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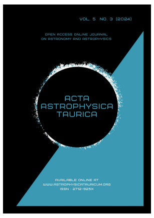

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Prospects for scintillation detectors based on matrices of silicon photomultipliers

A.F. Yanin[1], I.M. Dzaparova[1,2], E.A. Gorbacheva[1], A.N. Kurenya[1], V.B. Petkov[1,2], A.A. Shikhin[1]

[1] Institute for Nuclear Research of the Russian Academy of Sciences, prospekt 60-letiya Oktyabrya 7a, Moscow 117312, Russia
e-mail: `yanin@yandex.ru`
[2] Institute of Astronomy RAS, Pyatnitskaya 48, Moscow 119017, Russia
e-mail: `vpetkov@inr.ru`

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ABSTRACT

This paper discusses a prototype liquid scintillator detector, methods for retrieving information from it, and the potential use of Winston cones and Fresnel lenses. The application of Fresnel lenses and Cherenkov radiation for kiloton-size detectors was evaluated. The 128-channel data acquisition system MDU3-GI64X2 produced by AiT Instruments was used as an information acquisition system. Two ArrayJ-60035-64P-PCB matrices (SensL, Ireland), which consist of 64 individual J-series silicon photomultipliers (SiPMs), were used as receivers. Using photosensors based on such matrices in scintillation detectors is supposed to enable the acquisition of event images (snapshots), the analysis of which will provide a fundamental opportunity to differentiate various classes of events within the detectors.

Key words: Fresnel lens, Winston cone, data acquisition system

1 Introduction

In recent years, there has been a significant development and application of SiPMs and SiPM matrices, which are alternatives to their vacuum analogs. The development of SiPMs is being carried out by about two dozen Russian and foreign companies. The advantages of SiPMs include insensitivity to magnetic fields, a high gain factor (10^5–10^7), low supply voltage, high time resolution, and compact size. Disadvantages include a small sensitive area, a limited dynamic range, and high noise levels. SiPMs are currently used in medicine (positron emission tomography systems, gamma- and X-ray recorders, high-energy physics detectors, research instrumentation, and security systems.

An example of the extensive use of SiPMs is the T2K neutrino experiment. Within this experiment, about 60 thousand SiPMs were used as photosensors in the scintillation counters of various detectors. The FACT matrix of the Cherenkov telescope consists of 1440 individual Hamamatsu MPPC S10362-33-50C SiPMs. The camera of the ASTRI telescope is composed of 16 monolithic Hamamatsu S11828-3344m matrices, and each of them consists of 16 individual SiPMs.

SiPM matrices can have different individual silicon photomultipliers: 2×2, 4×4, 8×8, 12×12. We used an 8×8 variant (Fig. 1):

- the size of an individual SiPM is 6×6 mm^2;
- quantum efficiency of 50 % at the 420 nm wavelength;
- supply voltage of 26–31 V;
- the number of pixels in an individual SiPM is 22 292.

This work continues the work on the development and creation of a scintillation detector prototype based on SiPM matrices in Yanin et al. (2018). The data acquisition system has been upgraded into a more advanced one. Due to a change in the instrument base, the works on reconstructing the tracks of charged particles were continued.

It is known that when a charged particle passes through the scintillator, photons are emitted isotropically at each point of the track, as shown in Fig. 2. Capturing a luminous track of a particle provides a fundamental opportunity to determine the direction of its movement. Moreover, it is possible to measure the energy release along the particle track. The average number of photoelectrons $\bar{n}_{\rm pe}$ in an individual SiPM can be estimated (Petkov, 2016) as

$$\bar{n}_{\rm pe} = \bar{N}_{{\rm ph}(\Delta x)} \delta_R \times k_{\rm opt} \times Q_{\rm pd} \times k_{\rm scintR}, \qquad (1)$$

where $\bar{N}_{{\rm ph}(\Delta x)}$ is the average number of photons emitted along the track of length Δx; $\delta_R = A/4\pi R^2$ is the number of photons reaching an individual SiPM with aperture A and located at distance R (however, assuming that all photons that reach the matrix have previously passed through a Fresnel lens with a small loss coefficient, the aperture of the Fresnel lens, not that of the SiPM matrix, should be considered); $k_{\rm opt}$ is the transparency of the entire path; $k_{\rm scintR} = \exp(-K/L)$ is the absorption coefficient in the scintillator with attenuation length L.

