Development of a scintillation detectors based on the SiPM matrices: current status and prospects for the large volume neutrino detectors

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Abstract The matrices of silicon photomultipliers (SiPM) are promising multichannel photosensors for scintillation detectors. They can be used to reconstruct tracks of relativistic particles inside the detectors. The paper presents the first developments of detectors with direct contact of the SiPM matrices with the surface of a scintillation detector and with the use of Fresnel lenses, and also promising variants for large detectors of neutrino astrophysics and geophysics are proposed.

Keywords: matrices of silicon photomultipliers, charge-digital converters, VME standard, Fresnel lenses.

1. Introduction

In many areas of experimental physics, related to the collection of information in multichannel systems, silicon photoelectron multipliers (SiPM) are used instead of traditional vacuum photomultipliers. Silicon photomultipliers have many advantages over vacuum: insensitivity to magnetic field; high efficiency photon; compactness and mechanical strength [1-4]. The low power supply and the high gain of the SiPM (10^5-10^7) can greatly simplify electronic data readers. Performance and affordable cost make it possible to widely use SiPM in high-energy physics when creating detectors with a large number of photodetectors. An example of the mass application of the SiPM is the neutrino experiment T2K. In this experiment in the scintillation counters of various detectors, about 60,000 SiPMs are used as photodetectors [5]. For such large-scale projects, specialized multi-channel data acquisition systems based on special programmable microcircuits are being developed [5,6].

The development of production technologies for silicon photodetectors of increased area led to the creation of monolithic matrices of SiPM, which are used in positron emission tomography [7, 8]. Currently, SiPM and the matrices of them are widely used in nuclear medicine. Compared with the data collection systems used in high-energy physics, in nuclear medicine, in spite of the relatively small number of channels, data collection systems based on specially developed microcircuits also are used to read information [9].

In recent years, the matrices of SiPM have been widely implemented in gamma astronomy of superhigh energies [10]. When designing new telescopes of the camera (matrix) from vacuum photomultipliers, on which the Vavilov-Cerenkov light radiation is focused from the particle flux, they are replaced by matrices from the SiPM For experiments, both monolithic matrices and individual SiPMs are used. For example, the matrix of the Cherenkov telescope FACT is made of 1,440 separate Hamanatsu MPPC S10362-33-50C [11]. The camera of the telescope of ASTRI is assembled of 16 monolithic matrices of Hamamatsu S11828-3344m, each of which consists of 16 individual SiPM [12]. For each experiment, specialized multi-channel data acquisition systems based on the developed microcircuits have been created. The matrices of the SiPM are promising multichannel photodetectors of scintillators. Using such matrices, it is possible to select and study events in different parts of the scintillator [13]. For this purpose, the authors propose to use ArrayC-60035-64P-PCB (SensL, Ireland) consisting of 64 single SiPM C-series [14]. The substrate of such a matrix made of fiberglass. Board ABL-ARRAY64P-HDR [15], with 64 channels, is designed to amplify and read the signals from each of SiPM matrix.

2. The characteristics of scintillation detector with SiPM matrices

2.1. Objectives and results

At the Baksan neutrino observatory, a detailed study of this matrix and the development of prototypes for small detectors were carried out: with direct contact of the matrices with the surface of the plastic detector and using Fresnel lenses (***Fig 1***). Before the developers, the task was to build tracks of muons through detectors. For the realization of task was preliminarily developed and created the multichannel measuring system for the data collection from the matrices from the silicon photomultipliers into standard VME, which is in detail presented in [16]. A part of the electronics was developed and assembled on its own (128-channel delay line, master pulse generation circuit, plastic detector, etc.), and the main electronic units were

