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Development of camera prototype of ALEGRO atmospheric Cherenkov telescope

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A small-size prototype of the ALEGRO Cherenkov telescope camera has been developed. The paper discusses its design and construction. A mock-up of the registration channel of the ALEGRO Cherenkov telescope camera prototype was created and tested, on which the algorithm of operation was worked out and characteristics of the silicon photomultipliers and parameters of the amplifying path were determined. Based on the results of this work, a conclusion was made about the possibility and prospects of creating a unique high-altitude observatory ALEGRO for the study of GeV gamma-ray emission from energetic space objects.

Keywords: silicon photomultipliers, telescope camera, Cherenkov telescope.

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Currently, within energies 3−30 GeV, there are no sufficiently sensitive instruments to study wide populations of gamma-ray sources, since the physical detection area is too small for orbital instruments, and for the existing ground-based Cherenkov gamma-ray telescopes, the signal from broad atmospheric air showers caused by primary particles of such energies (3−30 GeV) turns out to be too weak (see, for instance, [1]). In order to fill this gap, in Ioffe Institute for a number of years they have been developing a project of unique high-altitude Cherenkov gamma-ray observatory ALEGRO, which will have an extremely low threshold for detecting cosmic gamma radiation at level 3−5 GeV [2].

As one of the steps towards creation of ALEGRO Observatory based on the existing infrastructure of TAIGA [3] observatory, located in Tunka Valley (Republic of Buryatia), it is planned to test a prototype detector camera developed in Ioffe Institute. Since TAIGA Observatory has been working with small Cherenkov telescopes TAIGA-IACT for several years, which have already proven their effectiveness and reliability in terms of technical solutions, it seems advisable to use the existing infrastructure to reduce the costs and accelerate the development process, providing for the possibility of operating ALEGRO prototype in one of TAIGA-IACT series telescopes.

The prototype of the camera (Fig. 1) is designed as a closed rectangular parallelepiped with overall dimensions $230 \times 230 \times 500$ mm and a weight of about 6 kg. The detecting plane with dimensions 123×123 mm contains 64 pixels with minimal gaps between each other. The pixels are connected to eight detector modules in rows of eight pixels. The detector modules are connected to the controller and power boards in the rear of the prototype camera. The prototype frame has eight mounting points and two windows for cooling fans.

Figure 2 shows a structural configuration of ALEGRO camera prototype. The principle of operation of the instrument is as follows. The camera pixels, which contain four MicroFC-60035 silicon photomultipliers and a preamp with a switchable gain (range), are connected to detector modules and transmit a signal to the TRIG trigger system and DRS4 analog memory chip. When the signal from a pixel exceeds the threshold set by the digital-to-analog converter DAC, the trigger system generates individual signals for each pixel to the field-programmable gate array FPGA (Cyclone III) module. The trigger signals from all modules are transmitted to FPGA (Cyclone III) of Controller board. When trigger conditions are met, the FPGA of the Controller board initiates a readout procedure, which consists of stopping and sequentially iterating the cells of DRS4 analog memory by means of control signals

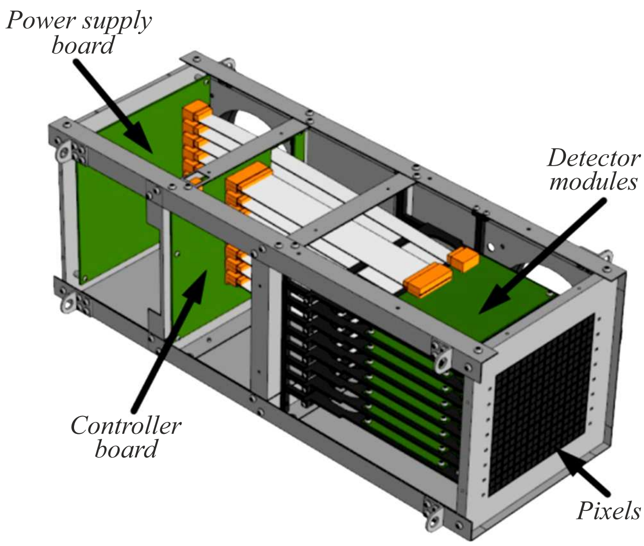

Figure 1. 3*D*-model of ALEGRO prototype camera design without casing.