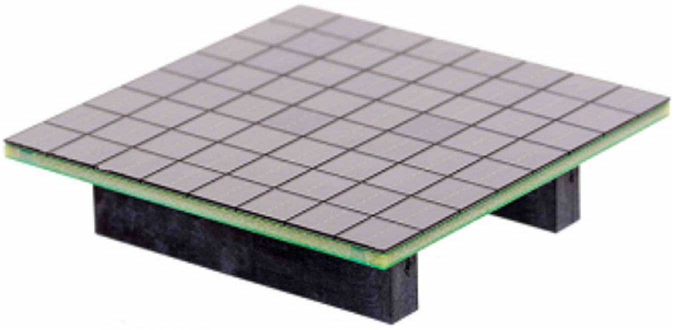

Fig. 1. The ARRAYJ-60035-64P-PCB matrix.

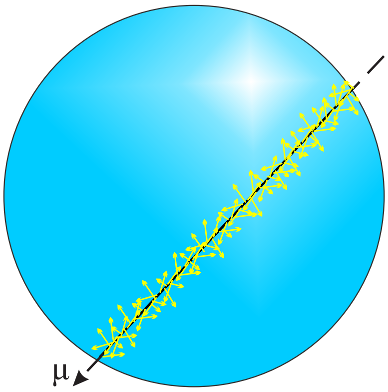

Fig. 2. Isotropic photon emission during the passage of a charged particle through scintillator.

2 Experimental instrumentation

Several large scientific installations have been created to detect neutrinos: Kamiokande II, Super-Kamiokande, KamLAND, and others.

KamLAND is the largest low-energy neutrino detector ever built, as well as the largest scintillation detector. Its main task is to solve the problem of neutrino oscillations by detecting antineutrinos from Japanese and South Korean nuclear reactors. The official ceremony of launching the neutrino telescope Baikal-GVD (Gigaton Volume Detector) was held on March 13, 2021. It is the largest installation of its kind in the northern hemisphere and one of the largest in the world (only the IceCube instrument built in Antarctica can compete with it). These installations use *vacuum* photomultipliers as photosensitive detectors, and they allow one to register the directions of charged particles due to Cherenkov radiation but do not directly record the tracks.

In this study we consider the possibility of using SiPMs for direct track registration through a large detector prototype. The 128-channel data acquisition system MDU3-GI64X2 was chosen as a recording setup, which includes two ArrayJ-60035-64P-PCB matrices of 64 SiPMs each, 128 channels of 12-bit integral analog-to-digital converters, and a high-speed computer communication channel using USB 3.0 (up to 150 MHz/s). It is possible to programatically change the integration time and threshold values (pedestals) for each channel. Figure 3 shows the functional scheme of the data acquisition system from SiPM matrices.

For the experiment, a light-isolated room was prepared in which a mobile table with a 500 mm diameter acrylic sphere filled with liquid scintillator was placed. This construction was additionally equipped with three small movable tables in three orthogonal directions (Fig. 4). Fresnel lenses are mounted on these tables. Each movable table in its turn has a movable matrix to adjust the focal length.

The centers of the matrices are on the main optical axes of the corresponding Fresnel lenses. The Fresnel lenses can be moved from the surface of the acrylic sphere to a distance of about 400 mm.

