JOINT INSTITUTE FOR NUCLEAR RESEARCH

Veksler and Baldin laboratory of High Energy Physics

FINAL REPORT ON THE START PROGRAMME

Creation of a scintillation detector for the SPIRO polarimeter

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Contents

1   Abstract

Two types of scintillation detectors, namely vacuum PMTs and Si-PMTs, used in experiments with radiation, as well as issues related to the use and operation of these detectors, were studied during the internship. The result of the work is the acquired knowledge of radiation detection, as well as practical skills in working with scintillation detectors and their design.

2   Introduction

Scintillation detectors are currently one of the main types of radiation detectors. They provide the ability to obtain energy spectra of various types of radiation, which is widely used in many industries from monitoring at nuclear power plants to use in medicine. As part of the production practice, a scintillation detector was created for the installation for measuring the spin polarization of particles. The aim of this project is to develop a functional device capable of detecting single particles, converting their energy into a proportional voltage signal and then amplifying this signal. The main tasks of the work are:

- literary review of the main functional elements;
- comparative analysis of devices for registration of radiation;
- development of functional and schematic diagram of the device;
- development of a printed circuit board;
- assembling the device and checking its performance.

In this work, attention is also paid to the novelty of using scintillation detectors based on the use of Si-PM with a scintillator crystal, the emission peak of which is in the region above 500 nm. In combination with traditional vacuum PMTs, whose sensitivity peak, on the contrary, is in the blue light region, this feature makes it possible to effectively use scintillators emitting in any region of the visible spectrum.

3 PMTs

3.1 Vacuum PMTs

A photomultiplier is an electrovacuum device in which the flow of electrons emitted by a photocathode is amplified by a system of dynodes (105 or more times). The photomultiplier consists of an input (cathode) chamber (formed by the surfaces of the photocathode, focusing electrodes, the first dynode), a multiplying dynode system, an anode, and additional electrodes. All elements are placed in a vacuum housing (cylinder).

The most common are photomultipliers in which the electron flow is enhanced using several special curved electrodes - dynodes, which have a secondary emission coefficient greater than 1. To focus and accelerate electrons, a high voltage (600–3000 V) is applied to the anode and dynodes. Sometimes magnetic focusing is also used, or focusing in crossed electric and magnetic fields.
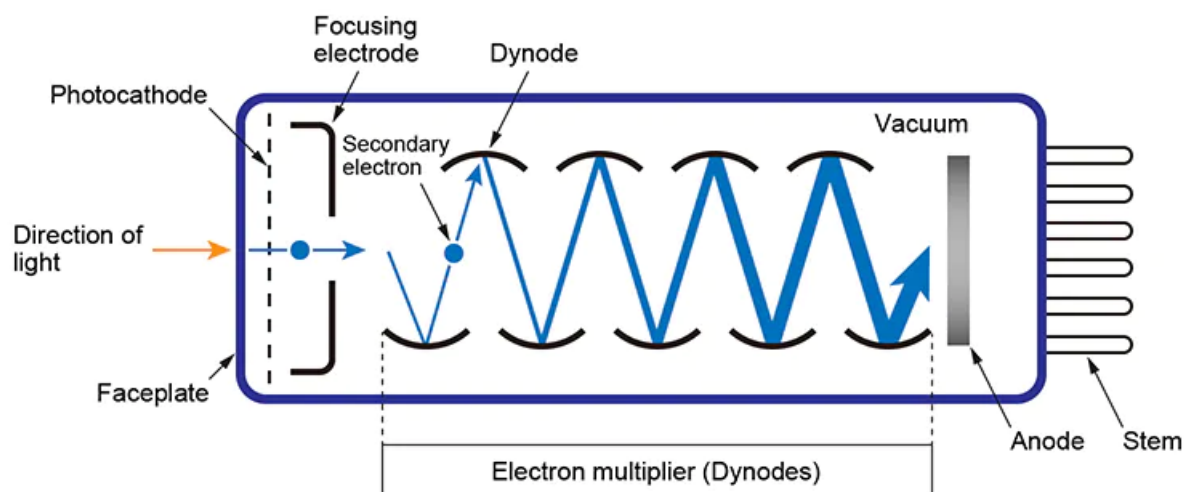

Figure 1: The device and principle of operation of a vacuum PMT

The principle of PMT operation is simple: a photon knocks out a primary electron from the photocathode, which is accelerated by an electric field up to 50-200 eV and pulled out to the first dynode. There, its energy at a very small penetration depth, on the order of the size of an atom, is completely dissipated by the excitation of the intrinsic electrons of the dynode material, so that several electrons already arise, excited not so strongly, but capable

of overcoming the surface potential barrier and exiting into vacuum. In this process, called secondary electron emission, a bundle of 3-5 or more electrons should be formed for each fallen one, otherwise the operation of the dynode system will be ineffective. Secondary electrons, like photoelectrons, have low energies, but the interdynode field pulls them out, accelerates them, and focuses them on the second dynode. Then everything repeats, up to the anode. This is the process of generating a useful signal at the output of the multiplier. [1]

But the primary electron from the photocathode (and dynodes) can also fly out without light, as a result of thermal or field emission. Their appearance, in no way connected with the light signal, excites the same multiplication process and also gives a measurable signal at the output. There are other reasons why current may occur at the anode. For example, leakage current through structural elements. All of them are parasitic, creating a noise signal called the PMT dark current. It should be divided into three main components, depending on temperature and supply voltage in different ways: thermal emission, field emission, and PMT leakage currents.

