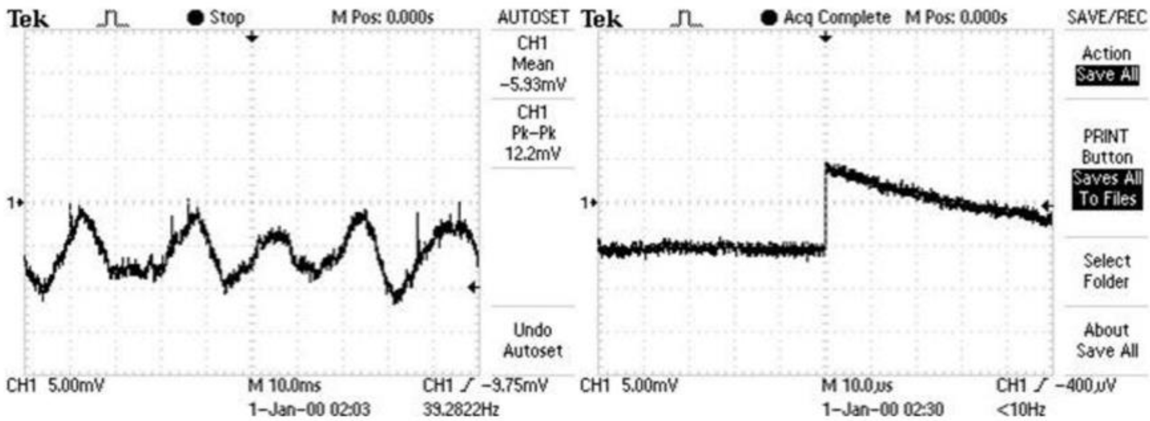


Figure 6. Pulse shape histogram of single pixels avalanche of MPPC S14160- 3010PS

ISSN 2462-2052 | eISSN 2600-8718 Journal of Science and Mathematics Letters
DOI: https://doi.org/10.37134/jsml.vol13.2.7.2025 Volume 13, Issue 2, 87-106, 2025

According to the obtained theoretical result, the best version of SiPM was the one with the most pixels, preferably at least 1-2 orders of magnitude more than the number of incoming photons in the range of the lifetime of the diode. For spectrometric purposes, it was worth choosing an S14160-3010 MPPC from Hamamatsu Photonics (2024). This was a (3×3) mm SiPM with almost 90,000 pixels with a pitch of 10 µm. It was possible to estimate that the typical number of photons in reference scintillators (like NaI(Tl)) was 1,000-10,000 for different energies of the incident gamma particle. The scintillator to be used with the SiPM had a slightly lower light output, 75% of NaI(Tl). It was about LYSO ($Lu_{1.8}Y_{0.2}SiO_5$), dimensions (26×4×4) mm. According to the recent conclusions, this crystal and diode should have fit by characteristics. In the test assembly, aluminium foil was used to collect light, and the MPPC was attached from the end cap. As the charge sensitive amplifier (CSA) and shaping amplifier (SA), CR113 and CR200-1u by Cremat were used, respectively (Cremat Inc., 2017; Cremat Inc., 2018). To supply the diode with reverse voltage, several sources were evaluated. These included a 400 W DC-DC converter (low voltage to high) with a conversion speed of 150 kHz, which is relatively smaller in capacity; a 1200 W DC-DC converter (low voltage to high) also operating at 150 kHz conversion speed but with a larger capacity; and a laboratory power unit, which served as an alternative source for comparison.

The 400 W DC-DC converter (Figure 7A) provided the best performance in this experiment, as it generated the smallest noise amplitude compared to other power sources. This minimized interference and allowed for a clearer and more stable signal. As a result, the 400 W converter proved to be the most effective option for ensuring high-quality data, as it maintained a consistent and reliable signal throughout the measurement process. The reduced noise levels made it easier to isolate the signal, leading to more accurate and precise measurements.



A) B)

Figure 7. Small converter [noise (**A**), signal (**B**)]

The 1200 W DC-DC converter (Figure 8A) exhibited a significantly higher noise level compared to the 400 W DC-DC converter, which interfered with the overall signal quality. The increased noise made it challenging to distinguish the signal from unwanted disturbances, reducing the clarity of the data. When the noise frequency became too high (Figure 8B), the signal became increasingly distorted, blending into a curved background line. This distortion made it difficult to isolate the true signal, further degrading the accuracy of the measurements. These results underscore the critical importance of controlling noise levels in the system to ensure high-quality and reliable signal detection, especially when working with high-power sources.

