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Electromagnetic Calorimeter for the SPD Experiment

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Abstract—A prototype of a Shashlyk-type electromagnetic calorimeter for the reconstruction of photons and electrons in the SPD experiment was built. The module is assembled from 4 cells of size 55×55 cm^2. The test setup included 4 modules and consisted of 16 cells placed as a 4×4 grid. The cells are made of 220 layers of scintillator and lead plates of widths 1.5 and 0.3 mm, respectively, and have a length of 12.6 radiation length and a Molière radius of 3.2 cm. The energy and time resolutions of the calorimeter, obtained from cosmic ray testing, are shown. The energy resolution of the calorimeter prototype was measured to be 9.6% for MIP energy deposition of 240 MeV, and the time resolution for a single cell to be about 215 ps. Daily variations of the signal amplitude are within 0.5%.

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1. GENERAL DESIGN OF THE CALORIMETER

The spin physics detector (SPD) [1, 2] is a future experiment at the NICA collider at JINR (Dubna, Russia) that aims to investigate the spin structure of the nucleon using charmonia, open charm, and prompt photon production as probes. The ability to detect photons and measure their momenta using an electromagnetic calorimeter is essential for studies with prompt photons, as well as for reconstruction of $\chi_{cJ} \to J/\psi\gamma$ decays.

The design of the electromagnetic calorimeter should meet the criteria imposed by the physics goals of the SPD experiment:

(1) Energy range of photons and electrons: 50 MeV–10 GeV.

(2) Energy resolution for the above-mentioned particles: ~$5\%/\sqrt{E}$ [GeV].

(3) Good separation of two-particle showers.

(4) Long-term stability: 2–3% in a six month period.

The energy range requirement follows from the kinematic range of secondary particles, which are produced in the interaction of two colliding protons with energies of about 10 GeV and emitted into 4π sr. A good energy resolution is required for the identification and quantitative measurement of energies of neutral pions. A good two-particle separation is needed to separate photon showers from π^0 decay to suppress background events in measurements with prompt photons. The long-term stability is necessary for polarization measurements featuring π^0 reconstruction in the calorimeter endcaps. Calorimeter instability may result in false asymmetry values.

While it is essential to meet the physics requirements imposed on the calorimeter design, one should also take into account the cost estimate and technical feasibility when choosing its granularity, as a larger number of cells leads to larger costs of manufacturing technology and readout electronics.

2. DESIGN OF THE CALORIMETER MODULE

The initial version of the module consisted of alternating layers of polystyrene scintillator and lead with thicknesses of 1.5 and 0.3 mm, respectively. The selected number of layers is 220, which sets the number of radiation lengths to $12.6X_0$. The lead plates are intended to absorb particle energy and develop the electromagnetic shower, whereas scintillator plates produce an amount of light proportional to the energy of particles. The properties of the absorber and scintillator define the Molière radius, which is equal to 3.5 cm for the selected structure. Energy resolution for 1 GeV photons is assumed to depend on the calorimeter sampling fraction and is expected to be 4.15%. The test results of the present work are given for this particular design of the module.

To improve the energy resolution for particle energies above 4 GeV, the next version of module design with 200 layers of 0.5 mm lead and 1.5 mm scintillator is being considered. This design has a Molière radius of 2.3 cm and an expected energy resolutionof 5.9%

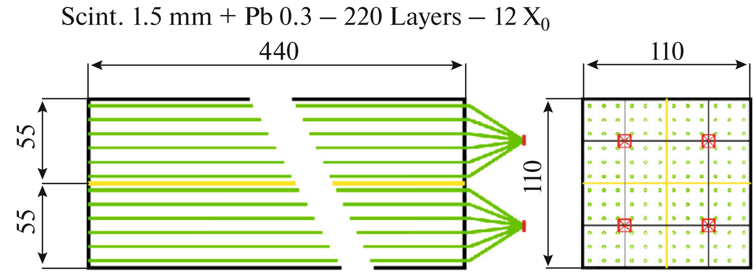

Fig. 1. Schematic drawing of one module of the SPD electromagnetic calorimeter prototype, consisting of 4 cells.

