The characteristics of fast scintillation detectors of time of flight and anticoincidence system of space-based gamma-ray telescope GAMMA-400 with silicon photomultipliers readout

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I. INTRODUCTION

The being developed scientific complex GAMMA-400 [1, 2] relates to the new generation of space observatories intended to perform an indirect search for signatures of dark matter in the cosmic-ray fluxes, precision investigation of characteristics of diffuse gamma-ray emission and gamma-rays from the Sun during periods of solar activity, gamma-ray bursts, extended and point gamma-ray sources in the wide energy range from several MeV up to TeV region, e^-/e^+ and cosmic-ray nuclei fluxes with energies up to ~10^{15} eV by means of the GAMMA-400 gamma-ray telescope represents the core of the scientific complex. For gamma-rays with the energy >100 GeV the expected angular and energy resolution are ∼0.01° and ∼2% respectively and e^-/p rejection factor is ∼$5{\cdot}10^5$ by preliminary estimations. The space observatory is planned for the launch at the end of this decade on the Navigator service platform [3] being designed by Lavochkin Association on the elliptical orbit with following initial parameters: an apogee ~300000, a perigee ~500 km, a rotation period ~7 days and inclination of 51.4º. At least 7 years of the active lifetime of the observatory is expected, reaching an unprecedented sensitivity in the indirect search of dark matter signatures and in the study of the unresolved and unidentified so far gamma-ray sources. The planned scientific complex main technical parameters are: weight ~2500 kg, power consumption ~2000 W, total scientific and service downlink transmission up to 100 GByte/day.