The thermal emission from the dynodes is insignificant compared to the thermal emission from the photocathode. Dynodes have a higher work function, and the electrons produced on them, on average, pass through a smaller amplification path. Field emission, on the contrary, occurs more often in a dynode system and leads to PMT instabilities at high supply voltages. The threshold for its appearance strongly depends on the quality of the fabrication of the dynode system. The value of the dark signal determines the limiting sensitivity of the PMT. It is possible to measure only such a luminous flux, which gives an output signal that exceeds the noise. But it turns out that a significant part of the dark current has parameters by which it can be isolated and filtered out in an amplifying device. This issue is extremely important, and it is impossible to discuss the measurement parameters of the PMT without discussing the method of recording its signal. Here it is necessary to take into account, firstly, that the PMT is a current source with infinite internal resistance. Indeed, an electron flow comes to the PMT anode, drawn from the last dynode by a relatively high potential, on the order of 100 V, and its small

changes do not affect the current value. Secondly, the temporal structure of the PMT useful signal and noise is also significant. [2]

3.2 Silicon PMTs

The Avalanche Photodiode (APD) is the most sensitive solid state device.
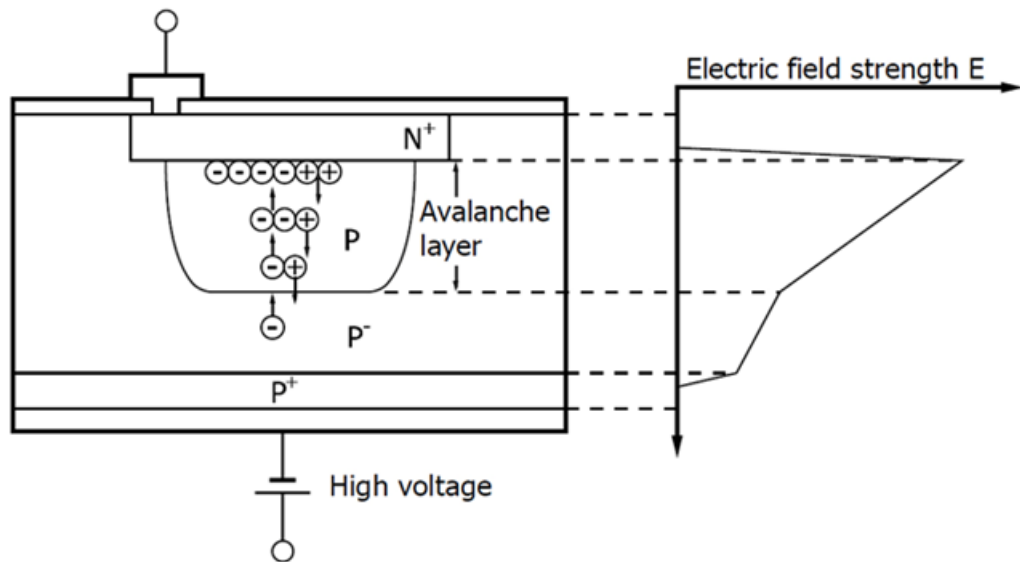
Figure 2: The device and principle of operation of a vacuum PMT

When a sufficiently large reverse voltage is applied, this configuration ensures that the generated carriers are multiplied. When electron-hole pairs appear in the depleted APD layer under the action of light, the electric field causes the electrons to drift towards n+, and the holes towards p+. When electrons get from the i-layer to the p-layer, their acceleration increases due to the high electric field strength in the p-layer, as a result of which such electrons accumulate sufficient energy to knock out other electrons from the valence band to the conduction band. In other words, the generation of secondary carriers occurs - electron-hole pairs. This phenomenon is called impact ionization. These secondary carriers are also accelerated by the electric field and generate new electron-hole pairs, which eventually causes a chain reaction of ionization.

When the APD operates in a linear mode (below the breakdown voltage), the avalanche extinguishes itself very soon due to frictional losses inside the

semiconductor. The multiplication factor of a conventional avalanche photodiode does not exceed 103. Applying a reverse bias voltage above the breakdown voltage allows the avalanche to be sustained and internal gains up to 107–108 to be achieved. To operate in this so-called Geiger mode, avalanche photodiodes with negative feedback have been developed that can control the avalanche process and prevent breakdown of the p-n junction.

It should be noted that an APD operating in the Geiger mode is a digital photodetector (as opposed to linear or analog) because its response is essentially binary. It is capable of registering only the fact of the passage of photons, but not their number, and therefore cannot be used as a power meter for incident radiation.