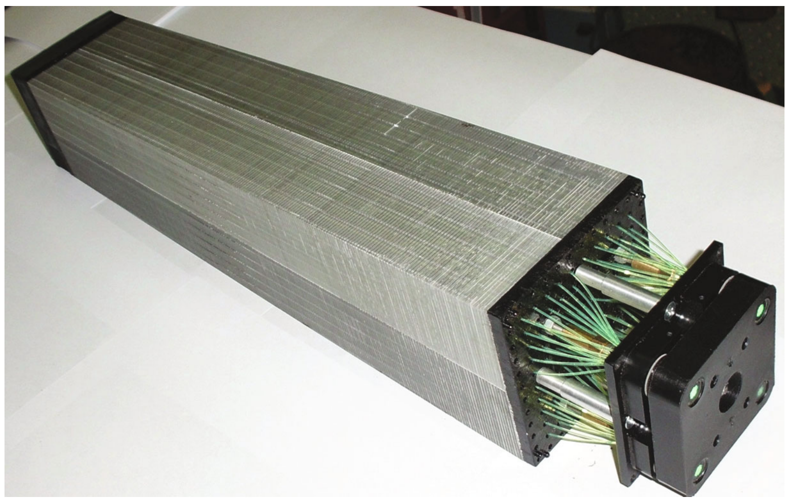

Fig. 2. Photo of a single module, consisting of 4 cells with 220 layers of scintillator and absorber with thicknesses of 1.5 and 0.3 mm, respectively. 4 bundles of fibers for guiding the light to the multi-pixel photon counters (MPPC) can be seen.

for 1 GeV photons. The thickness of the module is $18.5X_0$, which results in decreased leakage and improved spatial resolution.

The scintillator plates are made of polystyrene beads with added luminophore admixture of 1.5% *p*-terphenyl and 0.05% POPOP ($C_{24}H_{16}N_2O_2$) [3]. It has a scintillation time of about 2.5 ns and light output of 60% of anthracene, which is a good result. The radiation hardness of the scintillator is sufficient for radiation doses up to about 10 Mrad, which is important for operating the calorimeter in the radiation field of secondary particles in the vicinity of the interaction point.

The luminophore admixtures re-emit the energy of excitations in polystyrene in the form of visible light. The first admixture (*p*-terphenyl) emits light with maximum emission at the wavelength of 340 nm. This light is absorbed by the second admixture (POPOP) and is re-emitted into a spectrum with maximum emission at the wavelength of 420 nm, which is seen as a light blue glow.

Light from scintillator plates is gathered using wavelength shifting fibers (WLS) [4]. Fibers of type Y-11(200), manufactured by KURARAY, are used. The fibers absorb light from POPOP and re-emit it into a spectrum with maximum emission at the wavelength of 490 nm. 36 WLS fibers go along each cell, gather in one bundle, and transmit light into a multi-pixel photodiode (multi-pixel photon counter, or MPPC) of size 6 × 6 mm^2. In this prototype, counters of types S14160-6050, S13160-6025, S13160-6050 and FC-6035 [5] are used.

A module consists of 4 cells with cross section of 55 × 55 mm^2, combined into one tower with cross-section of 110 × 110 mm^2 and length of 440 mm. A scheme of the module is shown in Fig. 1. A photo of the module is shown in Fig. 2. In the photo (Fig. 2) a module of trapezoidal shape is shown, which is obtained after milling a rectangular parallelepiped at an angle of about 2 degrees. The cell size of 40 × 40 mm^2 at the front face and 55 × 55 mm^2 at the back face allows to implement projective geometry in the SPD electromagnetic calorimeter.

Nine modules of the calorimeter, each consisting of 4 cells, were manufactured for testing at experimental stands in VBLHEP and outside. Each module weighs 12 kg. Two assemblies of 4 modules (16 cells) were made and are used in the VBLHEP stand for tracking detectors testing (miniSPD) and in building

205 at the Polarimetry setup. Testing results for one of these assemblies are shown in the present work.