The idea of the experiment is as follows: when a luminous track appears and moves inside the detector, it is focused by the optics onto the surface of the matrix, illuminating individual SiPMs. The degree of illumination and the length of the track are determined by the number of photons captured

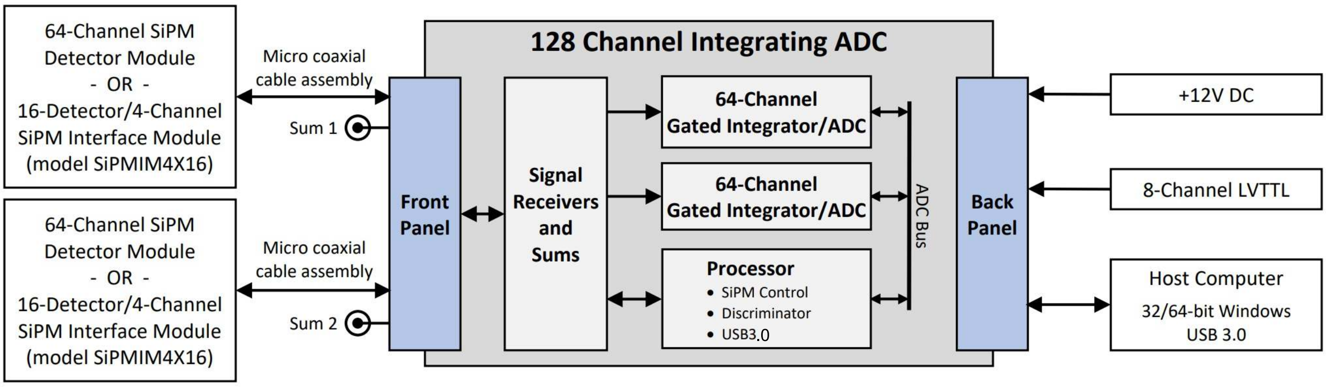

Fig. 3. Functional scheme of the 128-channel data acquisition system MDU3-GI64X2.

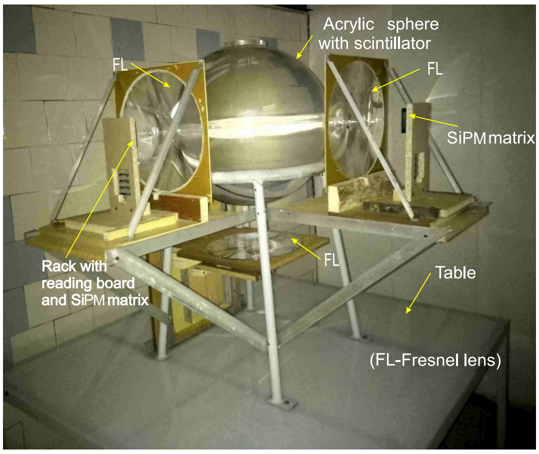

Fig. 4. Table with an acrylic sphere and necessary equipment.

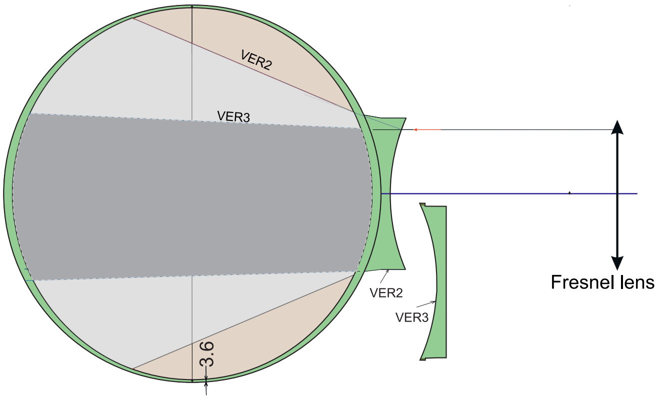

Fig. 5. Viewing zone with additional lenses.

by the matrix, the length of the track in the detector, and its distance from the matrix.

