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SiPM MEPhI megagrant developments in nuclear medicine

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Abstract

Three projects has been started in our laboratory as part of megagrant "High energy physics and nuclear medicine with silicon photomultiplier detectors" in NRNU MEPHI. The goal of these projects is development of devices for nuclear medicine in which replacement of photomultiplier tubes (PMT) with solid-state silicon photomultipliers promises various advantages. The first project is full-body SPECT, where replacement of PMT's could reduce size of the detector module and improve spatial resolution while keeping other parameters. The second project is development of a TOF-PET module. Replacement of PMTs with silicon photomultipliers makes it possible to use that detector not only in high magnetic fields but also for Time-of-Flight measurements (higher signal-to-noise ratio on final image) due to very high timing resolution of a SiPM. And the last project is the SiPM-based position-sensitive Gamma-spectrometer for dose monitoring in neutron-capture therapy based on SiPM's.

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Keywords: SiPM; gamma-camera; TOF-PET; SPECT

1. Introduction

Our laboratory "Silicon photomultipliers" is developing a prototype detectors based on silicon photomultipliers (SiPM) ([1-4]) in framework of Megagrant "High energy physics and nuclear medicine with silicon photomultiplier detectors". Russian domestic nuclear medicine is suffering from a crippling deficit of modern equipment for

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diagnostics. Almost all of this equipment was imported. Most of setups are in use for more than 10 years and now in need of either modernization or complete replacement. Systems based on the PMT are widely used in the radiology departments of hospitals all over the world [5]. However, it is impossible in principle to use PMT in magnetic fields, e.g. for development of a multimodal system combined with MR-tomography. In this case, we have to use other types of photodetectors, e.g. SiPMs. SiPM has advantage in a number of important parameters when compared with PMT: smallness, low operation voltage (<100 V), good time resolution (~100-150 ps) and low sensitivity to high intensity magnetic field. Our megagrant project includes experimental studies which results could be used for development of modern SPECT (Single Photon Emission Computer Tomography) and PET (Positron Emission Tomography) scanners and Gamma-spectrometer based on novel SiPM's.

2. Development of gamma camera

The first Megagrant project is about development of a full-body SiPM-based gamma camera [6]. The basic requirements for gamma camera is following: energy resolution about 10% on 140 keV line (^{99m}Tc), operation range of energies from 60 to 360 keV, spatial resolution FWHM less than 3 mm and maximum count rate of about 100 kHz. Classical SPECT monolithic crystal NaI(Tl) (lateral dimension is 50x40 cm^2) is planned to use as a scintillator, and 6x6 mm^2 KETEK SiPMs [7] as the photodetectors. One of the main problems associated with SiPM-based gamma camera is a large amount of channels and as a consequence one need to use an extra multichannel integrated electronics, which commercial embodiments are currently practically does not exist. The second problem is related to the presence of the dark noises in SiPM because their contribution from every channel greatly degrades energy resolution of the system.

In the framework of full-body gamma camera development, proof-of-principle prototype of the gamma camera module was assembled. The prototype consists of 64-channel matrix of 6x6mm^2 KETEK SiPMs (Fig. 1a), assembled at Scientific-Production Enterprise "Pulsar", Moscow. Front-end analogue readout and digitazing of the signals from the matrix is performed by 64-channel ASIC MAROC, which is commercially available and produced by French company WeeRoc [8]. Further processing of digitized signal was made on PC.

The experimental measurements with cylindrical scintillator NaI(Tl) (ø 20 mm x 40 mm) were carried out. The aim of the research was to check the possibility of obtaining of necessary energy resolution since the analyzed signal is a sum of the signals from an individual eight center channels covered by scintillator that operate under common bias voltage and have its own dark count rate. In addition, an integration time of the MAROC3 is 150 ns (maximum possible) that is less than decay time of NaJ(Tl), and consequently it leads to integrating only half of the light. As the result, the energy spectrum of the digitally summed signal from detectors with ^{137}Cs source has been built and energy resolution of 23.8% for 32 keV and 7.6% for 662 keV has been obtained (Fig. 1b). In fact, this result is close to resolution (25.2% for 32 keV and 8% for 662 keV) obtained with PMT XP2020 with the full integration of the signal (all light has been collected) on digital oscilloscope LeCroy WaveRunner 620Zi with the same scintillator (Fig. 1c).