To overcome this shortcoming, an array of independent APDs operating in the Geiger mode with a passive quenching circuit are connected in parallel to form a silicon photomultiplier tube (SiPM).
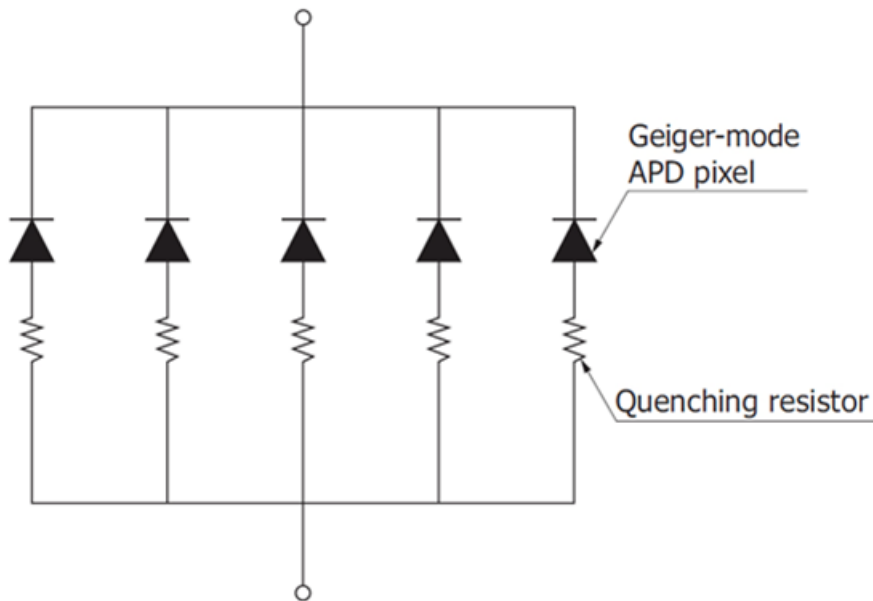

Figure 3: Scheme Si-PM

When a photon passes through, each SiPM pixel produces a pulse of the same amplitude. The pulses generated by multiple cells simply add up at the SiPM outputs. For example, if four photons fall on different pixels and are detected simultaneously, then the SiPM produces a signal whose amplitude is

equal to the height of the four superimposed pulses. Since the cell only emits one pulse, regardless of whether one or more photons hit it at the same time, the linearity of the SiPM deteriorates as the radiation flux density increases.[3][4]

4 Behavior of a vacuum PMT under various conditions

During the work, a vacuum PMT HAMAMATSU H10721P-210 was used. The H10720 and H10721 series are photosensor modules containing a PMT in a metal case and a high-voltage power supply circuit.
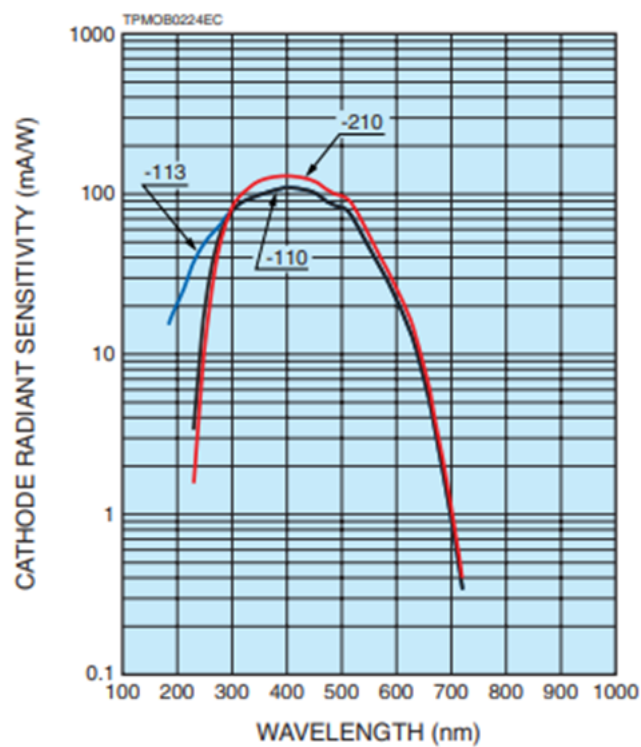

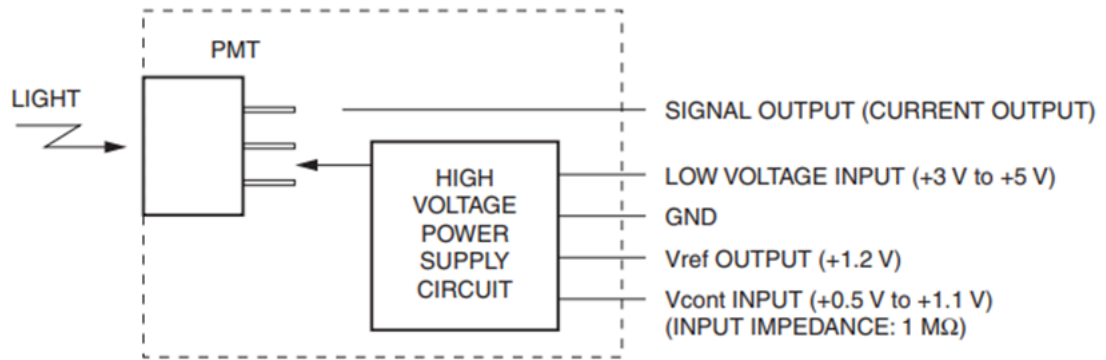Figure 4: Sensitivity spectrum H10721P-210