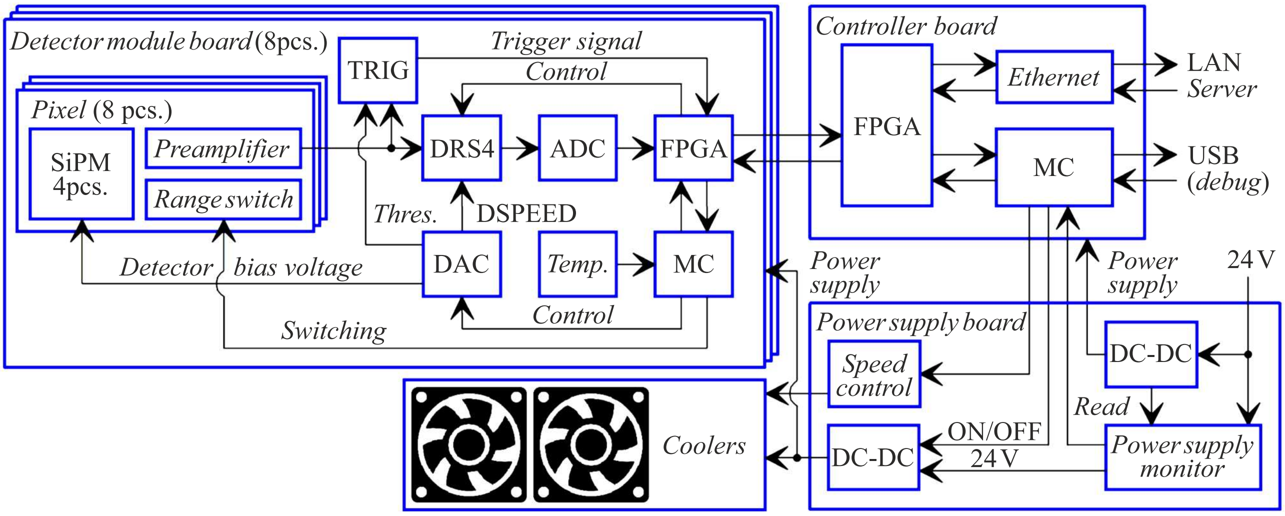

Figure 2. Structural configuration of ALEGRO telescope camera prototype.

with synchronous storage of digitized values from the analog-to-digital converter ADC.

The digitized values, which are an waveform 1024 points long for each pixel, are processed on an FPGA to determine the pulse amplitude at each pixel. The waveform itself is not saved, only the amplitude value is extracted from it as the difference between the signal level before the trigger and the maximum of the signal in a certain time window (for example, 10 ns). As a result, the values of the amplitudes of the signals that exceed the specified threshold and the timestamp of the event, which together form a record, are stored in the memory of FPGA controller. All memory entries are read by an external control computer via a local network.

Each detector module has a microcontroller that controls a digital-to-analog converter DAC to set the required threshold voltages, detector bias voltages, and DRS4 control voltages, including DSPEED voltage to control the analog memory sampling frequency. The module's microcontroller also switches the operating range of pixels and measures the temperature for a feedback circuit that corrects the bias voltage of the detectors and the rotation speed of the cooling fans.

The microcontroller of Controller board controls the power supply of individual modules, monitors their power consumption and adjusts the rotation speed of the cooling fans according to the readings from the modules.

For laboratory testing of the camera prototype, a model of detection channel was created (Fig. 3, *a*), which includes a sample of eight-channel detector module with a USB interface and one detector pixel on four MicroFC-60035 silicon photomultipliers.

The model of detection channel was tested in a dark chamber using a pulsed laser radiation source (frequency 5 MHz, pulse duration 8 ns, wavelength 650 nm). The output signal from the preamplifier was branched into a mock-up and oscilloscope LeCroy WaveRunner 620Zi with a bandwidth of 2 GHz to evaluate the correspondence of the shapes of the same detected pulses and calibrate the channel conversion coefficient.

Fig. 3, *b* illustrates the laser pulse oscillograms detected simultaneously by the mockup (DRS4) and oscilloscope (Osc). Central pulse has an amplitude of 1240 mV and width at half maximum (FWHM) of 10 ns. A comparison of the two waveforms shows a clear correspondence between the observed pulse shapes. The noise of DRS4 signal observed in Fig. 3, *b* can be explained by non-equivalency of DRS4 analogue memory cells between each other which leads to different pedestals for different cells. This effect can be compensated by calibration, by first measuring the individual cells' pedestals with the detector bias voltage turned off.