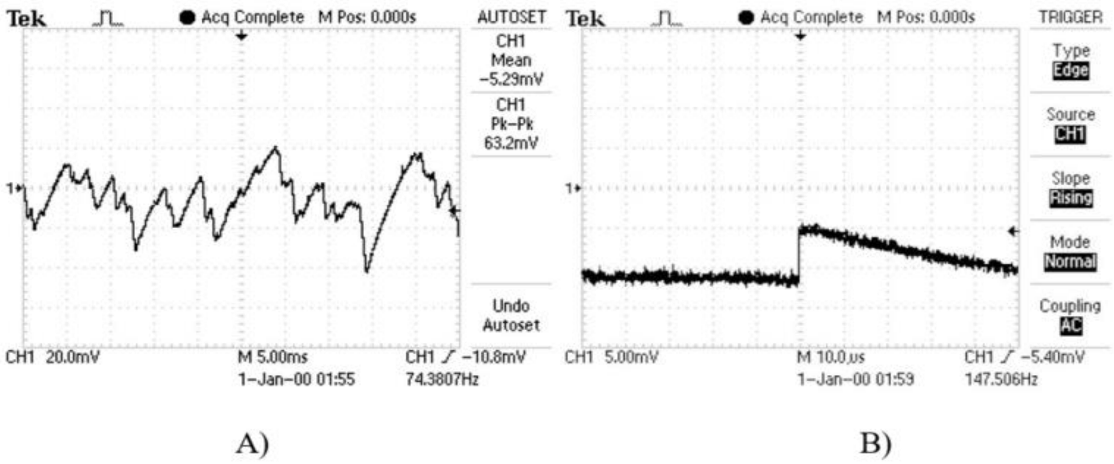


Figure 8. Big converter [noise (**A**), signal (**B**)]

The laboratory power unit (Figure 9) demonstrated a higher noise frequency compared to the 400 W DC-DC converter, which made it more challenging to maintain a clear and stable signal. Although the laboratory power unit was still capable of producing a usable signal, the elevated noise frequency introduced significant fluctuations, leading to a less stable background. These fluctuations interfered with the ability to accurately detect and measure the signal, causing potential distortion and reducing the overall quality of the measurements. The higher noise frequency resulted in more frequent disruptions, making it more difficult to isolate the true signal from the background noise, thereby negatively impacting the reliability and precision of the data collected.

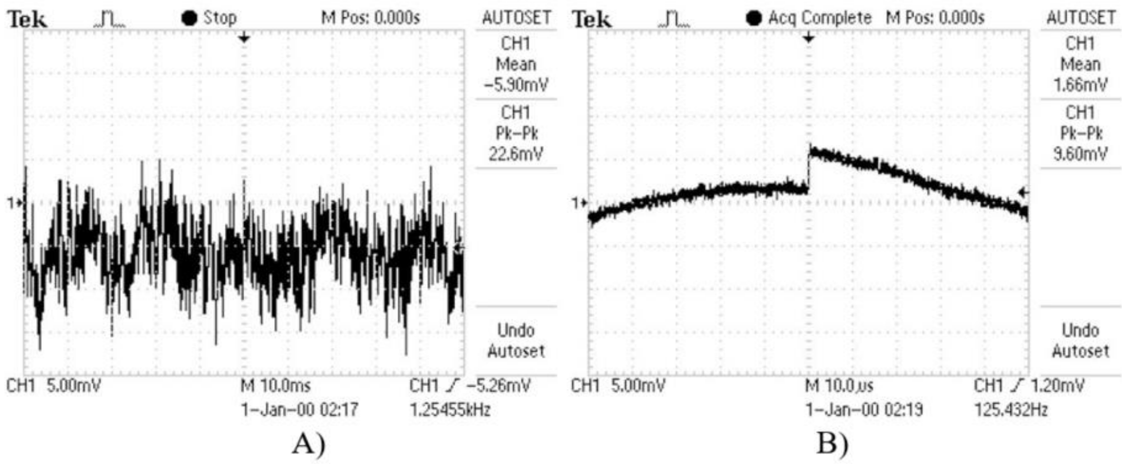


Figure 9. ATTEN [noise (**A**), signal (**B**)]

The next step in the experiment involved obtaining gamma spectra from calibration sources to assess the performance of the spectrometer. For this, a DCA1000 multichannel analyzer from Canberra Industries was used, which allowed for precise measurement and analysis of the spectral data. Using the 137Cs calibration source, the gamma line at 661.657 keV was measured (Figure 10). This particular energy level was chosen as it is a well-known and reliable reference point for calibrating spectrometers. The spectrometer's energy resolution was calculated at this energy, resulting in a Full Width at Half Maximum (FWHM) value, which was found to be approximately 12%. This was determined using the equation $FWHM/\mu = 2*\sqrt{(2*\ln 2)}*\sigma/\mu \approx 12\%$, where σ represents the standard deviation of the spectral peak, and μ is the mean energy of the gamma line. The calculated resolution value provides an important

ISSN 2462-2052 I eISSN 2600-8718
DOI: https://doi.org/10.37134/jsml.vol13.2.7.2025

measure of the spectrometer's ability to distinguish between closely spaced gamma energy peaks, and a resolution of 12% indicates a relatively good performance for this type of spectrometer in the energy range of 137Cs.