Figure 5: Functional diagram H10721P-210

In order to correctly estimate the PMT output signals, it is necessary to know the noise of the darkened PMT caused by the dark current. An oscillogram of a typical noise pulse is shown below (a 50 Ω load was used, since the output of the PMT is the output of a current source):
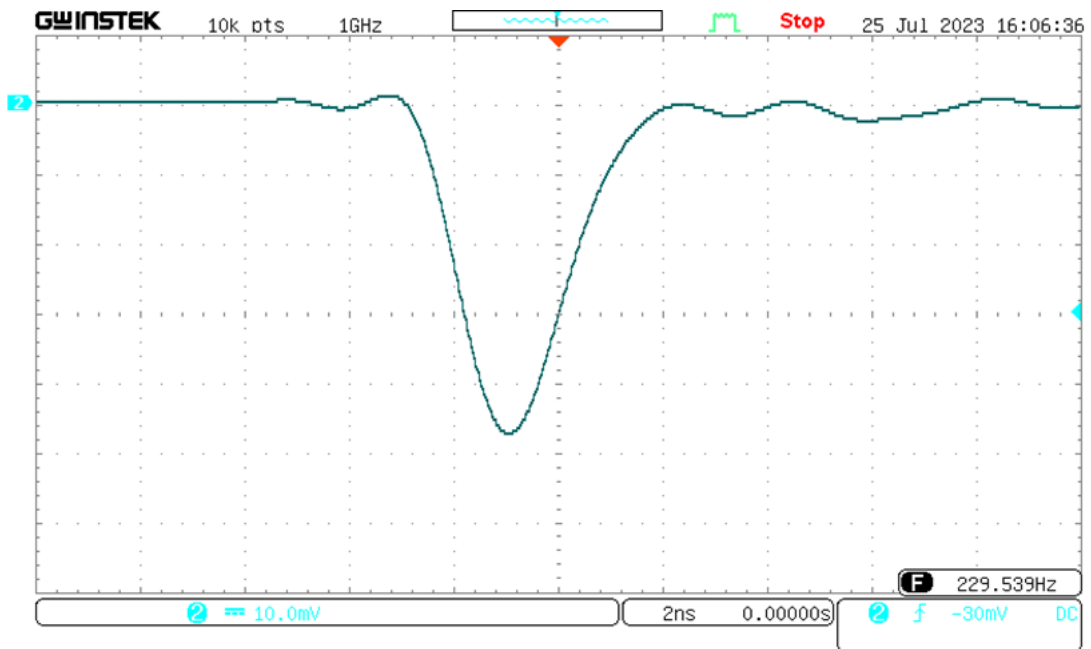

Figure 6: Typical noise pulse H10721P-210

It can be seen from the graph that the pulse has a Gaussian shape and lasts approximately 6 ns. This information will be needed to analyze pulses from various scintillators. It also turned out that the frequency of noise pulses does not exceed a couple of hundred hertz. In this case, if we change the voltage at the PMT control output, and, consequently, the PMT supply voltage, and

measure the noise amplitude, we will obtain the following data:

Control voltage, mV	Noise amplitude avg., mV	Amplitude logarithm
554	0	-
652	2	0,693147181
705	2,40	0,875468737
753	3,04	1,111857515
808	3,90	1,360976553
853	7,70	2,041220329
900	10,80	2,379546134
955	16,75	2,818398258
1004	19,75	2,983153491
1055	31,00	3,433987204
1100	46,25	3,834061464
1149	67,00	4,204692619

If, according to the obtained data, we plot the dependence of the noise amplitude on the control voltage, we will find that this dependence has an exponential form.
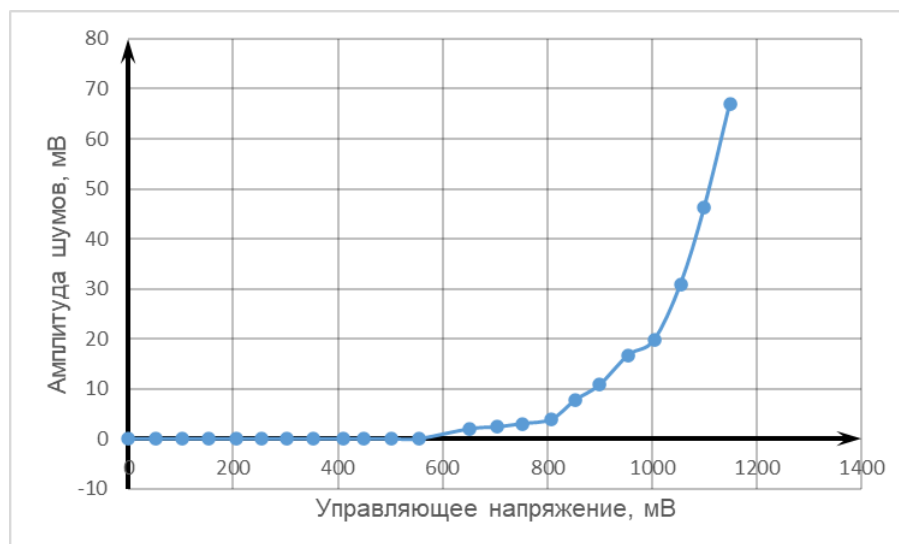