By using additional lenses, the internal volume of the sphere can be viewed at different angles. The photon capture in the viewing zone can be altered by placing different lenses directly on or near the acrylic sphere. Figure 5 shows two versions (ver2 and ver3) for using lenses. Figure 6 shows a) a typical viewing angle in the absence of additional lenses and b) a standard arrangement of sources and image receivers. One of the necessary conditions for obtaining a sharp image is a necessity for the object to be located at a distance greater than twice the focal length from the lens, and the image must be positioned between the focus and twice the focal length. We place the matrix next to the focal plane.

With the aim of testing the equipment, the cumulative energy release spectra were constructed from matrix 1, obtained by the data acquisition system and the LeCroy digital oscilloscope (Fig. 7). The shape of the spectrum corresponds to the expected one.

The attenuation coefficients of photons K were determined by their passing through the Fresnel lens. The calculations used 1000 frames of energy release A_i from 64 individual SiPMs with and without the Fresnel lens under identical incident photon flows:

$$K = \frac{\sum_{i=1}^{1000}\sum_{i=1}^{64} A_i(\mathrm{NoFresnel})}{\sum_{i=1}^{1000}\sum_{i=1}^{64} A_i(\mathrm{WithFresnel})} = \frac{993074}{861428} = 1.15. \quad (2)$$

The additional attenuation of the photon flux is shown in Dzaparova et. al. (2018), which depends on the angle of photon incidence on the matrix. For example, at 43° – by 30 %, at 51° – by 43 % (this is the limiting angle depending on the focal length of the used lens). Figure 8 presents some

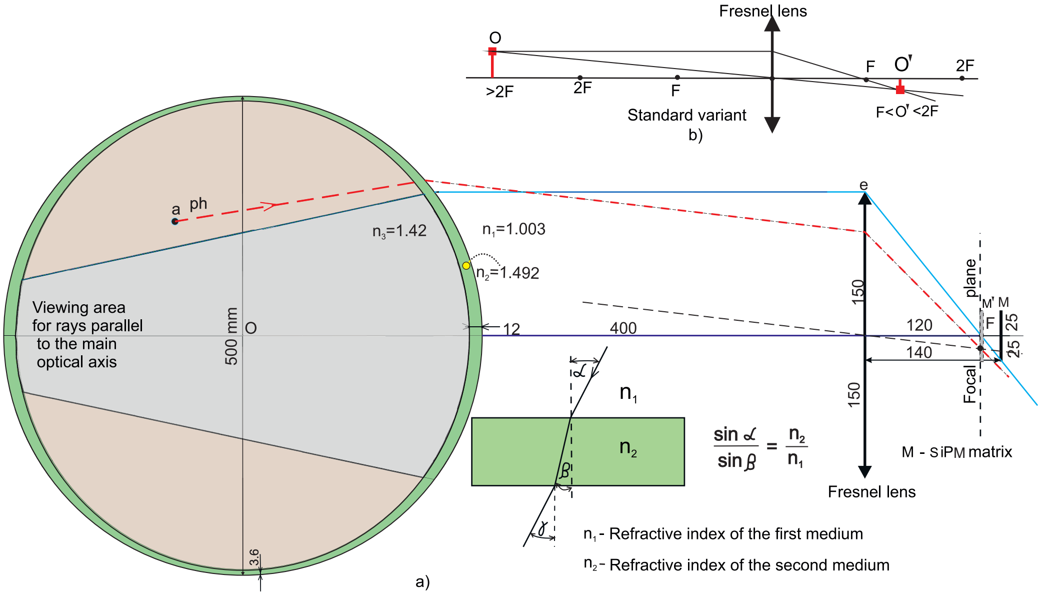

Fig. 6. Viewing zones without additional lenses.