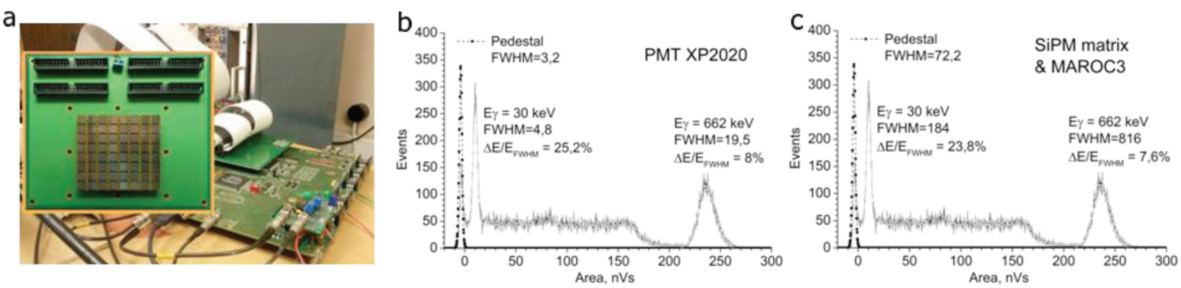

Fig. 1. (a) SiPM 8x8 elements matrix and MAROC3 readout board; (b) ^{137}Cs spectrum from PMT for 1μs integration time window; (c) ^{137}Cs spectrum from SiPM matrix and MAROC3.

In parallel, the Monte-Carlo simulation of the proof-of-principle prototype of gamma camera module using Geant4 libraries [9] (transportation of the photons) and MATLAB [10] program (simulation of SiPM characteristics) was performed. The model include optical properties of the cylindrical scintillator NaI(Tl) (ø 20 mm x 40 mm) and characteristics of the 64-channel SiPM matrix (PDE, gain, noise), used in experiment. Total charge spectrum has been obtained from 8 SiPMs located under the NaI(Tl) crystal. The energy resolution of this spectrum is about 7.6%. In the Fig. 2 total experimental and simulated spectra are shown.

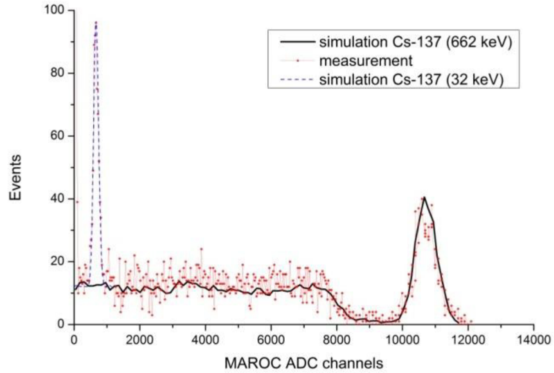

Fig. 2. Simulated and experimental ^{137}Cs spectra obtained with cylindrical scintillator NaI(Tl) (ø 20 mm x 40 mm) and 64-channel SiPM matrix (digital sum of 8 channels covered by scintillator).

In addition, ^{99m}Tc energy spectrum has been simulated with our model of the proof-of-principle prototype. Total simulated spectrum is shown in Fig. 3. The energy resolution of 140 keV peak is 13.9%. Measurements with 99mTc and the prototype in order to verify this result will be done as soon as possible.

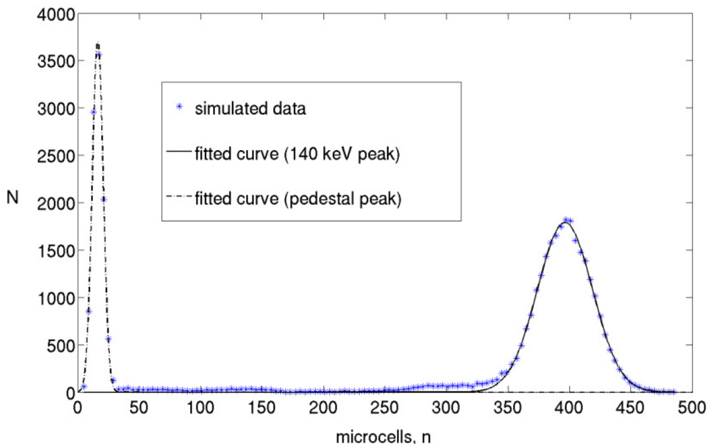

Fig. 3. Simulated ^{97m}Tc spectra obtained with cylindrical scintillator NaI(Tl) (ø 20 mm x 40 mm) and 64-channel SiPM matrix (digital sum of 8 channels covered by scintillator).