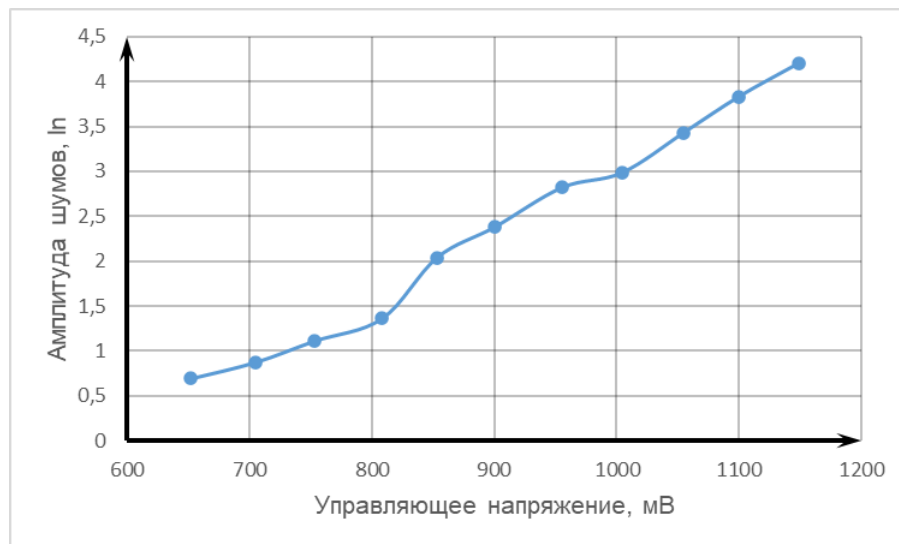Figure 7: Dependence of the noise amplitude on the control voltage

Figure 8: Dependence of the logarithm of the noise amplitude on the control voltage

Now that the main characteristics of a darkened PMT operating without the use of a scintillator have been clarified, it is necessary to check the compatibility of the PMT spectral response with various types of scintillators.

The plastic scintillator was used first, the emission peak of which is located approximately in the zone of the highest PMT sensitivity. As a result, when using a plastic scintillator, the PMT signal had the following form:
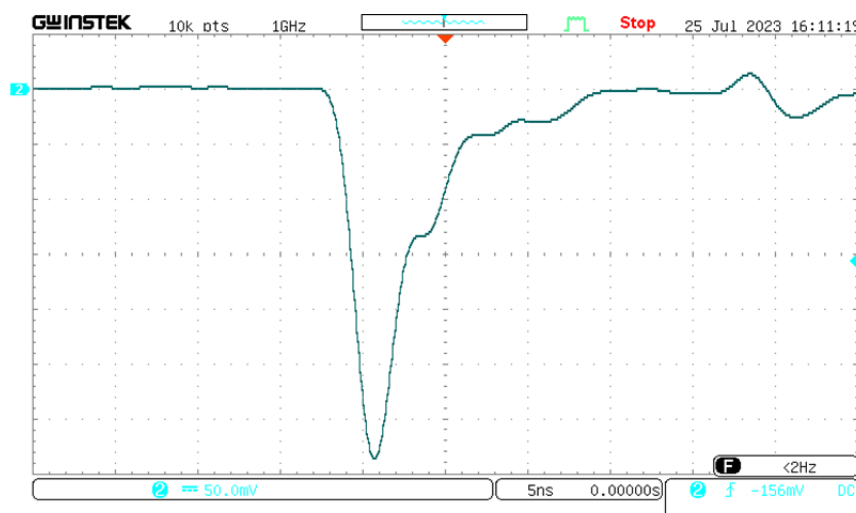

Figure 9: Signal when using a plastic scintillator

Comparing this graph with the graph of the noise signal, three important

details can be noted. First, the pulse from the plastic scintillator has a different shape, close to an exponential pulse: a relatively steep leading edge and a stretched trailing edge. This corresponds to theoretical calculations about the light pulse of the scintillator, which decays according to an exponential law. Secondly, due to the different pulse shape, its duration is approximately 15 ns versus 6 ns for the noise pulse. And thirdly, the amplitude of this pulse is much higher than the amplitude of noise pulses (200–400 mV are pulses from the scintillator, up to 50–60 mV are noise pulses).

Then a similar experiment was carried out using a GAGG scintillator, the emission spectrum of which was shifted to the red region, with a peak at 520 nm. Thus, the oscillogram should show the difference with the pulse from the plastic scintillator at least in the pulse amplitude.
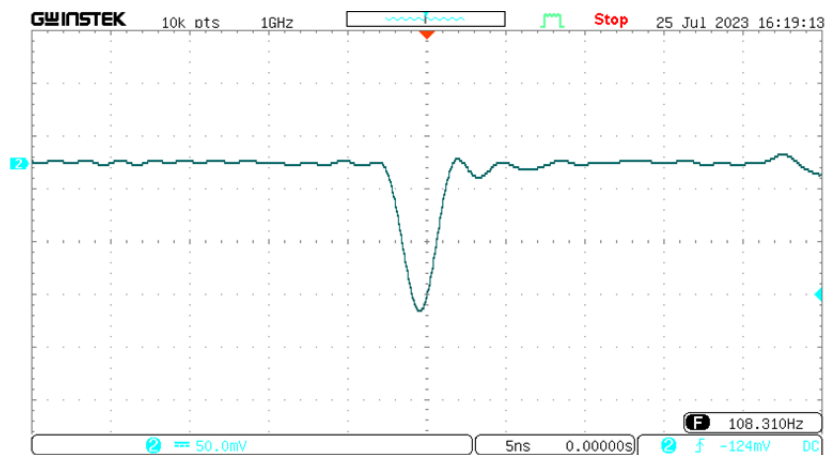