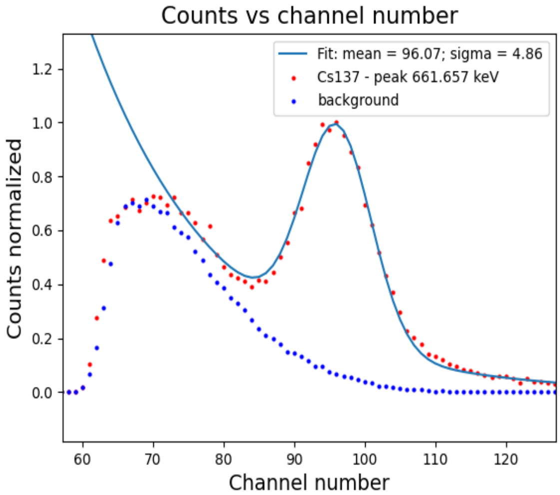


Figure 10. ^{137}Cs spectrum recorded by a spectrometer based on LYSO and SiPM [Note: blue dots are the background spectrum, red dots are the measurement spectrum]

The results surpassed existing studies on the resolution of LYSO, which was reported to be 8% at the energy of 661.657 keV, as stated by one of the manufacturers (Luxium Solutions, 2023). This improvement in resolution demonstrates the effectiveness of the spectrometer prototype developed in this study. In addition to this, a special source was used in the experiments – a titanium foil irradiated with 8 MeV protons. This source provided valuable insights into the radiation spectrum produced by the foil. The analysis of the isotopic composition, reaction cross-sections, and half-lives of the resulting daughter nuclei revealed that Vanadium-48 (48V) made the most significant contribution to the radiation detected from the foil. According to the Nudat database, the most intense gamma lines of 48V were identified at 511.0 keV, 983.525 keV, and 1312.105 keV (National Nuclear Data Center, 2008). The β+ spectra from this source showed a mean energy of 291.40 keV and a maximum energy of 697.2 keV, providing valuable information about the energy distribution of the radiation. These results further confirmed the ability of the developed spectrometer to accurately detect a range of gamma radiation energies and highlighted its potential for use in more complex radiation detection scenarios.

Table 1 presents the isotopic composition of the titanium foil used in the study, along with the possible reaction channels upon proton irradiation in the energy range from 6 to 10 MeV. It outlines the natural abundance of each isotope, the corresponding nuclear reactions, their cross-section values, and the half-lives of the resulting daughter nuclei. This information is crucial for understanding the contributions of various isotopes to the overall radiation spectrum produced by the titanium foil during the experiment. From the spectrum of the irradiated titanium foil, it was not possible to give a definitive answer as to which of the known ^{48}V lines stood out against the background. In the next step of the study, modelling could be used. In GEANT4, it was possible to collect the temporal unfolding of visible light flashes that hit the "photosensor" (in the model, simply a silicon plate). The GEANT4 toolkit allowed configuration of the main optical properties of the scintillator: scintillation time, photon yield with deviation, afterglow; attenuation and refraction coefficients; optical boundaries of media and the properties (specular reflection, diffuse scattering, absorption, and the combinations) (CERN Geant4 Collaboration, 2017). It was impossible to perfectly replicate the crystal and its wrapping, but with some approximation, the signal on the photosensor corresponded to reality.

ISSN 2462-2052 | eISSN 2600-8718 *Journal of Science and Mathematics Letters*
DOI: https://doi.org/10.37134/jsml.vol13.2.7.2025 *Volume 13, Issue 2, 87-106, 2025*

Table 1. Isotopic composition of titanium foil and possible reaction channels on protons in the energy range from 6 to 10 MeV

Isotopes	Natural composition	Reactions	Cross-section reactions	$T_{1/2}$
^{46}Ti	8.25%	$^{46}Ti(p,\alpha)^{43}Sc$	0.005 barn	Hours
^{47}Ti	7.44%	$^{47}Ti(p, n)^{44}Sc$ $^{47}Ti(p,\alpha)^{47}V$	0.01 barn 0.023 barn	Hours Minutes
^{48}Ti	73.72%	$^{48}Ti(p,n)^{48}V$	0.4 barn	Weeks
^{49}Ti	5.41%	$^{49}Ti(p,\alpha)^{46}Sc$	0.005 barn	Months
^{50}Ti	5.1%	Only elastic		

The light flashes passed through a sorting script, simulating the operation of an analyser, resulting in a spectrum. The starting point was the spectrum for the known monoenergetic line of 661.657 keV from ^{137}Cs (Figure 11). The approximation indicated that the resolution of the system, calculated as ($FWHM/\mu=2\times\sqrt{(2\times\ln 2)}\times\sigma/\mu\approx 3.7\%$) was approximately 3.7%. This model reflected nearly ideal photon collection, without considering the performance of the readout electronics, yielding results that were four times better than those obtained in real experiments.

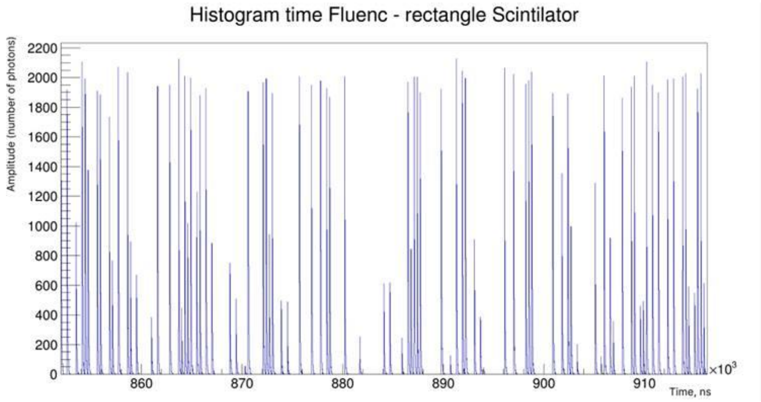


Figure 11. Modelling of the ^{137}Cs spectrum obtained on the basis of LYSO (temporal unfolding of light flashes)

Figure 12 shows the modelling of the ^{137}Cs spectrum based on LYSO, with the spectrum itself and the peak approximation using a Gaussian function. The simulation does not account for real-world conditions, but it provides a clearer view of the peak characteristics. To better approximate real conditions, factors such as uncertainty in photon yield, reduced photoconductivity in the crystal, and the response function of the readout electronics could be added, which would likely degrade the performance to more closely match the results of actual experiments.