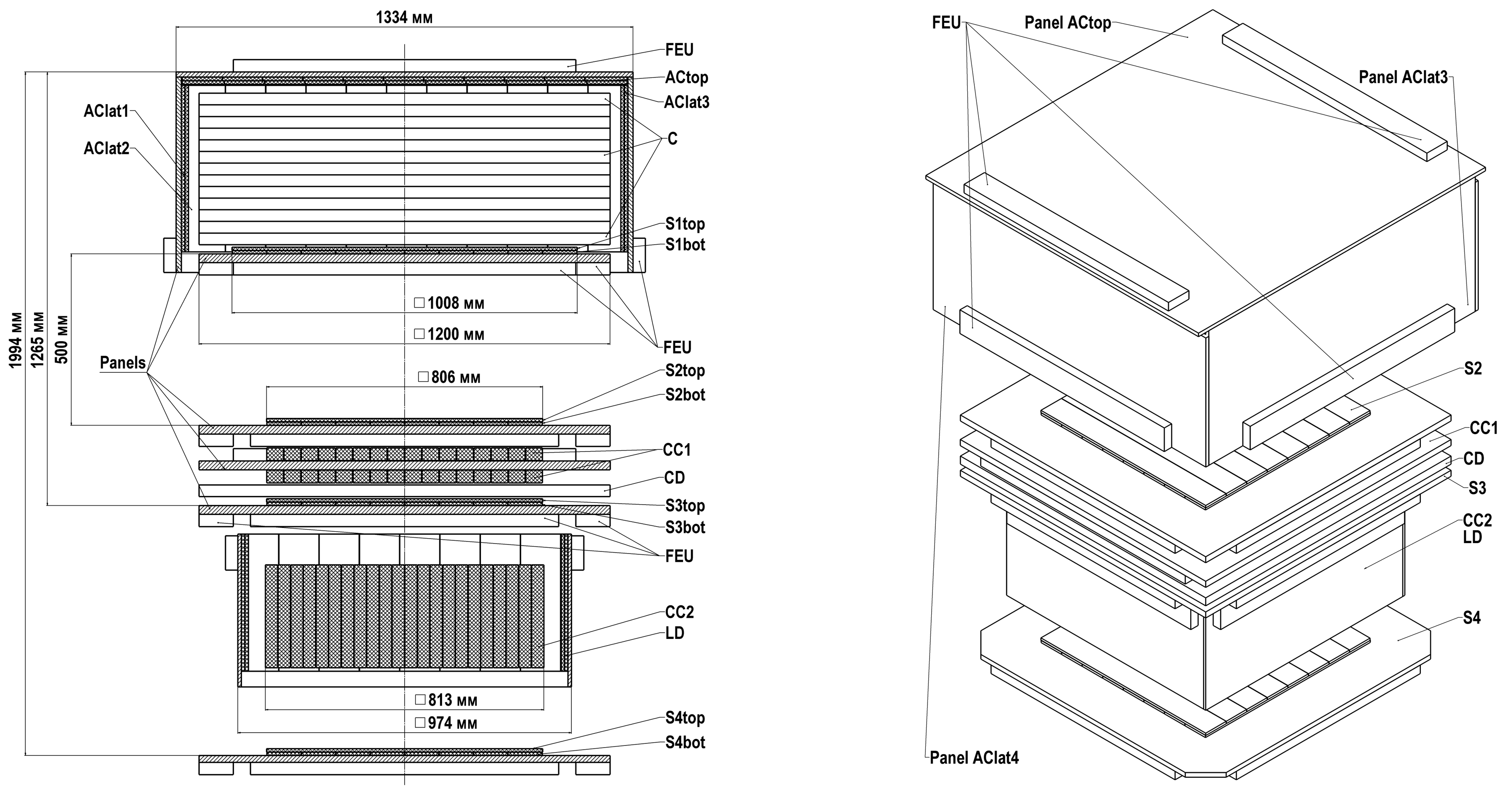

Fig. 1. The physical scheme of the GAMMA-400 gamma-ray telescope

The physical scheme of under consideration variant of GAMMA-400 gamma-ray telescope is presented in Fig. 1. The converter-tracker C is used for high precision determination of the gamma-quanta conversion point and reconstruction of the trajectory of the primary and secondary charged particles. The converter-tracker consists of 13 layers of double (x, y) SciFi (0.25 mm scintillation fibers) tracking coordinates detectors with total thickness about $1X_0$ (X_0 - radiation length). The first 11 layers are interleaved with tungsten conversion foils (first 7 layers of $0.1X_0$ and next 4 layers of $0.025X_0$). The last two layers have no tungsten. The AC is segmented anticoincidence detector (135 scintillator strips) includes one top detector AC_{top} and four lateral detectors $AC1_{lat}$–$AC4_{lat}$ surrounding convertor-tracker for discrimination between incoming charged particles and gamma-quanta with an efficiency of ≥99.95%. The LD is segmented anticoincidence detector (64 scintillator strips) includes four lateral detectors LD1–LD4 surrounding total-absorption calorimeter CC2. All anticoincidence counters, as well as S3 and S4 are made of two oriented in parallel layers of 1 cm thickness, 10 cm width BC-408 polyvinyltoluene scintillator strips with different length. The strips of one layer are displaced with respect to the strips of the other layer so that there are no rectilinear slits in the system. The time-of-flight system TOF provides a fast trigger to gamma-ray telescope readout electronics by measure the particles crossing time and position, and separates upward going particles from downward ones within 10^{-3} level. The TOF consists of hodoscope of four oriented perpendicularly layers of 1 cm thickness, 10 cm width, 100 cm (top) and 80 cm (bottom) length BC-408 plastic scintillation counters combined in two detector planes S1 and S2 located at the distance of 50 cm between the convertor-tracker C and coordinate-sensitive total absorption calorimeter CC2. The CC2 is 80 cm x 80 cm, ~$16X_0$ thick in vertical and ~$43X_0$ in transverse direction calorimeter based on the set of 440 CsI(Tl) crystals to measure the incoming particles energy with resolution of ~2% for gamma-rays with E_γ≥100 GeV and separate $e^\pm$ and photons from hadrons at ~$5{\cdot}10^{-5}$ level. The preshower CC1 consists of two CsI(Tl) planes with total thickness of ~$2X_0$, the coordinate detector CD with two layers of double (x, y) SciFi tracking detectors (identical to convertor-tracker ones without tungsten) and fast plastic scintillation detector S3. Below CC2 the leakage plastic detector S4 is mounted. Plastic detectors AC, LD, S1-S4 are included in fast trigger logic in the main (vertical) and lateral (transverse) gamma-ray telescope apertures. The construction and front-end electronics units FEU of all detectors are similar with the exception of absence of temporal analysis circuits in AC_{lat}, LD, S3 and S4, and difference in counters number, length and orientation. Each side of AC_{top}, S1-S4 and only one side of AC_{lat} and LD is viewed by photo sensor modules on the basis of matrix of silicon photomultipliers (SiPM) mounted on printed circuit boards.

The gamma-ray telescope's anticoincidence detector system is a complex of segmented two-layer scintillation counters based on polyvinyltoluene BC-408, with separate events registration in each segment by means of SiPM matrices. The top and lateral anticoincidence detectors AC_{top} and AC_{lat}1-4 form protection for the main aperture of the gamma-ray telescope (vertical direction), while detectors C3, C4 and LD form protection for the lateral aperture of the gamma-ray telescope (for particles falling onto the lateral surface of the CC2 calorimeter). A feature of the system is the use of a complex technique for compensating the «backsplash» effect caused by the impact on the anticoincidence system of low-energy secondary electrons and positrons resulting from the interactions of high-energy (> 5 GeV) gamma-rays with the gamma-ray telescope matter. In this case, erroneous blocking of «useful» events occurs, leading to a reduction of the detection efficiency. To compensate for this effect, the method of temporal analysis of the delay of the «backsplash» signal in the AC_{top} with respect to the signal from the time-of-flight system is used [4] in addition to segmentation of the detectors and making them multilayered. In this case, the segments of the corresponding detectors should have intrinsic time resolution of ~1 ns. More than 90% of “useful” events can be saved at the stage of fast hardware selection, using this technique according to preliminary estimates [5].