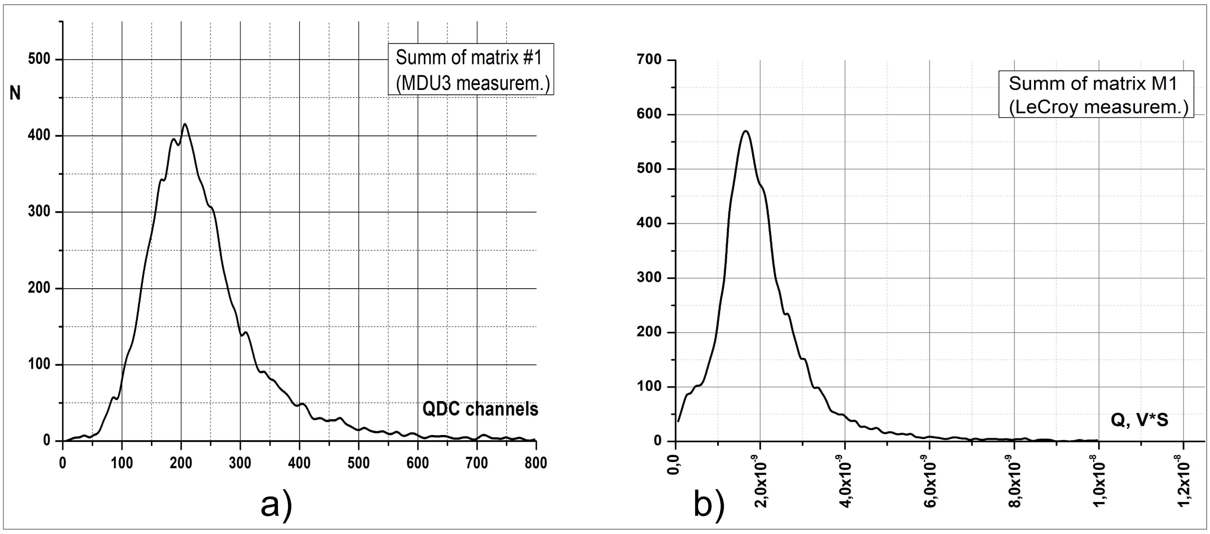

Fig. 7. Summarized energy release spectrum from matrix 1: a) for MDU3-GI64X2: b) for LeCroy oscilloscope.