3. MULTI-PIXEL PHOTODIODES AND READOUT ELECTRONICS

3.1. Multi-Pixel Photodiodes

All of the MPPCs used in this prototype have the same size of 6 × 6 mm^2, but have different dynamic and time characteristics. S13160-6025 series has the best response speed, low capacitance, and a large number of pixels, but the largest temperature coefficient of $K_T \sim 0.054$ V/°C. The temperature coefficient shows a linear dependence of the breakdown voltage on temperature and leads to change in signal amplification of several percent per degree. To achieve a calorimeter stability of about 2%, one needs to ensure the stability of the surrounding environment, or use the breakdown voltage compensation scheme $UOP = UBR + \Delta U - K_T \Delta T$, where:

• UOP is the operation voltage;

• ΔT is the deviation of the current temperature from the nominal one, e.g. 20°C;

• UBR is the breakdown voltage (break point);

• ΔU is the voltage bias.

S14160-6050 series has a high photo-detection efficiency, but fewer pixels, and thus a smaller occupancy, which is worse in terms of dynamic range [6]. This series has a small temperature coefficient. An optimal solution would be to manufacture a similar photodiode series, but with a smaller pixel size of 15–20 μm, which would make them more suitable for a calorimeter.

3.2. MPPC Readout and High Voltage Control

Four MPPCs are surface mounted on a circuit board. A thermistor is also installed to measure the photodiode temperature. The circuit board is connected to a module such that the photodiodes are placed at the positions of fiber bundles. There is no optical contact between the photodiode and WLS, instead, there is an air gap of about 0.1 mm. Optical grease is not used to avoid instability in the conditions of light guiding. A light insulating basket made of black plastic is installed on top of the circuit board.

The MPPCs are connected to the amplifier board using 10-pair flat twisted-pair cables of length 1 m. Two wires are used to send a base voltage of ~40 V and connect the thermistor. 4 pairs of wires transmit signals to the amplifiers [7]. Channel voltages are transmitted via signal wires as a small bias from 0 to 5 V. This way, the bias voltage can be precisely set in a small range, but with 10-bit precision (i.e. about 5 mV).

Voltage control is implemented on a software level, taking into account the temperature from the thermistor installed on the circuit board. This allows operation without special equipment for temperature stabilization. Signal stability of the order of 0.1–0.2% is achieved during measurement over an extended period of time.

3.3. Readout Electronics

The readout electronics consist of analog-to-digital converters ADC-64 [8] (Fig. 3). An ADC receives continuous-time samples of the input signal with a fixed frequency and provides a full digital representation of signals in time. Samples are received at a 64 MHz frequency, which corresponds to the time period of 15.625 ns. Each sample is measured with 12-bit precision. At present, there is an ADC-64-Ecal modification, which improves the precision to 14-bit and significantly extends the range of the measured amplitudes. The new ADC modification also allows for operation in strong magnetic fields, which is necessary for experiments at the NICA accelerator complex.

An Ethernet connector for data transfer can be seen in Fig. 3, as well as a coaxial input for readout synchronization, which serves as a trigger. The ADC can also operate in streamer mode due to dedicated firmware. The usage of White Rabbit technology provides sub-nanosecond synchronization accuracy.

4. COSMIC RAY TEST RESULTS

For the testing on cosmic rays, a small setup of 4 modules (each 11×11 cm^2) of total cross section 22×22 cm^2 was used. The cells, each 55 × 55 mm^2, are assembled in a 4×4 setup. A schematic drawing of the setup is shown in Fig. 4. The modules are placed vertically, while the direction of registered cosmic rays is determined by the trigger counters. The counters are multi-pixel photodiodes of type FC6035 and size 6 × 6 mm^2. All the photodiodes are included in a coincidence trigger for the ADC. The trigger includes a signal from the generator, which starts the LEDs for control, calibration of calorimeter cells using estimates of light yield, and long-term stability control. Data acquisition is conducted at the ADC using software provided by the developer. During the data taking period of 5–6 days, statistics of the order of one million triggers was obtained.

The setup allows to measure energy depositions and trajectories of cosmic ray particles. Relativistic muons with energy above 250 MeV pierce through the calorimeter and form a peak in deposited energy. To select straight tracks of particles, which pass vertically through one module, only those events are selected, where the number of hits is equal to 1.