3. Development of PET-module

The most widespread, perspective and effective diagnostic procedure in nuclear medicine is PET. For this reason the second project of our laboratory in collaboration with “POSITOM-PRO” company is related to the development of TOF-PET (time-of-flight PET) module using SiPM, that should satisfy the following requirements: 10-15%

energy resolution on 511 keV line, spatial resolution of about 3-4 mm FWHM, maximum count rate no less than 100 kHz and time resolution of about 300-400 ps - the level that achieved by state-of-art commercial TOF-PETs.

Seifert et al. [11] showed that the best timing resolution of single scintillator coupled to SiPM is obtained with very low threshold of about a few fired microcells in order to separate from noise only. One reason for the time resolution worsening is a slope of the leading front of the detector signal. The steeper the slope the less time jitter related to the obtaining of the cut-off time. Thus, it is necessary to amplify the signal and at the same time to keep the slope of the front (to transmit the high frequencies without distortion). We have developed our own amplifier based on IC OPA695 with three cascades. First two of which have gain $\sqrt{10}$ and third one has gain 10. Input impedance of the amplifier is 10 Ohm and the time constant of the differentiation was 20 ns. We measured coincidence time resolution as a function of the threshold at setup showed on Fig. 4. The double-side polished LYSO crystal 3.5x3.5x20 mm^3 was coupled with two 3x3 mm^2 KETEK SiPMs in special case with white reflector. The SiPMs pulses were additionally shaped by RC-circuits, which were placed between first two cascades of amplifiers. From each amplifier we had have two signals: "energy" signal was taken after RC shaper and "time" signal after all three cascades of amplification. All four signals from two amplifiers were analyzed with the digital oscilloscope LeCroy 620Zi (bandwidth 2Ghz) for different software thresholds.