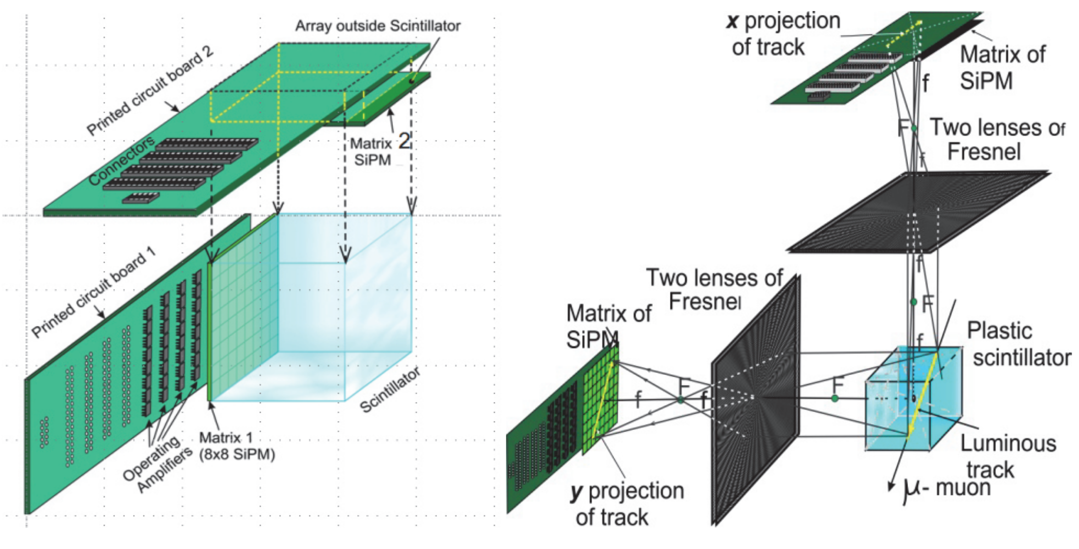

Fig1. *Left: scheme of experiment with direct contact of matrices with a scintillator. Right: working variant of a prototype of a scintillation detector with silicon photomultipliers using Fresnel lenses.*

purchased (industrial computer, VME crate, two SiPM matrices, charge-sensitive converters (QDC) and etc.). For the experiment with direct contact of the matrices with the scintillator (***Fig1, left***), the resulting tracks are shown in ***Fig2 a, b, c***. For an experiment using Fresnel lenses (***Fig1, right***), the tracks are shown in ***Fig2 d, e, f***. Width of tracks for the first case, generally, wider since there is no focusing of photons.

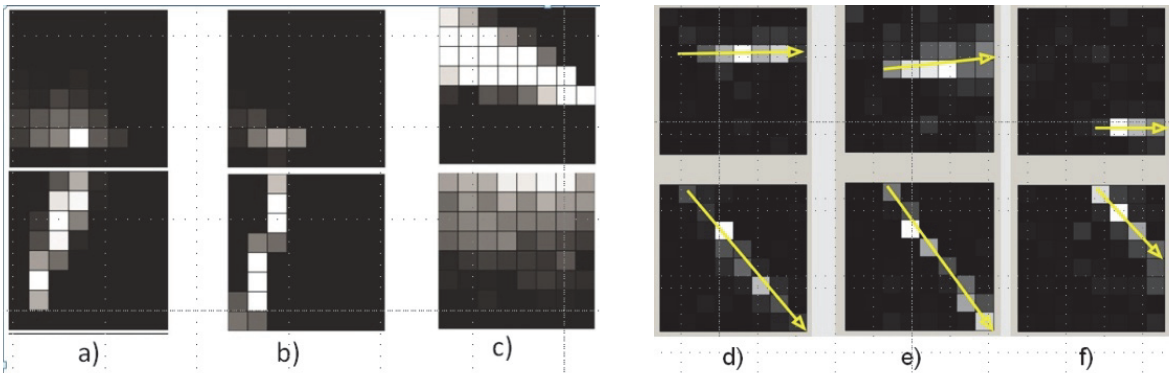

Fig2 a,b,c. *- tracks obtained for the experiment with direct contact of the matrix with the detector.* ***d,e,f*** *- tracks obtained for the variant with the use of Fresnel lenses.*

When placing an object (in this case a detector) at a distance of more than 2 focal lengths from the lens, the image size is reduced (Fig3). For this reason, the size of the detector can significantly exceed the size of the matrix. The most sharp parts of the object can be focused only on a certain distance. But since the object has extended geometric dimensions, then the focusing deteriorates to the near and far edge of the detector. For example, in Fig3 the defocusing for near edge of the detector of 118x118x118 mm^3 in size will be equal to 3.86 mm, that it is much less than the SiPM size (for the far edge the defocusing will be less – 3.06 mm). The size of the detector with Fresnel lenses can be reduced by lowering the focus requirements, because even with poor focusing, the center of the track can be determined by mathematical processing.