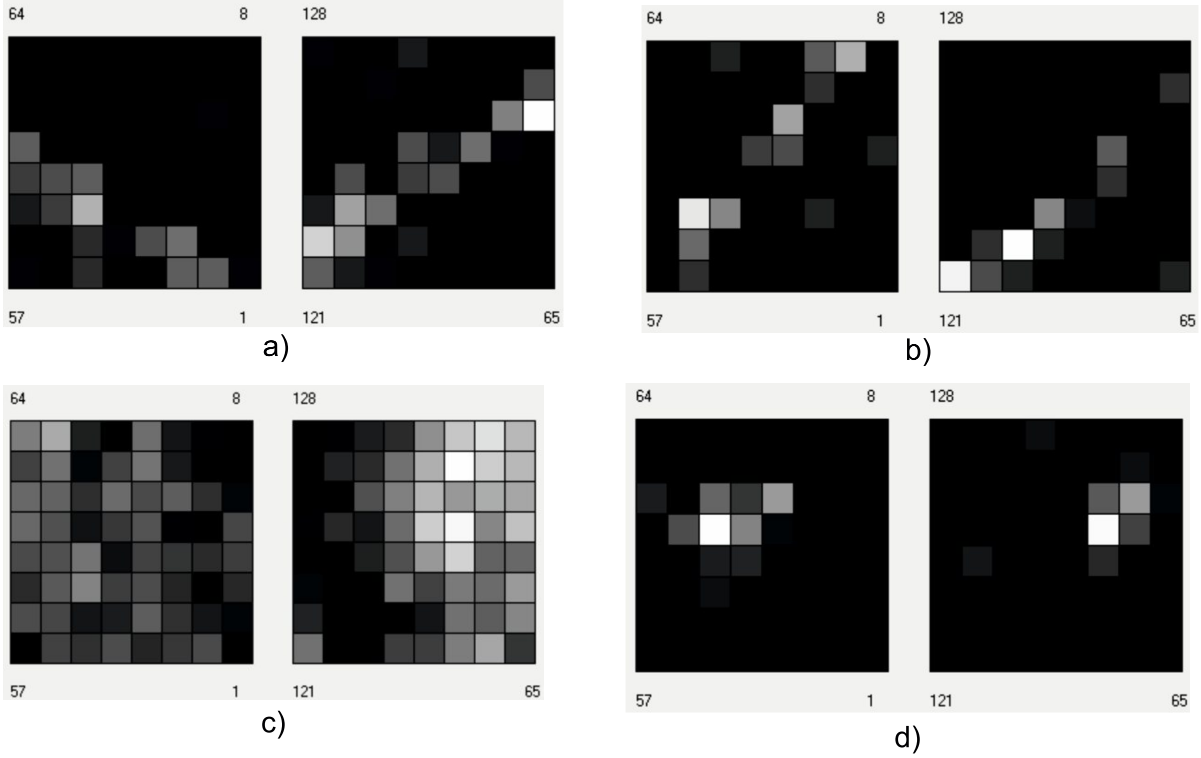

Fig. 8. Some variations of tracks for two orthogonal directions.

tracks for two orthogonal directions. There are distinct tracks (a, b), extensive illuminations (c), and local illuminations (d).

3 Potential use of SiPM matrices in kiloton-size detectors

Large detectors are being developed at INR RAS for the Baksan Neutrino Observatory to study natural neutrino fluxes in geophysics and astrophysics. The suggested detector volumes range from 5 to 20 kt. Petkov (2016) has shown that for a detector with a scintillator mass of 5 kt and a lens aperture of 2000 cm^2, at a track length of 1.2 cm, one photoelectron can be registered at the center of the detector (Fig. 9). Recalculated for a Fresnel lens with a diameter of 300 mm (aperture 706.8 cm^2), this corresponds to 0.35 photons. For star collapse, the average neutrino energy is 10–12.5 MeV, corresponding to 3.5–4.4 photons. After passing through the Fresnel lens, it accounts for 3.04–3.8 photons. Taking into account quantum efficiency, this results in 1.52–1.9 photoelectrons.

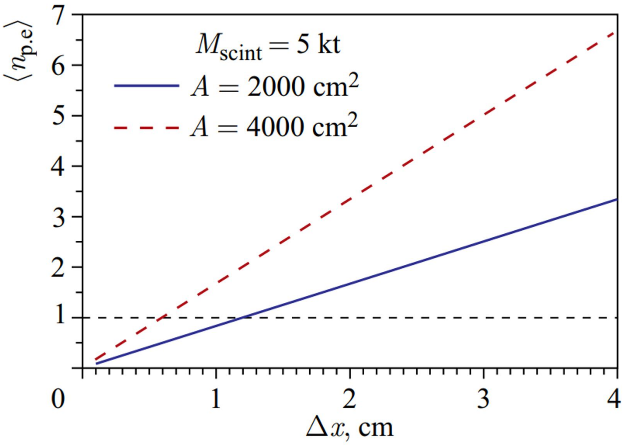

Fig. 9. Dependence of photoelectron registration on the track length for apertures of 2000 and 4000 cm^2.

4 Calculating the track length on the SiPM matrix

An alternative method for estimating a luminous track length for electrons (positrons) is used, which is determined as $2 \mathrm{MeV}/(\mathrm{g} \cdot \mathrm{cm}^{-2})$, i.e., 2 MeV/1.25 cm (assuming the specific gravity of the scintillator is approximately 0.8). Since the average energy of positrons during the collapse is 10–12.5 MeV, the track length in the scintillator amounts to (6.25–7.5) cm. A five-centimeter track in the scintillator perpendicular to the matrix at a distance of 10 m creates a trace on the SiPM matrix of 0.6 mm, which is considerably smaller than the size of an individual SiPM. To equal at least the size of an individual SiPM, the track length in the scintillator at a distance of 10 m should be 50 cm, equivalent to an energy of 80 MeV (Fig. 10). Up to 12.5 photoelectrons that reach the SiPM matrix would be distributed proportionally across the space between adjacent SiPMs. For a track to cross the entire surface of the matrix, an energy release in the range of 400–600 MeV would be required.