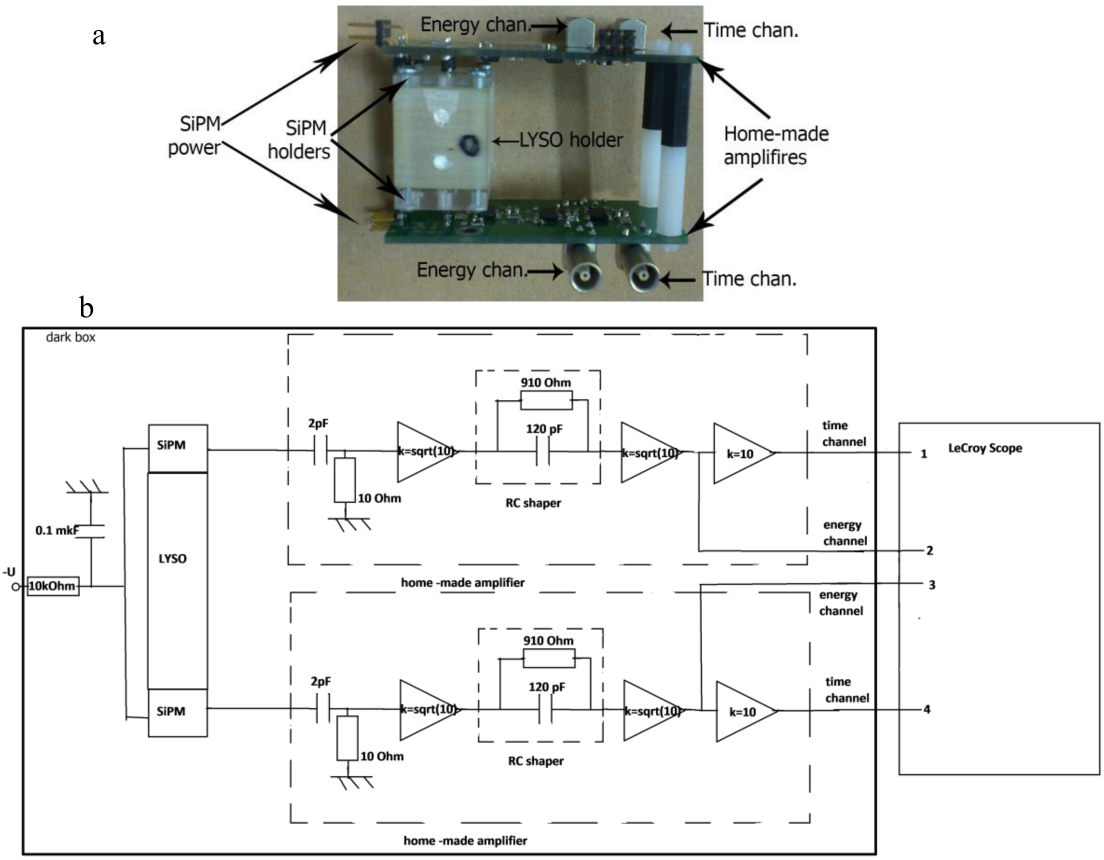

Fig. 4. The experimental setup for CRT measurements: (a) setup for coupling of a two 3x3 mm^2 KETEK SiPMs with scintillator LYSO 3.5x3.5x20 mm^3; (b) scheme of measurements.

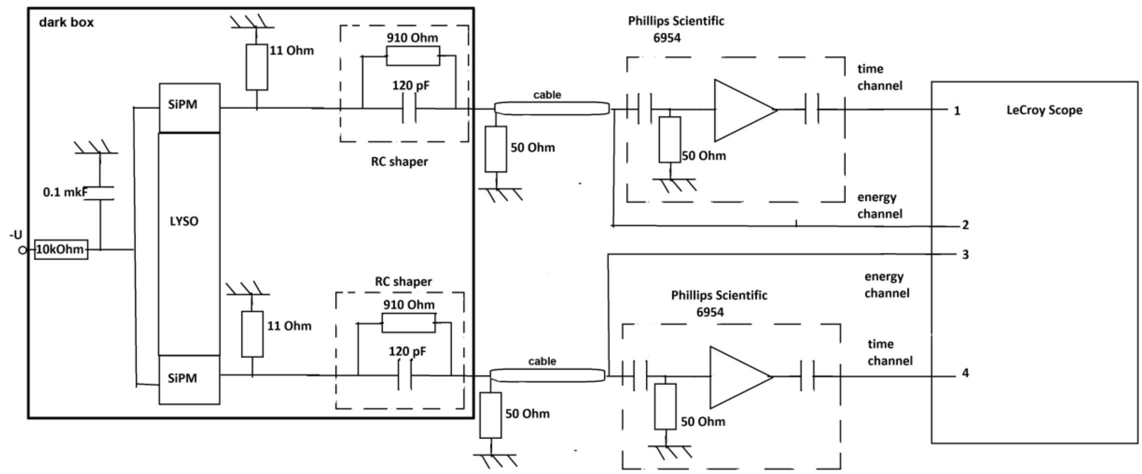

Fig. 5. The scheme of the CRT measurements with two 3x3 mm^2 KETEK SiPMs coupled with scintillator LYSO 3.5x3.5x20 mm^3; at the case of Phillips Scientific 6954 amplifier using.

All measurements were also made with commercial wideband amplifier Phillips Scientific 6954 for comparison. This amplifier has gain 100, 50 Ohm input impedance and only one output. So in that case the scheme of the measurements was a little bit different (see Fig. 5). The bais supply filter and RC shaper were placed on a PCB close to SiPMs. The signals were transferred outside the dark box by 50Ohm cables where they were splitted to energy (without amplification) and time (with amplification) channels.

For both amplifiers 25 thousand waveforms have been recorded and been processed offline. Firstly, the signals from both SiPM energy channels were summorized and the histogram of the total charge has been plotted (see Fig. 6) and the center of photo peak has been determined. Events that had charge sum in the range of ±2σ (Gaussian fit) from peak center were used for time analysis.