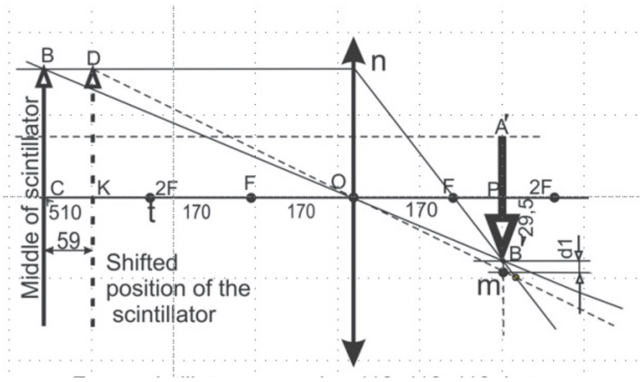

Fig3. *Depth of focus for scintillator size 118x118x118 mm.*

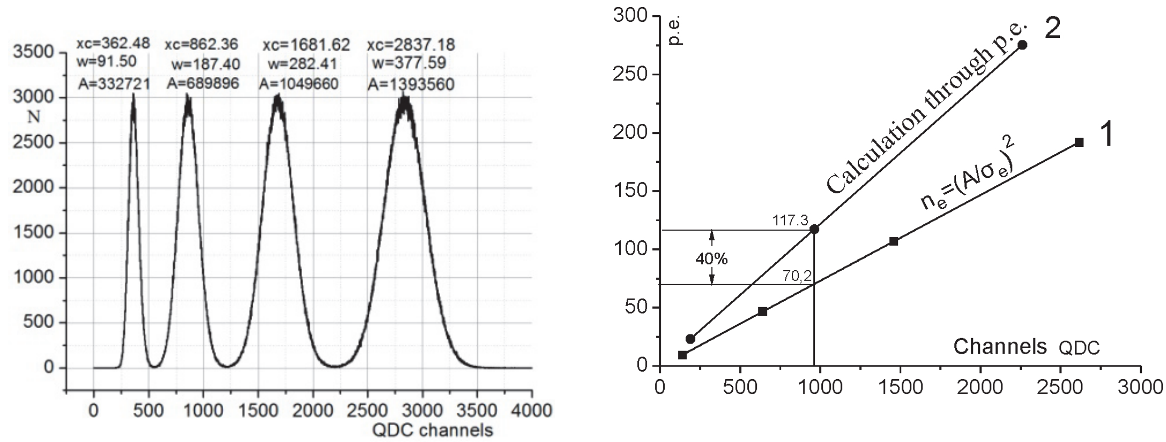

Fig4. *Left: the spectrum of SiPM with the fixed flows of the photons. Right: calibration of SiPM. 1-calibration by method 1, 2 - calibration by method 2.*

2.2. Calibration

Two methods of calibration were used.

1) Using a blue LED emitting light with a wavelength of 430 nm (which agrees well with the wavelength emitted by the scintillator used), stable fluxes of photons (but different in intensity) were fed to the SiPM matrix. Data was processed using QDC (***Fig4, left***). The QDC was run during the duration of the trigger signal for 225 ns, which is slightly longer than the pulse duration coming from the SiPM matrix. The formula (1) was applied to the obtained data and plotted 1 (***Fig4, right, line 1***).

$$n_e=(\bar{A}/\sigma_e)^2 \quad (1)$$

n_e – is the average number of photoelectrons, $\bar{A}$ – is the mean value of the charge obtained with a constant flux of photons, σ_e – is the root-mean-square deviation of charges depending on several parameters.