Figure 10: Signal when using GAGG

However, as can be seen from the figure, it turned out that the signal from the GAGG scintillator also differs in the shape of the pulse itself. In this case, the pulse amplitude, as expected, is significantly less than the pulse amplitude from the plastic scintillator. As a result, we can conclude that such scintillators of the GAGG type are less suitable for working with vacuum PMTs. Explanation: since the amplitude of pulses from GAGG is less than the amplitude of pulses from a plastic scintillator, most of the pulses from particles can be mistaken for noise pulses. It is also problematic to somehow separate pulses from noise and pulses from particles, because they have identical shape and duration.

5 The problem of using GAGG with vacuum PMTs

To solve the problem of using the GAGG scintillator for particle detection, it was decided to change vacuum PMTs to silicon ones. For this, the Si-PM MicroFC-60035-SMT was chosen. This element is a 6 mm by 6 mm assembly containing 18980 avalanche photodiodes with a fill factor of 64%. The supply voltage is 24.2–24.7 V, while the recommended overvoltage level is 1–5 V. But the most important feature of this SiPM is the spectral response. The sensitivity peak is 420 nm, the spectrum is from 300 to 900 nm.
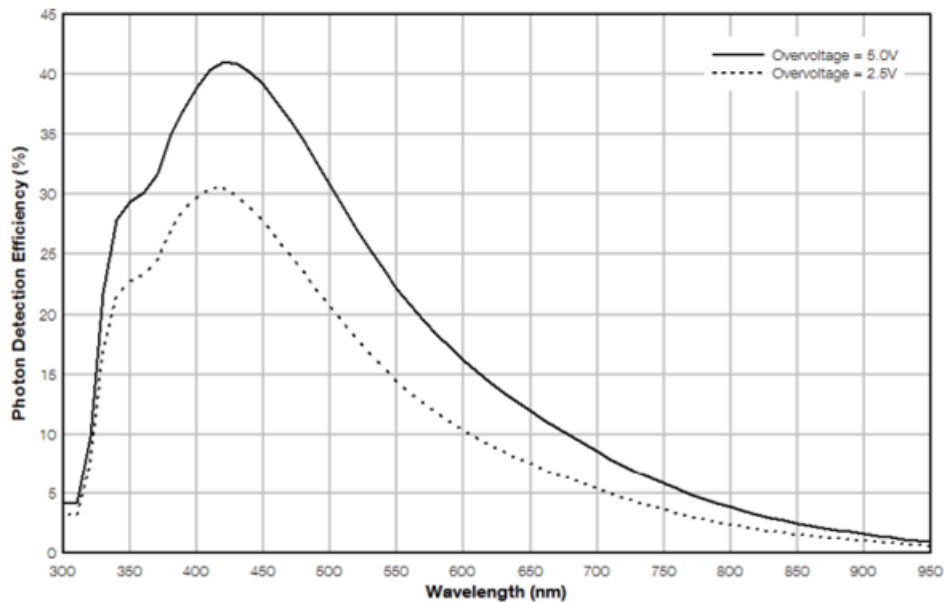

Figure 11: Spectral sensitivity of SiPM

It should be noted that the dark noise of Si-PMs is small compared to vacuum PMTs. To reduce the noise of silicon detectors, it is sufficient to provide the necessary level of darkening of the detector, ideally, so that photons from the scintillator fall on it. For vacuum PMTs, the main source of noise is the structural elements of the PMT itself, so additional dimming will not lead to the absence of noise.

For the experiment, one Si-PM was used, connected according to the scheme presented below.
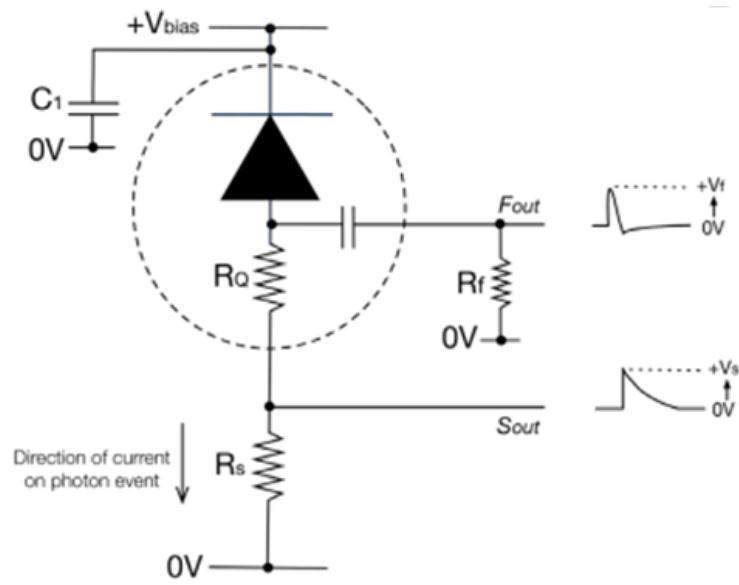
Figure 12: Scheme of switching on a single Si-PM