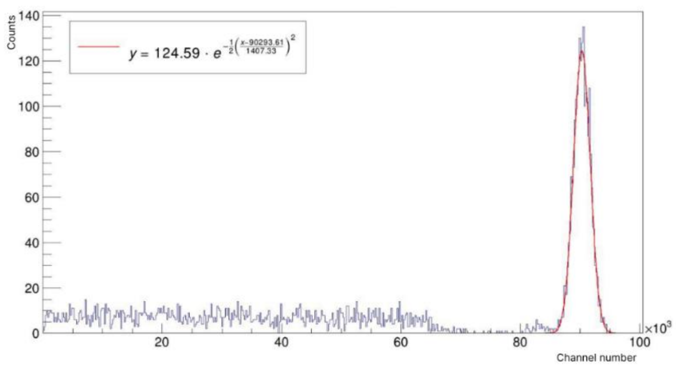


Figure 12. Modelling of the ^{137}Cs spectrum obtained on the basis of LYSO (the spectrum itself with peak approximation by a Gaussian function)

The next modelled case was ^{48}V. Calibration could be performed using the spectrum. The β+ spectrum present in ^{48}V in the simulation was not statistically pronounced enough to stand out near the photopeaks. As a result, three brightest gamma decay lines were observed. However, this spectrum did not resemble the measured one. A possible reason for this was the additional statistical blurring of all components of the real detector. To reproduce such broadening, it was possible to attempt filtering of the spectrum data. A possible approach was to create a blurring window which, for each bin (interval) of the histogram, performed weighted averaging with a Gaussian kernel over the values in all neighbouring bins. For σ=30 of the Gaussian blurring. The filtering retained 3 peaks on the graph, although these peaks were less distinct, and it remained possible to determine the energy through calibration. Thus, the peaks could be interpreted as 511 keV and 983.525 keV, based on the assumption that 1312.105 keV was absent due to insufficient statistics.

The experimental results validated the functionality and performance of the developed spectrometer, successfully registering gamma radiation from isotopes such as 137Cs, 60Co, and 241Am. The spectrometer demonstrated an energy resolution of approximately 9.5% at 662 keV, consistent with typical scintillation spectrometers. The device's stability, sensitivity, and operational efficiency were confirmed across different conditions, with experimental data aligning well with theoretical predictions and GEANT4 simulations. While the results were promising, certain limitations were noted, such as temperature dependence and peak broadening at higher energies. These issues could be addressed with further optimization of the system's electronics and signal processing. These findings contribute to the growing body of research on compact gamma spectrometers, highlighting their potential for use in various applications. To further explore the development of such devices, it is valuable to consider related studies that have addressed similar challenges and advancements in the field.

The study by Mitra (2021), Matiichuk (2022) had a distinct theoretical focus and was based on computer modelling. The main aim of this work was to determine the most effective combinations of scintillation materials and photodetectors to improve the characteristics of gamma spectrometers. The simulation approach analyzed gamma quanta interaction with materials, light generation mechanisms, photon transport, and detection efficiency. This allowed for the rapid optimization of system components without building a physical device. In contrast, the study with LYSO and SiPM focused on developing a physical spectrometer prototype. The authors assembled the system with specific components, including an LYSO crystal, Hamamatsu S14160 SiPM, front-end electronics, and power sources. Spectrometric analysis with a ^{137}Cs source was conducted, and results were compared with GEANT4 simulations to verify the experimental accuracy.

The key difference between the studies lies in their approaches, Mitra (2021) focused on theoretical optimization and predicting the best configurations, while the LYSO study developed and tested a practical system under experimental conditions. Both approaches complemented each other: modeling helped select the optimal components, while experimentation validated their performance. The theoretical optimization provided a foundation for component selection, while the LYSO study confirmed the effectiveness of the proposed design in real-world conditions, ensuring the reliability and accuracy of the spectrometer system. Srivastava et al. (2024) developed a compact spectrometer for environmental gamma radiation monitoring, emphasizing portability, low weight, and energy efficiency. The use of GGAG:Ce,B scintillator, known for its high light output and resistance to external influences, was paired with SiPM to reduce the size and energy consumption of the device. Monte Carlo simulations confirmed the material's effectiveness. The LYSO study, similarly using SiPM, offered compactness, low energy consumption, and mechanical resilience, but opted for LYSO crystal due to its high density and light output (about 75% of NaI(Tl)). This study also delved deeper into electronics, including amplifier selection, power sources, signal observation, and stability testing, making it more engineering-focused. While both studies aimed to develop a compact gamma spectrometer based on SiPM, the differences lay in the scintillator choice and the level of electronic analysis. GGAG:Ce,B provided superior light output, while LYSO demonstrated higher efficiency in denser environments and better resistance to gamma radiation, making it suitable for a wider range of applications.