$$\sigma_e^2 = \sigma_s^2 + \sigma_{led}^2 + \sigma_{q.e.}^2 + \sigma_{i.-p.g}^2 \quad (2)$$

where σ_s –mean-square deviation caused by the variation of the photon density in *space* in the direction investigated SiPM. This option is basic and will occur even for the case where the led emits a stable number of photons in each pulse generator; σ_{led} - root-mean-square deviation caused by the variation in the number of photons emitted by the *LED*; $\sigma_{q.e.}$- the root-mean-square deviation due to the *quantum efficiency* of the SiPM; $\sigma_{i.-p.g}$ - root-mean-square deviation due to the presence of inter-pixel gaps (not all the photons moving in the direction investigated SiPM reach the active zone – part of the photons falls in the– *inter-pixel gaps*). The parameters σ_s and σ_{led} are the main.

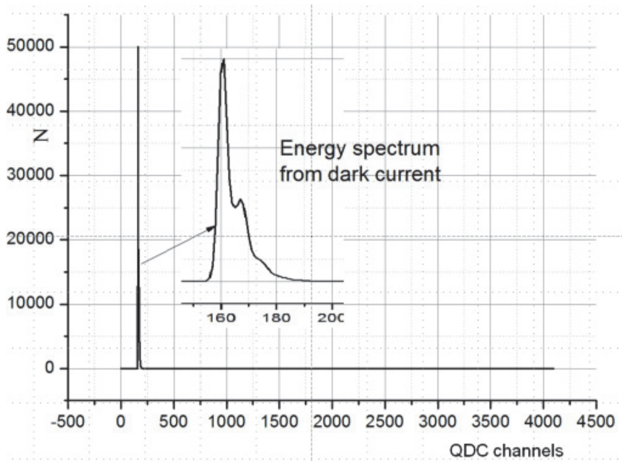

Fig5. *Spectrum of SiPM in the absence of photons.*

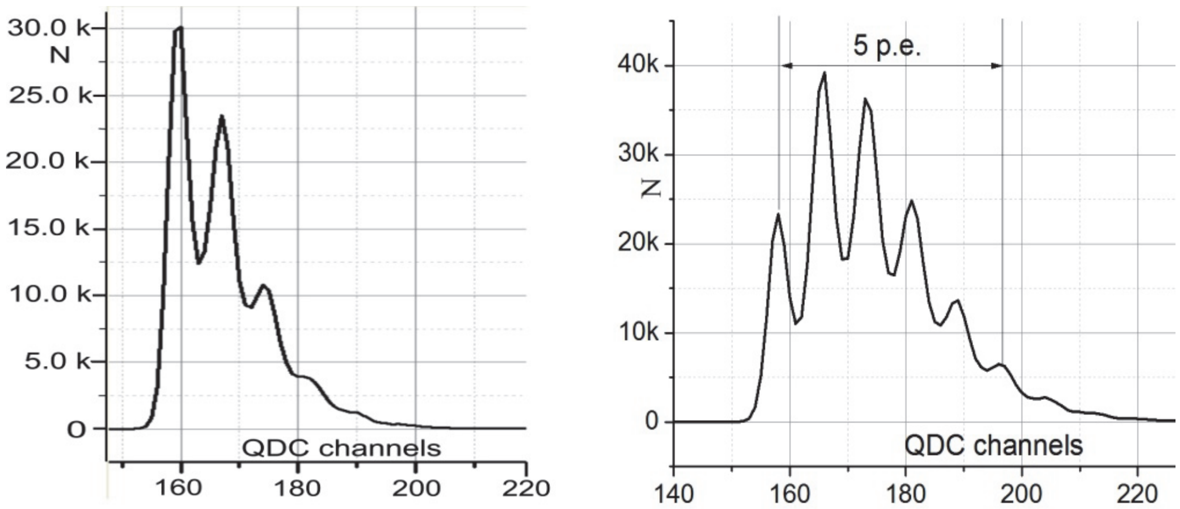

Fig6. *Dependence of the number of photoelectrons on the charge upon additional irradiation with photons. Left: - in addition to the dark current a small amount of photons (n) is added. Right: the number of photons is n + m*