As a result, using the Si-PM, it was possible to obtain the following signal from the GAGG scintillator:
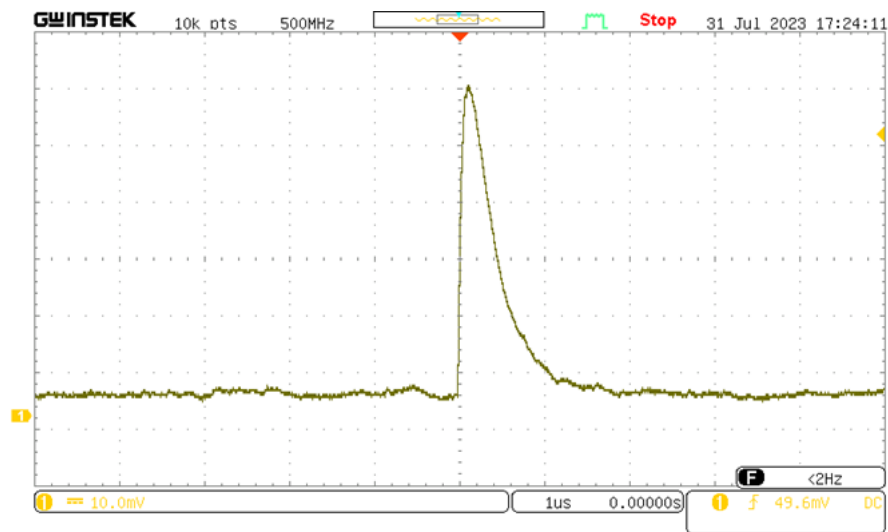

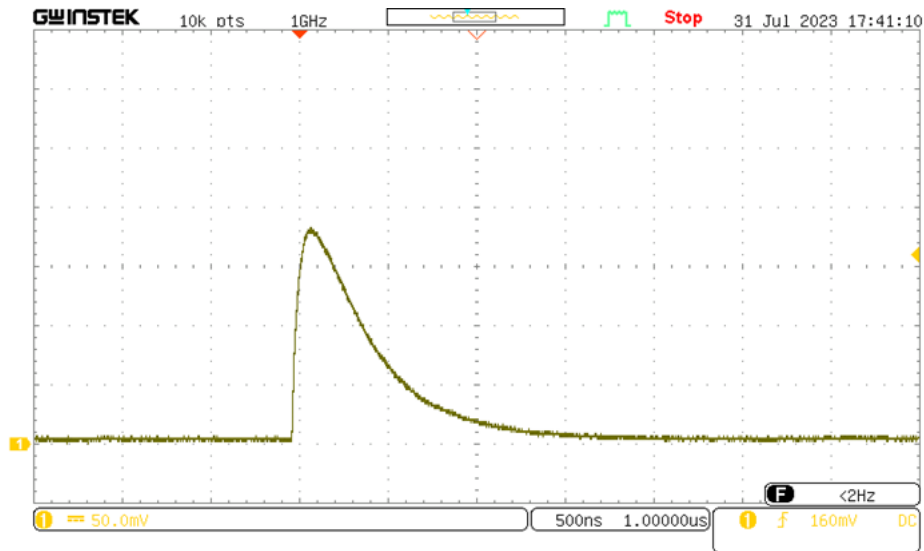Figure 13: Pulse with GAGG obtained using Si-PM

Figure 14: Pulse with GAGG obtained using Si-PM

As can be seen, when using the Si-PM, it was possible to obtain a signal from the GAGG scintillator. The resulting pulse also has an exponential shape, which was observed using a vacuum PMT and a plastic scintillator. However, it should be noted that if in that case the pulse duration was less than 100 ns, then in this case it reaches 1 µs. This is due to the fact that Si-PM has a capacitive nature, so the count rate of such detectors is much lower than that of vacuum PMTs. Also, do not forget about the dead time (the recovery time of the cell charge), during which the cell is not able to register photons.

6 Development and justification of the electrical circuit diagram

For proper operation, the circuit required to amplify the signals received from the entire SiPM assembly, as well as from each detector individually, must meet the following requirements:

- the presence of filters in the power circuits, providing minimal interference from the power source, which can lead to distortion of the amplitude value of the signals from the Si-PM.
- the presence of amplifiers, the bandwidth of which allows for the maximum

linear amplification of signals from the detectors. This property is especially important for amplifiers with "fast" detector outputs.

All of the above requirements for SiPM signal amplifier circuits have been covered in the documentation and user manual for these detectors. Based on these sources, a two-stage RC filter was chosen for the power circuit; amplifiers for the "fast" outputs of the detectors were made on an amplifier stage with a common base, which stands out for its high speed among other types of transistor switching, and its speed also depends on the type of transistor, which allows you to build high-frequency amplifiers; it was decided to make an amplifier for the general output of the Si-PM assembly on a differentiator, since the main useful information about the signal is "contained" in its leading edge (the signal quickly rises to the amplitude value that we are interested in, and then relatively slowly returns to the base level), for which it was necessary to use an op-amp with current feedback, which has a larger bandwidth compared to classical op-amps.[5]

7   Conclusion

In the course of the work, the creation of a scintillation detector for the installation for measuring the spin polarization of particles was successfully completed. The aim of the work was to create a device capable of detecting pulses from single particles and generating a voltage signal proportional to the energy of these particles. The results of the work performed are of great importance for the project to study the anisotropy of space, which is carried out as part of the work at the NICA booster.