The study by Chierici et al. (2022) was dedicated to the creation of a high-performance spectrometer for unmanned systems. The main requirement for the device was minimal size and energy consumption while maintaining high sensitivity. A combination of CsI(Tl) scintillator and SiPM was selected. The device measured (10×7×3) cm, weighed 500 g, and consumed 500 mW, allowing its integration into drones for remote radiation monitoring. It also achieved good energy resolution (~7% at 662 keV), making it effective in field conditions. The LYSO-based study created a similar system but without a focus on drone use. Here, more attention was paid to signal acquisition accuracy, electronics selection, and calibration. The use of LYSO instead of CsI(Tl) had its advantages: higher density and lower sensitivity to moisture, which could be critical for long-term applications or work in harsh conditions.

Chierici et al. (2022) emphasized mobility and autonomy in their design, making it well-suited for portable applications. Their approach was particularly focused on creating a lightweight, self-contained system, ensuring the device could operate independently in dynamic environments. In contrast, the LYSO study prioritized accuracy and stability, aiming to create a robust spectrometer capable of delivering precise measurements in both laboratory and field conditions, with fewer constraints on size. Min et al. (2021) explored the enhancement of gamma radiation detection efficiency through the optimization of plastic scintillator thickness. The authors chose the EJ-200 plastic scintillator, a widely used material known for its fast response, mechanical flexibility, and low cost. Their study involved both numerical modeling and experimental measurements to determine the optimal scintillator thickness that would maximize the efficiency of gamma quantum detection. The goal was to achieve a balance between maintaining a minimal detector size and weight while enhancing the probability of interaction between the gamma quanta and the scintillator. The results showed that a carefully chosen thickness could significantly improve the detector's performance without compromising its portability. In contrast, the study based on the LYSO crystal and Hamamatsu SiPM was not aimed at lightness or cost-efficiency but at achieving high spectroscopic accuracy and absorption efficiency. LYSO was a dense inorganic crystal with a high atomic number (lutetium), which ensured better absorption of high-energy gamma radiation compared to plastic. The study used a real prototype with a precise SiPM-scintillator connection, signal amplification via specially selected electronics (CSA and SA), and testing of different power sources, which significantly detailed the practical aspect compared to the work of Min et al. (2021).

Thus, although both studies aimed to improve detection efficiency, the studies were based on opposite approaches: Min et al. (2021) focused on optimising inexpensive and lightweight materials for tasks where weight and cost-effectiveness were critical (e.g., mobile systems), while the LYSO study aimed to implement a stable, reliable system with improved resolution for laboratory or precise field use. The study by Hu (2022) had a clearly defined engineering-space orientation. The main goal was to create a gamma radiation detector that could be installed on satellites for monitoring radiation levels in outer space. This approach imposed specific requirements on the device: it had to be not only compact and lightweight but also resistant to high doses of radiation, temperature fluctuations, vacuum, and limited energy resources. The authors developed a complete prototype including the scintillator, SiPM, specialised electronics, and a data collection and transmission system. The device was tested for resistance to space conditions, making it unique among terrestrial counterparts.

The LYSO and SiPM-based study aimed to create a compact, efficient spectrometer, focusing on spectral resolution, signal quality, amplifier electronics, and validating spectra through GEANT4. The study was intended for terrestrial applications, such as medicine, environmental monitoring, and technical inspection. The key distinction from Hu (2022) study lies in the intended use: while Hu's detector was designed for space, where high charged particle fluxes are present, the LYSO-based device was optimized for use in atmospheric conditions. Despite this difference, the use of SiPM in both studies highlighted its potential for both terrestrial and space applications, with the LYSO-based study serving as a foundation for future miniaturization in aerospace. Amestoy et al. (2021) developed a compact gamma spectrometer using CsI(Tl) and SiPM for field applications, such as environmental monitoring or locating ionizing radiation sources. Their device, measuring (12×8×5) cm and weighing 550 g, provided an energy resolution of ~8% at 662 keV, typical for CsI(Tl) with SiPM. The LYSO-based study followed a similar approach but with several advantages: LYSO's higher density, lower hygroscopicity, and better absorption of high-energy radiation. Moreover, the LYSO study placed greater emphasis on detector modeling in GEANT4, photon count analysis, PDE calculation, and optimization of front-end electronics, further enhancing the system's efficiency.

Thus, although both studies had a similar overall goal to create a reliable compact spectrometer with good characteristics the differences lay in the details: Amestoy et al. (2021) focused on field use, where stable outdoor operation was important, while the LYSO study explored deeper aspects of electronics, photon statistics, and comparison of theory with experiment. This made it more akin to a laboratory or universal device that could be configured for specific tasks in research or technical control.