2) The second method is more complex, but it is more precise. It was noticed, that in the energy spectrum of SiPM in the conditions of only dark current the weakly expressed photon maximums appear (***Fig5***). If additionally the matrix of SiPM irradiated by photons, then maximums appear much clearer (***Fig6, left***). If the photon flux still slightly increases, the peaks appear even better, but the relative number of low-electronic events (for example, one-electron or two-electron events) may decrease. (***Fig6, right***). From this figure it is possible to find how many channels QDC in the single photoelectron. ***Fig7*** shows the number of photoelectrons as a function of the number of channels for all SiPMs of both matrices. Channel 6 (SiPM 6) of matrix 2 is defective. And in ***Fig4***, ***right*** curve 2 shows the dependence of the number of photoelectrons on the charge for SiPM 65. The sensitivity is approximately 40% higher than for the first method. The difference can be explained as follows.

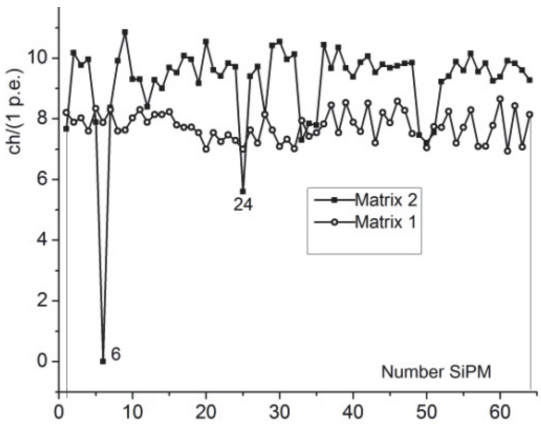

Fig7. *Dependence of the number of QDC channels per 1 p.e. for each SiPM of both matrices.*

If we eliminate at least one parameter from the total root-mean-square deviation σ_e, for example, σ_{led}, then the width of the peaks for both ***Fig4, left*** and for ***Fig6, right*** decreases, and the number of photoelectrons, according to formula 3, increases. Thus, the slope of line 1 from ***Fig4, right*** will increase. For ***Fig6, right***, the width of the peaks will also decrease, but the inter-peak spacing will not change, ie the sensitivity in photoelectrons is always the maximum.

$$n_e = \bar{A}^2/(\sigma_e^2 - \sigma_{led}^2) \quad (3)$$

But because the σ_{led} parameter is unknown, formula 1 is applied as an estimate. It is also useful in a relatively large flux of photons when individual peaks in the spectrum are no longer distinguishable.

2.3. Prospects

A large detector for the Baksan neutrino observatory is also being developed at the Institute for Nuclear Research of the Russian Academy of Sciences in order to study natural neutrino fluxes in geo- and astrophysics (Fig8). The estimated volume of the detector is 5-20 kt. Our theoretical calculations [17] allow us to conclude that it is possible to register short tracks. For example, for a detector with a scintillator mass of 5 kt with a lens aperture of 2000 cm^2 and a track length of 1.2 cm, one photoelectron can be registered at the center of the detector (the sensitivity of our data collection system is not worse than 6 channels per 1 photon (see Fig7), which should allow to record such events even taking into account optical losses). In practice, it is problematic to use Fresnel lenses for obtaining a large aperture due to of the large dimensions of the optical system. Initially, it was planned to collect photons using a truncated cone with a reflective inner surface. But as can be seen from Fig9, most of the photons do not reach the exit hole of the cone because with each reflection from the walls of the cone the angle of reflection increases (up to the unfolding of the photons in the opposite direction). For some photons, the angle $\alpha < \beta < \gamma$. To solve this problem, it is proposed to place a Fresnel lens with a focal length F at the beginning of the cone. At the point of focus place a fiber bundle with a polished end or a special matching optical adapter (Fig10). Not only photons moving parallel to the axis of the cone, but also at some angle to the axis, will enter the optical fiber entry zone.