4.1. Energy Resolution of the Calorimeter for MIP

Signals, obtained with cosmic muons, are used for amplitudes alignment and calorimeter energy calibration. Only events with exactly one cell hit were

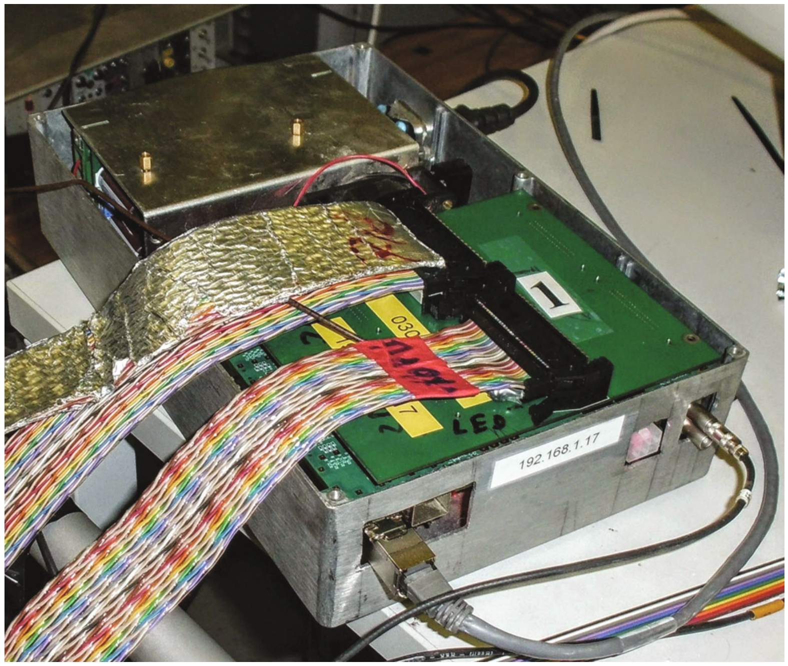

Fig. 3. 64-channel ADC-64 with 4 connected lines, each with 16 channels.

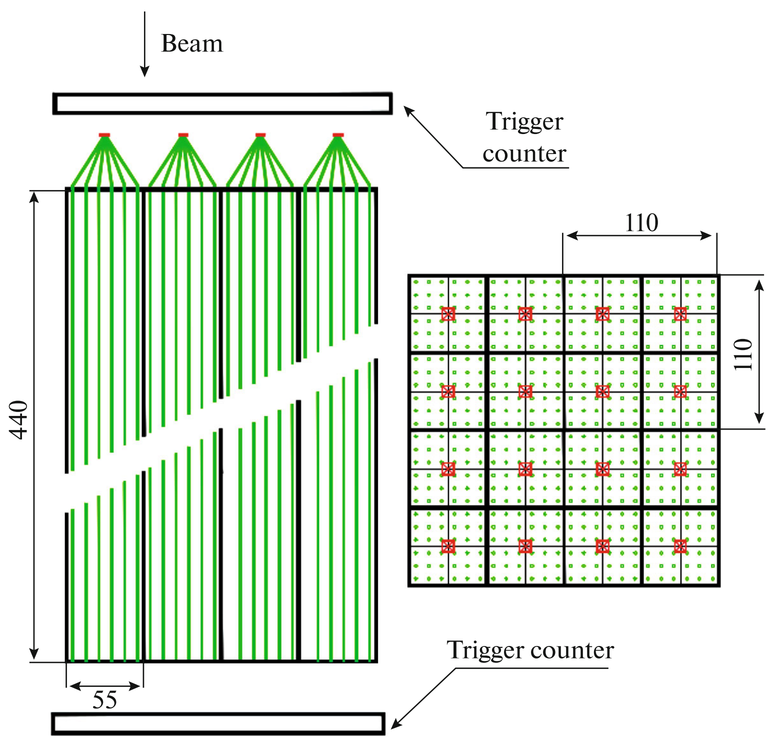

Fig. 4. Schematic drawing of the electromagnetic calorimeter prototype used for cosmic ray testing.