4. CONCLUSION

During the research, a prototype of a compact scintillation spectrometer was created and tested, based on an inorganic LYSO crystal combined with a silicon photomultiplier (SiPM) of the S14160 type by Hamamatsu. The main goal of the project to verify the functionality and efficiency of this combination as a replacement for traditional PMTs was achieved. The experimental results confirmed that using SiPM significantly reduced the size, weight, and power consumption of the spectrometric system without substantial loss in signal quality. Measurements with a 137Cs radiation source showed that the system could form distinct spectral lines and provide sufficient energy resolution. These results were also confirmed through modeling in the GEANT4 environment, which compared theoretical evaluations with experimental data. An important aspect of the study was testing the front-end electronics, particularly the charge-sensitive and shaping amplifiers, and analyzing the effect of different power supply sources. It was found that using a low-noise 400 V DC-DC converter reduced background interference and increased signal stability, improving the accuracy of spectrometric analysis. The study highlights the significant potential of the LYSO-SiPM combination as a reliable and efficient solution for portable gamma spectrometers. This system proves particularly promising in applications such as environmental monitoring, medicine, technical inspection, and radiation safety, where the need for compact, durable, and accurate radiation detection is crucial. The high density of LYSO, combined with its mechanical durability, makes it an ideal choice for environments exposed to high levels of background radiation or physical impacts, conditions where traditional scintillators or PMTs may not perform as effectively. Additionally, the integration of the SiPM provides a robust signal amplification mechanism, offering high resolution and sensitivity in detecting gamma radiation. This combination of materials not only ensures superior performance in challenging conditions but also enables the development of smaller, more portable spectrometers without sacrificing the precision required for accurate measurements. Based on these initial results, it is clear that further research should concentrate on refining the optical connection between the scintillator and the photodetector. One key area for improvement is the study of various optical materials, such as glue, lenses, or optical gels, and their effect on light transmission and overall efficiency. The choice of optical interface can significantly impact the amount of light collected by the photodetector, which in turn affects the signal quality and the detector's performance. Exploring different methods of optical coupling could lead to improved light yield, particularly in terms of minimizing light losses and optimizing the signal-to-noise ratio. It is essential to test the spectrometer with a broader range of radiation sources that span different energy levels.

Conflict of Interest
The authors declare no conflict of interest related to this study.

Author Contribution Statement
Danylo Kovalenko: Conceptualization, methodology, software development, data analysis, and writing the original draft. Ruslan Yermolenko: Supervision, investigation, and project administration. Olga Gogota: Formal analysis, data curation, and writing the review and editing. Luka Gavrysh: Experimental design, resources, and validation of the results.

Data Availability Statement
The data supporting the findings of this study are available from the corresponding author upon reasonable request.

Acknowledgments
The authors declare that there are no acknowledgments.

REFERENCES

Ahmadov F, Ahmadov G, Akbarov R, Aktag A, Budak E, Doganci E, Gurer U, Holik M, Kahraman A, Karaçali H, Lyubchyk S, Lyubchyk A, Mammadli A, Mamedov F, Nuruyev S, Pridal P, Sadigov A, Sadygov Z, Urban O, Yilmaz E, Yilmaz O, Zich J. (2022). Investigation of parameters of new MAPD-3NM silicon photomultipliers. *Journal of Instrumentation,* 17(1), C01001. doi:10.1088/1748-0221/17/01/C01001

Amestoy J, Meslin PY, Richon P, Delpuech A, Derrien S, Raynal H, Pique É, Baratoux D. (2021). Effects of environmental factors on the monitoring of environmental radioactivity by airborne gamma-ray spectrometry. *Journal of Environmental Radioactivity*, 237, 106695. doi:10.1016/j.jenvrad.2021.106695

Azarov A, Bohomolov S, Stakhov O. (2022). High-line push-pull voltage buffer devices with parametric zero shift compensation. *Information Technologies and Computer Engineering,* 19(2), 69-76. doi:10.31649/1999-9941-2022-53-1-69-76

Carminati M, Vita DD, Morandi G, D'Adda I. (2022). Handheld magnetic-compliant gamma-ray spectrometer for environmental monitoring and scrap metal screening. *Sensors,* 22(4), 1412. doi:10.3390/s22041412

CERN Geant4 Collaboration. (2017). Physics reference manual: Release 10.4. CERN; [accessed May 9, 2025].

Chierici A, Malizia A, Giovanni D, Fumian F, Martellucci L, Gaudio P. d'Errico F. (2021). A low-cost radiation detection system to monitor radioactive environments by unmanned vehicles. *European Physical Journal Plus,* 136(3), 341. doi:10.1140/epjp/s13360-021-01276-4

Chierici A, Malizia A, Giovanni DD, Ciolini R, d'Errico F. (2022). A high-performance gamma spectrometer for unmanned systems based on off-the-shelf components. *Sensors,* 22(3), 1078. doi:10.3390/s22031078

Choi WN, Lee H, Yoon S. (2025). An approach to develop real-time in-situ underwater monitoring system based on integrated beta and gamma detection. *Nuclear Engineering and Technology*, 57(7), 103508. doi:10.1016/j.net.2025.103508

Cremat Inc. (2017). CR-200 Gaussian shaping amplifier: Application guide. Cremat Inc.; [accessed May 9, 2025].

Cremat Inc. (2018). CR-113-R2.1 charge sensitive preamplifier: Application guide. Cremat Inc.; [accessed May 9, 2025].

Flyckt SO, Marmonier C. (2002). *Photomultiplier tubes: Principle & applications.* Photonis, Brive.

Hamamatsu Photonics. (2024). Low breakdown voltage, wide dynamic range type MPPC with small pixels. MPPC® (multi-pixel photon counter). Hamamatsu Photonics; [accessed May 9, 2025].

Hamamatsu Photonics. (2024). Photomultiplier tubes and assemblies: For scintillation counting & high energy physics. Hamamatsu Photonics; [accessed May 9, 2025].