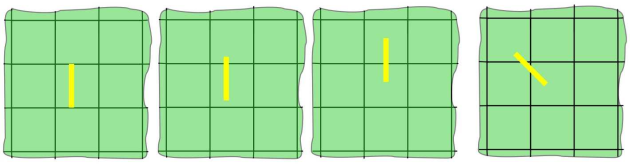

Fig. 10. Possible positions of tracks on the matrix across individual SiPMs with an energy release of 80 MeV at a distance of 10 m.

The track length on the matrix can be increased by extending the focal length of the Fresnel lens. For example, if the focal length is increased from 90 mm to 180 mm, the track length changes from 0.6 mm to 1.2 mm. Consequently, the average number of photons reaching an individual SiPM is halved. However, if the Fresnel lens diameter is doubled, the aperture becomes four times larger, and the signal amplitude increases by a factor of 2. However, a significant increase in the aperture of the lens should be avoided due to potential focus disturbance.

5 Conclusions

The results obtained with a kiloton-size detector prototype give confidence in the potential use of SiPM matrices in such detectors, especially taking into account a rapid development in this field. At present, low supply voltage (below 30 V for SensL), high response speed (fractions of a nanosecond), the possibility of producing large-area SiPMs, the capability for coding the incidence of the averaged photon beam point, etc., seem to be appealing factors.

Kiloton-size detectors are required for the detection of weakly interacting particles. Accordingly, there are various detectors such as scintillation, Cherenkov (mostly using ultrapure water), and combined ones. Cherenkov radiation allows one to detect the direction of the arrival of charged particles. Moreover, modern detectors are highly sensitive. For example, Kamiokande II, Super-Kamiokande, and KamLAND have sensitivity thresholds of 7.5, 5.5, and 1 MeV, respectively. This is sufficient to detect a stellar collapse. The creation of large-volume installations is necessary for a further development of low-energy neutrino astrophysics. Detectors based on *vacuum* photomultipliers have reached an advanced level of perfection, but this is only one of possible ways in the development of neutrino astrophysics. Another way is the use of *silicon* photomultipliers, which already surpass vacuum photomultipliers in some parameters and continue to improve.

The main challenges to be overcome in the development of a large-volume detector include

- an effective photon collection system. It may be necessary to divide the large detector volume into a number of smaller ones. This allows reducing the maximum distance to the track formation sites, thereby increasing the track length on the matrix and the number of photons reaching the matrix;
- determining the optimal aperture for a kiloton-size detector or its individual components (if it is divided into several parts);
- reducing detector noise levels by cooling scintillators and SiPMs, refining the technology, improving the light output and transparency of the scintillator. A scintillator with a transparency of 18 m is already available in the country (Novikova, 2018). SiPMs have been cooled using Peltier elements for several years;
- research has shown that the use of Winston cones for SiPM matrices does not have a positive effect due to the lack of lens-like optical properties, but they can be applied to individual SiPMs as they allow photons to be collected from a given angular direction;
- optimization of data acquisition and processing systems. This will include improvements to the optical schemes used to collect information;

- developing a methodology for constructing images of the particle tracks registered in the detector.

Based on the research carried out at BNO of INR and the analysis of projects of other scientific groups, it can be concluded that SiPM matrices have great prospects in developing kiloton-size detectors due to a number of technical parameters (high quantum yield, large gain factor, low supply voltage, high time resolution, compact size, and reduced cost in mass production).

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