selected. The bordering cells have more events with smaller amplitudes due to angled tracks. We perform calorimeter calibration using only vertical tracks. Each maximum value in terms of ADC units is mapped to a corresponding energy deposition. The energy scale is determined from a Monte Carlo simulation as the scale factor between energy deposition of an electron with 1 GeV energy and a relativistic muon with energy

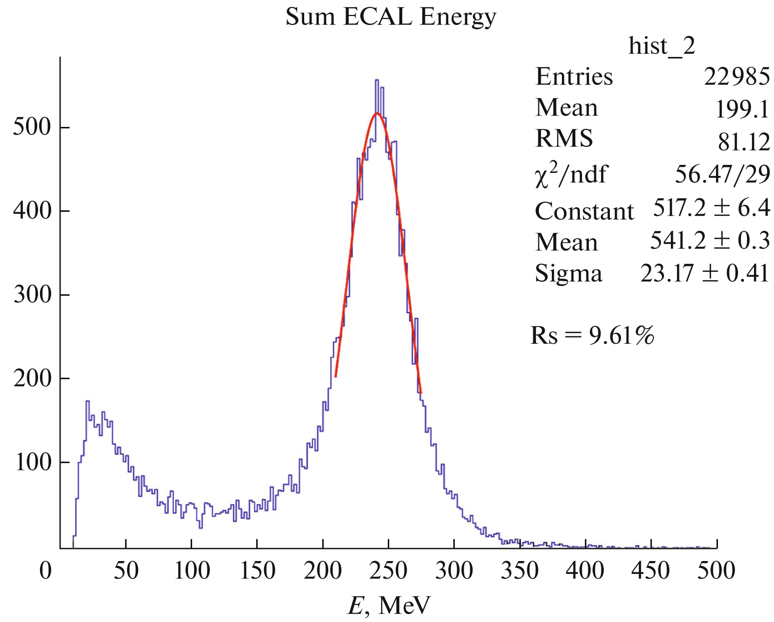

Fig. 5. Total energy deposition in the calorimeter, obtained by summing up signals from 16 cells while selecting 1-hit events.

above 1 GeV in the scintillator plates for the given structure. Using this proportion, we estimate the MIP signal in this calorimeter to be 240 MeV. This value, divided by the position of the muon peak maximum, is used as a calibration coefficient for each cell. This calibration procedure involving MIP energy deposition is not absolute or conclusive. Primarily, it aligns the amplification coefficients in each cell to ensure equal response of each cell. The measured electron or photon energy can be further revised by reconstructing neutral pions or calibrating the calorimeter using electron or photon beams of a given energy.

The electromagnetic calorimeter prototype measures electron or photon energy by summing up signals from all 16 cells. Each cell can only contain a fraction of the energy deposited by the particle in the calorimeter unless the particle is a relativistic muon or MIP. If the calorimeter is calibrated with a precision of several percent, the total energy weakly depends on the particle angle and resolution increases only by 1.4%.

The energy resolution of the calorimeter for vertical cosmic ray particles is 9.6% (Fig. 5). This number corresponds to the energy deposition of 240 MeV. Assuming that the resolution depends on energy as $E^{-1/2}$, the energy resolution at 1 GeV is estimated to be 5%.

4.2. Dependence of Calorimeter Response on the Number of Photoelectrons

Cosmic ray testing allows to obtain the dependence of energy and time resolution on the number of photoelectrons (NPE) produced during MIP passing through a cell. The time is calculated as zero intersection of the waveform separately for each channel. This method, constant fraction discriminator, is used to determine the time value on a constant fraction of the pulse leading edge. The energy and time resolution of the calorimeter depend on NPE as $1/\sqrt{\text{NPE}}$.

Different conditions of light guiding were used in this 4-module calorimeter. These conditions included forming of reflective surfaces on edges of WLS or using the fibers as U-shaped loops. Differences in light-guiding conditions lead to large variations in NPE in the range between 1000 and 5000 photoelectrons per MIP for different cells. In terms of the amount of deposited energy, this corresponds to 4000–20000 NPE/GeV.