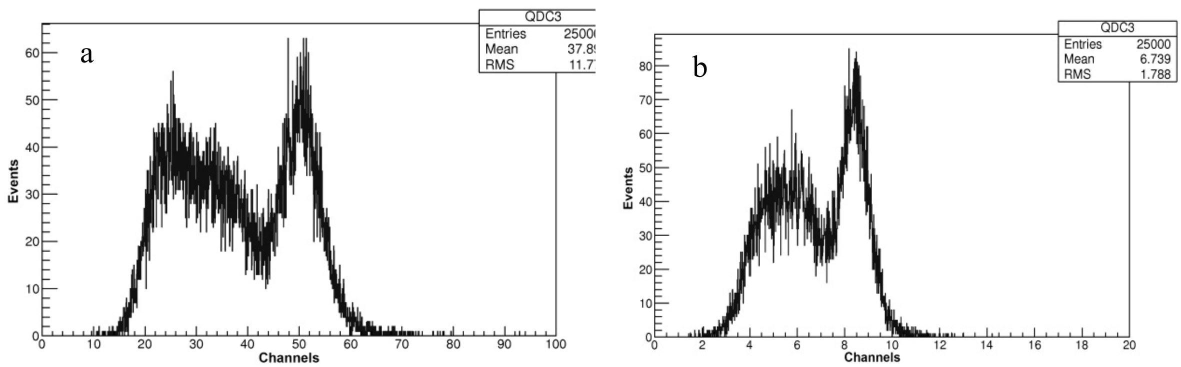

Fig. 6. Histograms of the sum of the charge from two SiPMs coupled to both side of scintillator LYSO 3.5x3.5x20 mm^3 irradiated by 662 keV gammas (^{137}Cs). (a) Signals taken from home-made amplifier; (b) without amplifier (in the case of using of the Phillips Scientific 6954 for CRT measurements).

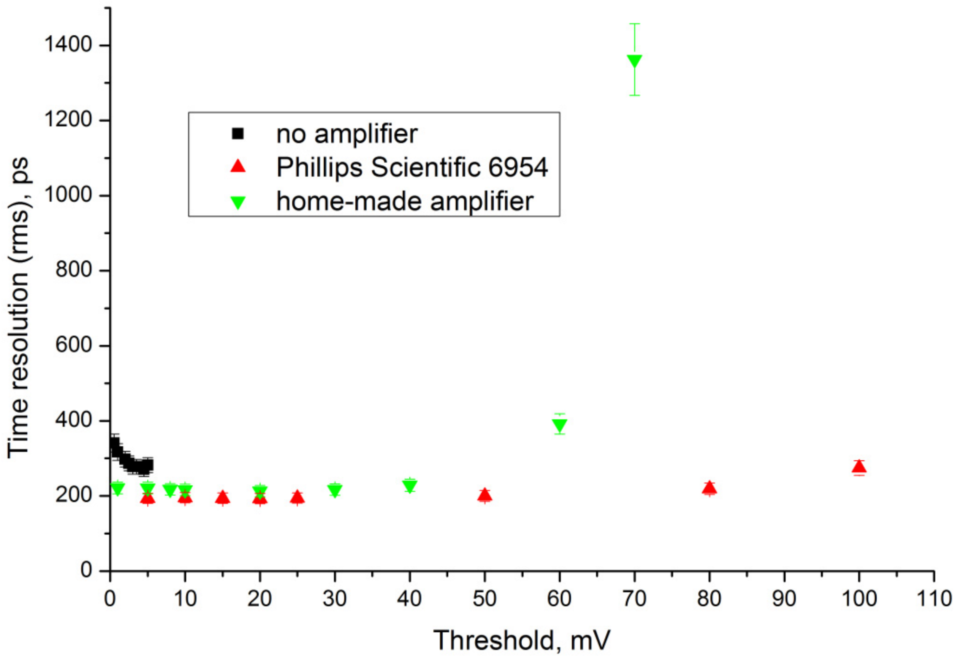

Fig. 7. Coincidence timing resolution (rms) as function of threshold for registration of a ^{137}Cs photons with LYSO crystal 3.5 mm x 3.5 mm x 20 mm viewed by two 3x3 mm^2 KETEK SiPMs.

For time calculations we used iteration algorithm. First, we should define where a pulse starts. For that purpose we set such threshold which is obviously higher then the noise level and found where it intersects the waveform (inside the time range of interest). Using waveform points around this time we fitted the front by the linear function and found the point where it intersects the linear fit of the baseline. Second, we set the threshold for time measurements and find when the pulse crosses that threshold. To do it, we select waveform points above and below chosen threshold and apply the linear fit to them. And finally the time of front crossing is defined as the time when the linear fit (the second one) intersects the measurement threshold level but with one additional requirement – it should be later then the start of the pulse (the time point found during the first step). That additional condition helps to cut-out the noise signals and allows to use very low thresholds. Applying this algorithm for both SiPMs we calculated the time differences between them. Finally, we plotted the time differences for a given threshold for events preselected for time analysis.