Depending on the direction of arrival of photons, the point of their focusing will be slightly closer or slightly farther than the point F. This is because the photons in the inner walls of the truncuted cone near the exit hole will be reflected directly in the fiber. For large apertures you can take a relatively small cones and cascade them with the optional cone with fiber. In Fig10 shows how 4 truncated cones are combined along the Y coordinate and the total signal is transmitted to one of the silicon PMT matrices. The summing cone can be placed in a convenient place (even at a great distance) because of signal attenuation in the optical fiber at a distance of tens of meters virtually no. The same applies to the SiPM matrix. Thus, it is possible to generate almost any aperture with small dimensions of the cones. The response time of a silicon photomultiplier subnanosecond, so with proper electronics it is possible to obtain a temporal resolution of detectors better than 1 ns.

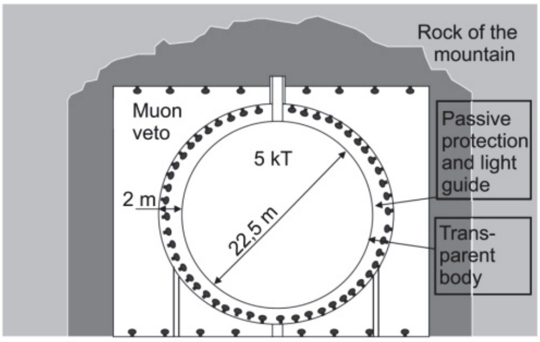

Fig8. *The large detector for the Baksan neutrino observatory with the aim of studying the fluxes of natural neutrinos in geo- and astrophysics.*

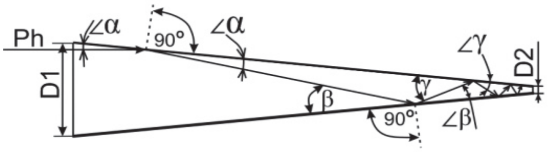

Fig9*. Passage of a photon inside a truncated cone with a reflective inner surface.*

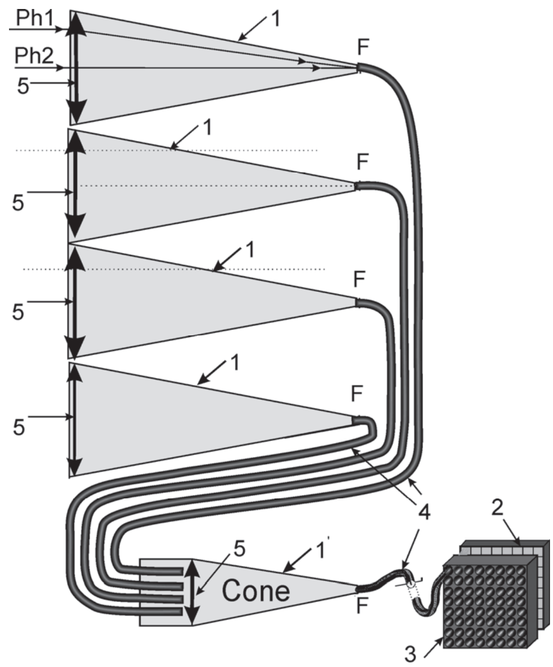

Fig10*. Cascading truncated cones to obtain a large aperture: Ph - photon, 1 - truncated cone, 1 '- summation cone, 2 - SiPM matrix, 3 - mechanical interface matrix, 4 - fiber bundles, 5 - Fresnel lens, F - focal length.*

3. Conclusion

- By direct contact of the matrices with the scintillator, there is a limit on the size of the detector. The use of the optical system removes this restriction. This improves the ratio signal/noise.
- We used a Fresnel lens made of optical acrylic with a threefold increase with the size of A4. Such mass production of lenses are available, inexpensive, and can have a large size.

- The depth of sharpness of the optical system suffices, that light track on a matrix had a width less size one SiPM, that confirm the brought pictures over with the use of the optical system.
- The experiments with optic were performed with a detector the size of 50x59x59 mm^3. We plan to increase the size of the scintillator to 500x500x500 mm^3.
- There are good opportunities for using cascaded truncated cones with Fresnel lenses for detectors of a kiloton class.
- It is possible to use 3-D printers to manufacture of cones. Additionally, in a single process can produce all needed fixing.

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