Knowing the number of photoelectrons for each cell allows to calculate the energy resolution for separate cells. The NPE dependence of the energy resolution is displayed in Fig. 6 (left) showing that the limit for large values of NPE is $P1 = 6.2\%$.

The time resolution for calorimeters of such types is about 200 ps for MIP (Fig. 6, right) and can be improved for high-energy electrons. A time distribution for a single cell is shown in Fig. 7. The time information can be applied to identify particles in the energy range of 50–1550 MeV.

4.3. Long-Term Stability

The temperature dependence of the calorimeter stability was investigated using daily temperature variations in the range of 18–22°C. During the measurement of signals from cosmic ray particles over 5 days,

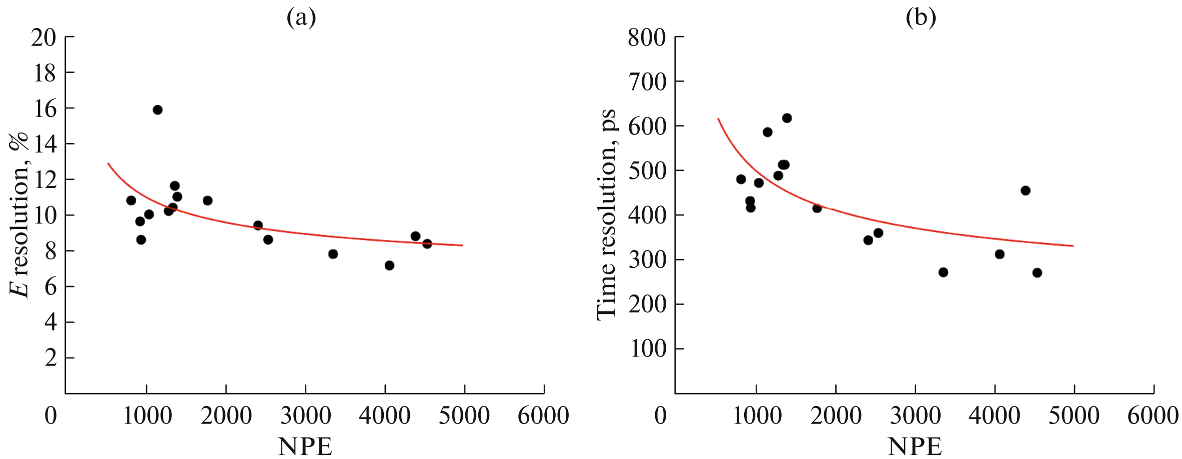

Fig. 6. Dependence of the time and energy resolution for different calorimeter cells on the number of photoelectrons (NPE). The fitted curve, which corresponds to the function $P0/\sqrt{\text{NPE}} + P1$, is shown in red.

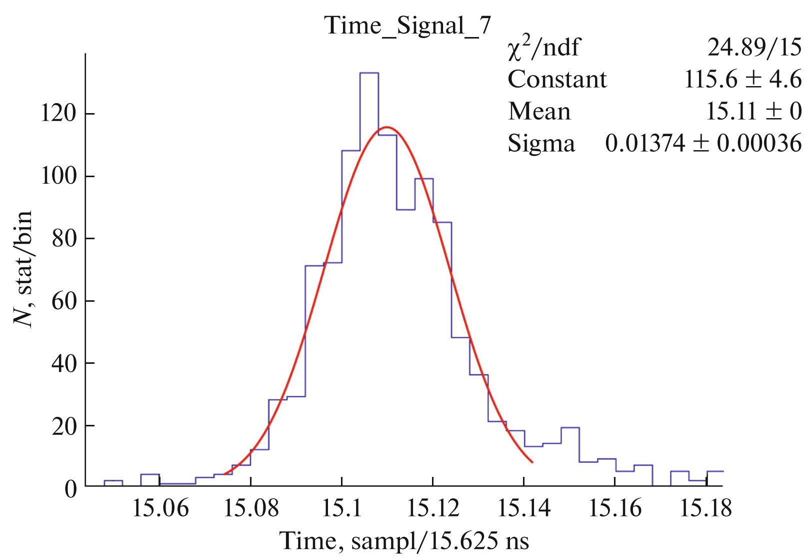

Fig. 7. Time spectrum for a single cell. The time resolution corresponds to 215 ps.

signals from the LEDs of 1 Hz frequency were also measured.