The results obtained showed that the developed scintillation detector performs its functions, providing the formation of pulses that characterize the energy of the registered particle, while providing some flexibility in the operating conditions of the detector, due to the possibility of using a wide range of scintillators. This will make it possible in the future to create compact scintillation detectors based on semiconductor elements.

Also, the results of this work can be applied in various areas where it is

necessary to obtain the energy spectrum of radiation: monitoring systems for nuclear power plants, spectral analysis, medical physics and other areas.

In conclusion, the developed scintillation detector, as well as the results of its tests and its functionality, represent a step in expanding the use of scintillation detectors based on semiconductor elements.

8   Bibliography

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[3] G. E. Stillman and C. M. Wolfe, "Avalanche photodiodes," in Infrared Detectors II, R. K. Willardson and A. C. Beer, Eds. New York: Academic, 1977.
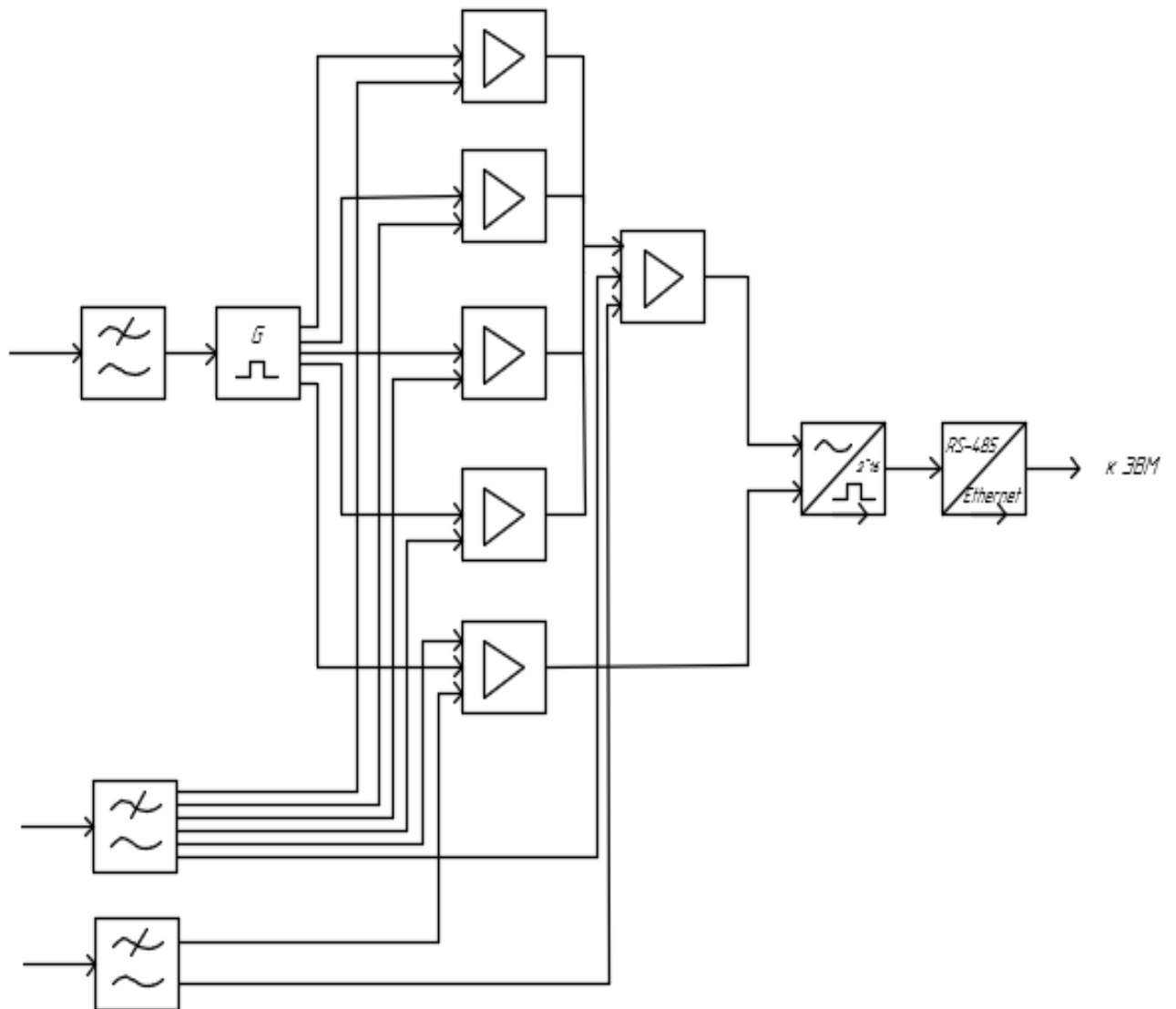
[4] Stefan Gundacker and Arjan Heering, "The silicon photomultiplier: fundamentals and applications of a modern solid-state photon detector", Phys. Med. Biol., vol. 65 (2020) 17TR01

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9   Acknowledgments

10 APPENDIX A. Functional diagram of the device

11   APPENDIX B. Circuit diagram