Separate pixel tests at a preamp gain of 100 with oscilloscope detection of the dark count output signal made it possible to obtain the distribution of the dark count amplitudes and calculate the value of the single-photon signal, which, at an overvoltage of 6 V, amounted to 37 mV per photoelectron (a photoelectron is hereinafter referred to as a single signal from one triggered microcell of a silicon detector). With the overvoltage of 1 V the single-photon signal reaches 7 mV per photoelectron. Thus, taking into account the operating range of the amplifying path, the maximum detected signal from a pixel is 200 and 40 photoelectrons in the overvoltage range of 1 and 6 V, respectively. In the future, the gain can be adjusted and expanded by introducing the possibility of switching the pixel gain to register both small signals and signals with a large number of photons.

The rate of dark count for a pixel consisting of 4 silicon photo-multipliers was about 9 MHz at a temperature of 25°C. The measured photo-detection efficiency (PDE) of MicroFC-60035 multiplier at 5 V for method described in

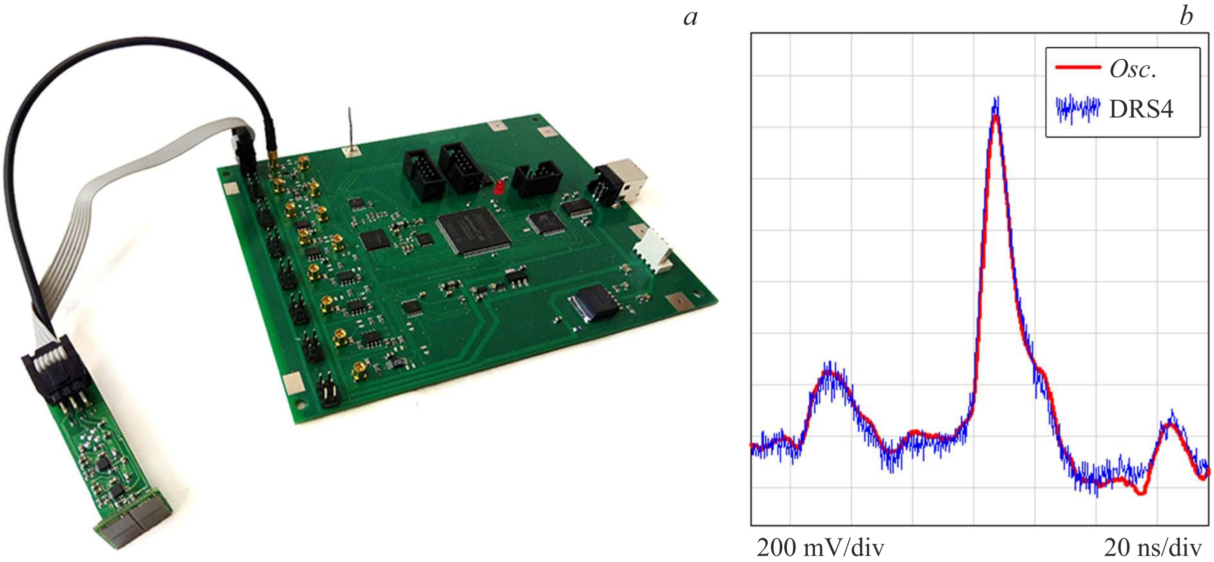

Figure 3. Photo of created mockup of the detection channel (*a*) and comparative superposition of two oscillograms of one pulse (*b*).

article [4], was 10.3% (at wavelength of 650 nm) at detector temperature of 25°C, which is consistent with 12% at 21°C declared by the manufacturer taking into account reduced PDE due to high detector temperature. At this stage of the study, PDE measurement was carried out only for a wavelength of 650 nm due to the availability of inexpensive sources of monochromatic radiation, i.e. red lasers. Maximal sensitivity (about 40% at overvoltage of 5 V) SiPM MicroFC-60035 have at a wavelength of about 420 nm. Clarifying the effectiveness of registration of selected SiPMs is a subject for further research.

As a result of the studies, a structural configuration, electrical circuit diagrams and 3*D* design model of the prototype camera of ALEGRO telescope were developed. The model of detection channel of ALEGRO telescope camera was tested in order to refine the algorithms of operation and determine the parameters of the detectors. Further development of the project involves adjusting the schemes, structure and design of the prototype camera based on the available mockups, creation of prototypes, as well as conducting laboratory tests and field observations as part of TAIGA Observatory.

Conflict of interest

The authors declare that they have no conflict of interest.

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