The photodiode temperature is constantly monitored using a high-voltage system. The voltage bias on photodiodes is corrected during temperature measurement using a linear dependence: $U_{\text{out}} = U_{\text{bias}} - k(20 - T)$.

The daily temperature variations during the measurement were about 5°C. A temperature coefficient of $k = 0.034$ V/°C is used for temperature compensation of the operating voltage. After the compensation, variations in signal amplitude are constrained within ±0.4%. The plots are normalized to the start of the measurement. The first 300 signals (5 min) are used to normalize the full measurement period. The calorimeter can operate with the stability of ~0.8% if the temperature compensation of operating voltage is maintained, as can be seen from the results shown in Fig. 8.

5. SUMMARY

The energy resolution of the preliminary version of the module design for the SPD electromagnetic calorimeter was obtained from cosmic ray testing and estimated to be $\sim 5\%/\sqrt{E}$[GeV] for deposited energies below 1 GeV, which satisfies the requirements of the SPD experiment. This result is comparable to the resolutions of the COMPASS ECAL0 calorimeter [6, 9] and the MPD calorimeter [10], which are designed to

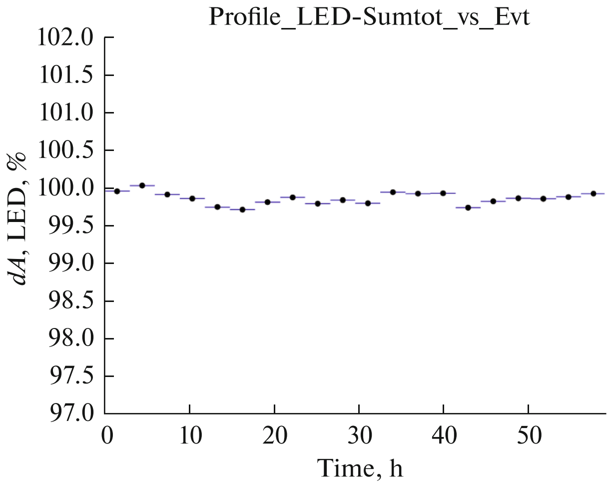

Fig. 8. Dependence of sum (average value) of signals from calorimeter (in % with respect to the first 5 min of measurement period) on the time of measurement (in h) with temperature-dependent voltage compensation.

operate in a similar energy range. The next version of the module design is proposed and is aimed at decreasing the longitudinal leakage and improving the energy resolution for energies above 4 GeV. The condition on long-term calorimeter stability also appears to be met as the long-term signal variations were measured to be about 0.5%.

REFERENCES

1. NICA Home Page. https://nica.jinr.ru/projects/spd.php.
2. SPD Home Page. http://spd.jinr.ru/.
3. IHEP Web Page. http://exwww.ihep.su/scint/mold/product.htm.
4. Kuraray Web Site. http://kuraraypsf.jp/psf/ws.html.
5. Hamamatsu Web Site. https://www.hamamatsu.com/eu/en/product/optical-sensors/mppc/index.html.
6. I. Chirikov-Zorin et al., "Performance of Shashlyk calorimeter read out by SiPMs with high pixel density," Preprint of Joint Inst. for Nuclear Research, No. E13-2018-30 (Dubna, 2018).
7. HVSys Web Site. http://hvsys.ru/.
8. AFI Electronics Web Site. https://afi.jinr.ru/ADC64.
9. N. Anfimov et al., "Tests of the module array of the ECAL0 electromagnetic calorimeter for the COMPASS experiment with the electron beam at ELSA," Phys. Part. Nucl. Lett. **12**, 566–569 (2015).
10. C. Shen et al., "Development of Shashlik electromagnetic calorimeter for the NICA/MPD," JINST **14**, T06005 (2019).