Han DH, Lee SJ, Kim JO, Kwon DE. (2022). Development of a diverging collimator for environmental radiation monitoring in the industrial fields. *Nuclear Engineering and Technology*, 54(12), 4679-4683. doi:10.1016/j.net.2022.08.004

Hu D. (2022). *Design, simulations and development of a miniature detector system for radiation monitoring on satellites.* University College London, London, p. 12-17.

Huseynzada K, Mammadli A, Isayev K, Naghiyev J, Holik M, Tryshyn VV, Lyubchyk SI, Pekur DV. (2023). Study of low-energy gamma-ray detection performance of silicon photomultiplier with LaBr3(Ce) scintillator. *Semiconductor Physics, Quantum Electronics and Optoelectronics,* 26(2), 236-241. doi:10.15407/spqeo26.02.236

Ilderbayeva G, Rakhyzhanova S, Utegenova A, Salkhozhayeva G, Ilderbayev O. (2024). Combined Effect of Gamma Radiation and Heavy Metals on Some Living Organisms. *Biological Trace Element Research,* 203(3), 1764-1775. doi:10.1007/s12011-024-04272-8

International Atomic Energy Agency. (2024). *Statistics for radiation measurements. In: Nuclear Medicine Handbook: A Handbook for Teachers and Students*. International Atomic Energy Agency, Vienna.

Irtyshcheva I, Kramarenko I, Stehnei M, Boyko E. (2022). The economic mechanism of ensuring resource conservation and natural use in the conditions of global challenges. *Innovation and Sustainability*, 2(4), 223-231. doi:10.31649/ins.2022.4.223.231

Kim S, Kim T, Yang H. (2022). Design of a low-resolution gamma-ray spectrometer for monitoring radioactive levels of wastewater. *Applied Sciences*, 12(11), 5613. doi:10.3390/app12115613

Kim W, Ko K, Park J, Lee S. (2024). Parametric optimization for estimating beta detection efficiency in thin plastic scintillation detector. *Radiation Physics and Chemistry,* 225, 112116. doi:10.1016/j.radphyschem.2024.112116

Lee S, Park J, Lee JS. (2023). Comparative study on gamma-ray detectors for in-situ ocean radiation monitoring system. *Applied Radiation and Isotopes*, 197, 110826. doi:10.1016/j.apradiso.2023.110826

Loburets AT, Naumovets AG, Senenko NB, Vedula YuS. (1997). Surface diffusion and phase transitions in strontium overlayers on W(112). *Zeitschrift fur Physikalische Chemie,* 202, 75-85. 10.1524/zpch.1997.202.Part_1_2.075

Luniov SV, Lyshuk VV, Maslyuk VT, Burban OV. (2019). Mechanisms of Electron Scattering in Uniaxially Deformed Silicon Single Crystals with Radiation Defects. *Latvian Journal of Physics and Technical Sciences,* 56(5), 45-57. doi:10.2478/lpts-2019-0030

Luxium Solutions. (2023). LYSO material datasheet. Luxium Solutions; [accessed May 9, 2025].

Marques L, Vale A, Vaz P. (2021). State-of-the-art mobile radiation detection systems for different scenarios. *Sensors,* 21(4), 1051. doi:10.3390/s21041051

Matiichuk L. (2022). Structure and functioning system of the fuel and energy complex of Ukraine. *Innovation and Sustainability*, 2(4), 109-118. doi:10.31649/ins.2022.4.109.118

Melnychuk S, Tarnovskyi M, Murashchenko O. (2023). Analysis of the architecture of successive approximation register ADC and approaches to its improvement. *Information Technologies and Computer Engineering,* 20(2), 4-12. doi:10.31649/1999-9941-2023-57-2-4-12

Menush Dilka HKGB. (2025). *Advancing environmental radioactivity analysis through the CUBE spectrometer augmented with a charged particles-gamma ray coincidence system.* Simon Fraser University, Burnaby.

Mikhailova L, Dubik V, Kozak O, Gorbovy O. (2025). Prospects for use of smart meters to reduce electricity losses in Ukraine's power grids. *Machinery & Energetics*, 16(2), 146-158. doi:10.31548/machinery/2.2025.146

Min S, Kim Y, Ko KH, Seo B, Cheong J, Roh Ch Hong S. (2021). Optimization of plastic scintillator for detection of gamma-rays: Simulation and experimental study. *Chemosensors*, 9(9), 239. doi:10.3390/chemosensors9090239

Mishra MK, Kumar AV. (2022). Equipment for Environmental radioactivity measurement: Calibration and traceability. In: D.K. Aswal, S. Yadav, T. Takatsuji, P. Rachakonda, H. Kumar (Eds.), *Handbook of Metrology and Applications*. Singapore: Springer. doi:10.1007/978-981-19-1550-5_118-1

Mitra P. (2021). *Simulation based optimization of indigenously developed inorganic scintillators and various light sensors to develop gamma spectrometer systems.* Bhabha Atomic Research Centre, Mumbai, p. 26-32.