Fig. 7 shows the dependence of the time resolution (rms) versus second threshold for two amplifiers and for the case without it. One can see that for low thresholds our amplifier is close to the Phillips one from the point of view of a time resolution. However, it still have to be improved. Further enhancement will be continued.

4. Development of detector for dose monitoring in neutron capture therapy (NCT)

The third project is a development of the detector for dose monitoring in neutron capture therapy (NCT). NCT is a perspective and modern method, since the interaction of the thermal neutrons occurs predominantly with tissues, which contain pharmaceutical based on boron-10. Key problem related to the method of procedure is the absorbed dose estimation inside area of interest. Reaction of the thermal neutrons with Boron is presented on the Fig. 8.

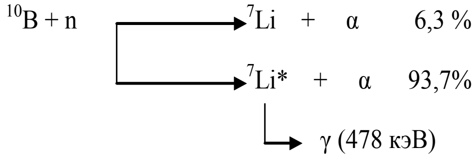

Fig. 8. Reaction scheme of the neutron capture on ^{10}B.

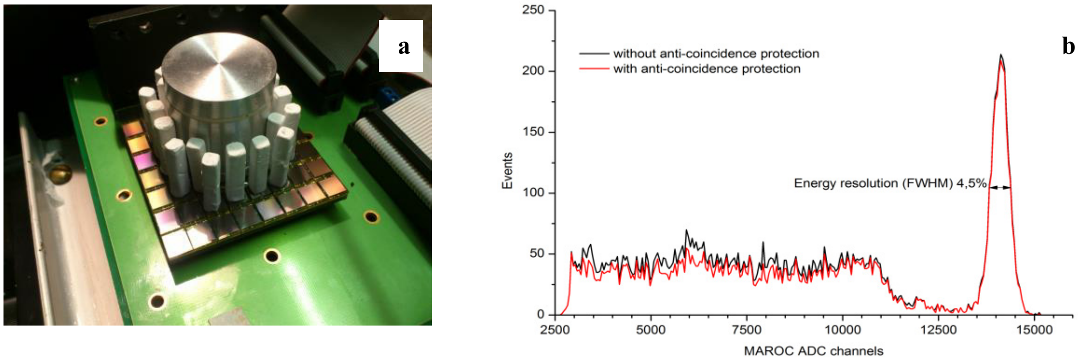

Fig. 9. (a) Experimental prototype of gamma-spectrometer for NCT; (b) energy spectrum from this prototype, source ^{137}Cs.

Short-range alpha-particles emitted in that reaction locally delete tumor tissues, while an accompanying gamma radiation (478 keV) can be used to estimate the absorbed dose. However, due to the fact that neutron radiation is accompanied by background gamma radiation with different energies including annihilation gamma-quantum (511 keV), detector for dose measurement must have high energy resolution (~ 3%) for 478 and 511 keV peaks separation. It was suggested to utilize a $LaBr_3(Ce)$ scintillation crystal, that have the best energy resolution, combined with a SiPM matrix for readout. The usage of SiPM matrix allows to create a dose detector, that is capable of not only to estimate the dose in the region of interests but also to recreate a dose distribution profile in real time during irradiation procedure. To decrease a contribution of the (было "a") background events it is suggested to use an active shield surrounding $LaBr_3(Ce)$ and operate it in anti-coincidence mode. To perform the measurements the test prototype was assembled in which $LaBr_3(Ce)$ cylindrical crystal made in Chernogolovka is surrounded by LYSO crystals. 64-channels matrix of 6x6mm^2 KETEK SiPMs was used as the photosensor for both $LaBr_3(Ce)$ main crystal and LYSO active shield. MAROC3 test board was used as the readout electronics (Fig. 9a).

The measurements with ^{137}Cs source were performed, resolution of 4.5% (662 keV) was obtained and result of using of the active protection was demonstrated (Fig. 9b). Currently, we have improved $LaBr_3(Ce)$ crystal with higher light output. The protection geometry is being optimized as well.

5. Conclusion

Utilizing of silicon photomultipliers in detectors for nuclear medicine can improve not only its performance but give us possibility to place them in regions with high magnetic fields. We have developed proof-on-principle gamma camera prototype and position-sensitive dosimeter for neutron capture therapy. Development of next generation PET-module prototype with the time resolution on 100 ps level is ongoing.

Acknowledgements

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