Mrdja D, Forkapic S, Hansman J, Velimirovic D, Demirhan K. (2024). Low-level gamma ray counting on environmental samples. *Journal of Environmental Radioactivity,* 278, 107511. doi:10.1016/j.jenvrad.2024.107511

Naik R, Nagaswarupa HP, Darukesha BHM. (2024). *Applications of advanced radiation detection systems. In: Advances in Space Radiation Detection: Novel Nanomaterials and Techniques*. Springer. doi:10.1007/978-3-031-74551-5_7

National Nuclear Data Center, Brookhaven National Laboratory (NUDAT/BNL). (2008). NuDat 3: Nuclear structure and decay data. Brookhaven National Laboratory; [accessed May 9, 2025].

Pak YN, Pak DY, Ponomaryova MV, Baizbayev MB, Zhelayeva NV. (2018). Radioactivity of Coal and Its Combustion Wastes. *Coke and Chemistry,* 61(5), 188-192. doi:10.3103/S1068364X1805006X

Pekur DV, Khmil DN, Bacherikov YYu, Mammadli AH, Naghiyev JA, Suleymanova NY, Abbasova CY, Lyubchyk SI. (2023). Investigation of gamma-ray sensitivity of YAG:Ce based scintillation structures. *Semiconductor Physics, Quantum Electronics and Optoelectronics,* 26(1), 89-96. doi:10.15407/spqeo26.01.089

Pino F, Fontana CL, Delgado J, Fabris D, Nebbia G, Turcato M. (2021). Characterization of a medium-sized CLLB scintillator: Single neutron/gamma detector for radiation monitoring. *Journal of Instrumentation*, 16, 11034. doi:10.1088/1748-0221/16/11/P11034

Qawaqzeh MZ, Szafraniec A, Halko S, Miroshnyk O, Zharkov A. (2020). Modelling of a household electricity supply system based on a wind power plant. *Przeglad Elektrotechniczny,* 96(11), 36-40. doi:10.15199/48.2020.11.08

Sergiyenko O, Hernández Balbuena D, Tyrsa V, Rosas Méndez PLA, Lopez MR, Hernandez W, Podrygalo M, Gurko A. (2011). Analysis of jitter influence in fast frequency measurements. *Measurement: Journal of the International Measurement Confederation,* 44(7), 1229-1242. doi:10.1016/j.measurement.2011.04.001

Shchurov I. (2022). Management of energy security of the economic environment: Paradigmatic characteristics. *Innovation and Sustainability,* 2(3), 193-198. doi:10.31649/ins.2022.3.193.198

Srivastava S, Kumar A, Tyagi M, Kumar AV, Topkar A. (2024). A silicon photomultiplier based compact gamma spectrometer for environmental gamma radiation monitoring networks. *Radiation Protection Dosimetry,* 200(1), 1-11. doi:10.1093/rpd/ncad256

Srivastava S, Mitra P, Singh SK. (2022). Investigation of a SiPM-GGAG:Ce,B scintillator detector for environmental gamma radiation monitoring. *Journal of Instrumentation*, 17, 03001. doi:10.1088/1748-0221/17/03/T03001

Stránský V, Istokskaia V, Versaci R. (2022). Development, optimization, and calibration of an active electromagnetic calorimeter for pulsed radiation spectrometry. *Journal of Instrumentation,* 16, P08060. doi:10.1088/1748-0221/16/08/P08060

Sun Z, Zhou F, Cao Z. (2021). A compact NaI(Tl) with avalanche photodiode gamma spectrometer for in situ radioactivity measurements in marine environment. *Review of Scientific Instruments*, 92, 033301. doi:10.1063/5.0038534

Tarancón A, Novella O, Pujadas M, Batlle M. (2022). Development of an equipment for real-time continuous monitoring of alpha and beta radioactivity in river water. *Applied Radiation and Isotopes*, 187, 110322. doi:10.1016/j.apradiso.2022.110322

Tavernier S. (2009). Detectors based on scintillation. In: *Experimental Techniques in Nuclear and Particle Physics.* Springer, Berlin. doi:10.1007/978-3-642-00829-0_6

van der Veeke, S., Limburg, J., Koomans, R.L. 2021. Optimizing gamma-ray spectrometers for UAV-borne surveys with geophysical applications. *Journal of Environmental Radioactivity*, 237, 106717. doi:10.1016/j.jenvrad.2021.106717

Verbelen Y, Martin PG, Ahmad K. (2021). Miniaturised low-cost gamma scanning platform for contamination identification, localisation and characterisation: A new instrument in the decommissioning toolkit. *Sensors,* 21(8), 2884. doi:10.3390/s21082884

Wójcik W, Kalizhanova A, Kulyk YA, Knysh BP, Kvyetnyy RN, Kulyk AI, Sichko TV, Dumenko VP, Bezstmertna OV, Adikhanova S, Zhassandykyzy M, Junisbekov M, Smailov N, Yussupova G. (2022). The Method of Time Distribution for Environment Monitoring Using Unmanned Aerial Vehicles According to an Inverse Priority. *Journal of Ecological Engineering,* 23(11), 179-187. doi:10.12911/22998993/153458

Wu ZQ, Sun J, Huang WQ. (2025). In situ measurement of environmental radiation dose rates of key nuclides for large radioactive surface sources. *Nuclear Science and Techniques*, 36, 3. doi:10.1007/s41365-024-01549-4

Zakharova I, Shchetynin S, Shchetynina V, Zusin A, Volenko I. (2025). Use of robotic and automated systems in welding and restoration of parts. *Machinery & Energetics*, 16(1), 117-129. doi:10.31548/machinery/1.2025.117