II. THE EXPERIMENTAL SETUP AND RESULTS OF MEASUREMENTS

The prototype of the anticoincidence detector system is an assembly of polyvinyltoluene BC-408 scintillation strip with dimensions of 1280 mm x 100 mm x 10 mm, wrapped with TYVEC reflection material and placed in 0.6 mm thick carbon fiber housings. The strip is viewed from two opposite ends by modules of photodetectors. The current version of the prototype uses matrices of six 6mm x 6mm SiPM mounted on a printed board with dimensions of 90 mm × 11.5 mm. To improve the optical contact of SiPM with the scintillator surface the silicon grease BC-630 is used. Taking into account the need for obtaining both time and amplitude information from detectors, the SiPM type OnSemi MicroFC-60035-SMT-C1 having an additional «fast» output with a low capacitance are used, which allows simultaneously receive both a timing signal with a front of 2÷4 ns from the «fast» output, without additional analog signal shaping, and a signal with a front of ~200 ns from the «slow» output to measure the energy deposition in the detector segments. Signals from «fast» SiPM outputs are summed on a matrix of Schottky diodes type Skyworks SMS 7621-006LF, mounted on the same printed board as the SiPM (two diodes for each «fast» SiPM output to reduce the noise contribution from not active SiPM in matrix [6]). The summed «fast» signal is additionally amplified by a factor of ~10 by an InGaP-based preamplifier type MMIC HMC589AST89ET mounted on a separate board, located at a distance of 5 mm from the SiPM board and connected to it through board-to-board connectors. The photodetector module is connected by cables of ~10 cm long to the FEU containing secondary power supplies and an additional signal amplification unit (~50 times) based on two AD8000 operational amplifiers. The signals from «slow» SiPM outputs are summed and fed into a preamplifier-shaper with pole-zero cancellation circuit based on two AD8000 operational amplifiers to form output analog signals with a rise time of ~3 ns and a width of ~10 ns placed in the same FEU.

The measurements were carried out on the beam of secondary positrons of the C-25P “PAKHRA” synchrotron [7] with an average energy of ~250 MeV, a FWHM of ~3 MeV and an average intensity of ~10^3 $cm^{-2}s^{-1}$. The initial beam is limited by a lead collimator Ø15 mm and 50 mm thick. To form the beam trigger signal, a hodoscope [8] of three counters based on a polystyrene SC-301 scintillator 3 mm x 15 mm x 15 mm in size wrapped with a MYLAR reflection material and placed on the beam axis behind the collimator at a distance of 10 cm from each other is used. The triple coincidence signal from hodoscope’s counters forming the trigger signal with duration of 20 ns. The measured time resolution of the hodoscope is 104 ± 2 ps. To analyze temporal and amplitude information from the prototype, four-channel digital oscilloscope LeCroy WaveRunner 620Zi is applied. The amplified «fast» or shaped «slow» analog signals from each end of the detector are split into two parts: one part is fed directly to the input of the oscilloscope for amplitude analysis, while the second one is fed to the input of the constant fraction discriminator (CFD) type ORTEC 935. The output CFD signal with duration of 20 ns goes to another input of the oscilloscope for temporal analysis, and also, through the delay lines type CAEN N108, to the inputs of double coincidence module LeCroy 622 for detection efficiency measurements. The coincidences of trigger signal with pulses from each end of the prototype, as well as with the logical sum (by OR) of signals from the ends, are registered. The trigger signal from the hodoscope is applied to the external synchronization input of the oscilloscope too. During the sessions, the amplitude and time resolution of the detector as a function of beam impact position relative to the detector center for «fast» and shaped «slow» signals were studied. The charged particles detection efficiency was measured only for the «fast» SiPM output because of lack of accelerator time in this sessions. All measurements were carried out for the detection threshold corresponding to ~0.5 MIP (Minimum Ionizing Particles energy deposition) for energy deposition at the center of the detector strip. Statistics at each point was ~10^6 particles for measurements of the detection efficiency and ~10^4 for other. The main measured results in Fig. 2 are shown. The using of the «fast» signal gives a ~20% better time resolution then «slow» one with additional analog signal shaping (185 ± 1 ps for the «fast» SiPM output versus 224 ± 2 ps for «slow» one, for particles falling at the center of the detector) and ~30% worse amplitude resolution (29 ± 1% versus 22 ± 1%, respectively). The detection efficiency for the «fast» signal is as good as 0.981 ± 0.001, which corresponds to the value of 0.9996 for a two-layer detector.

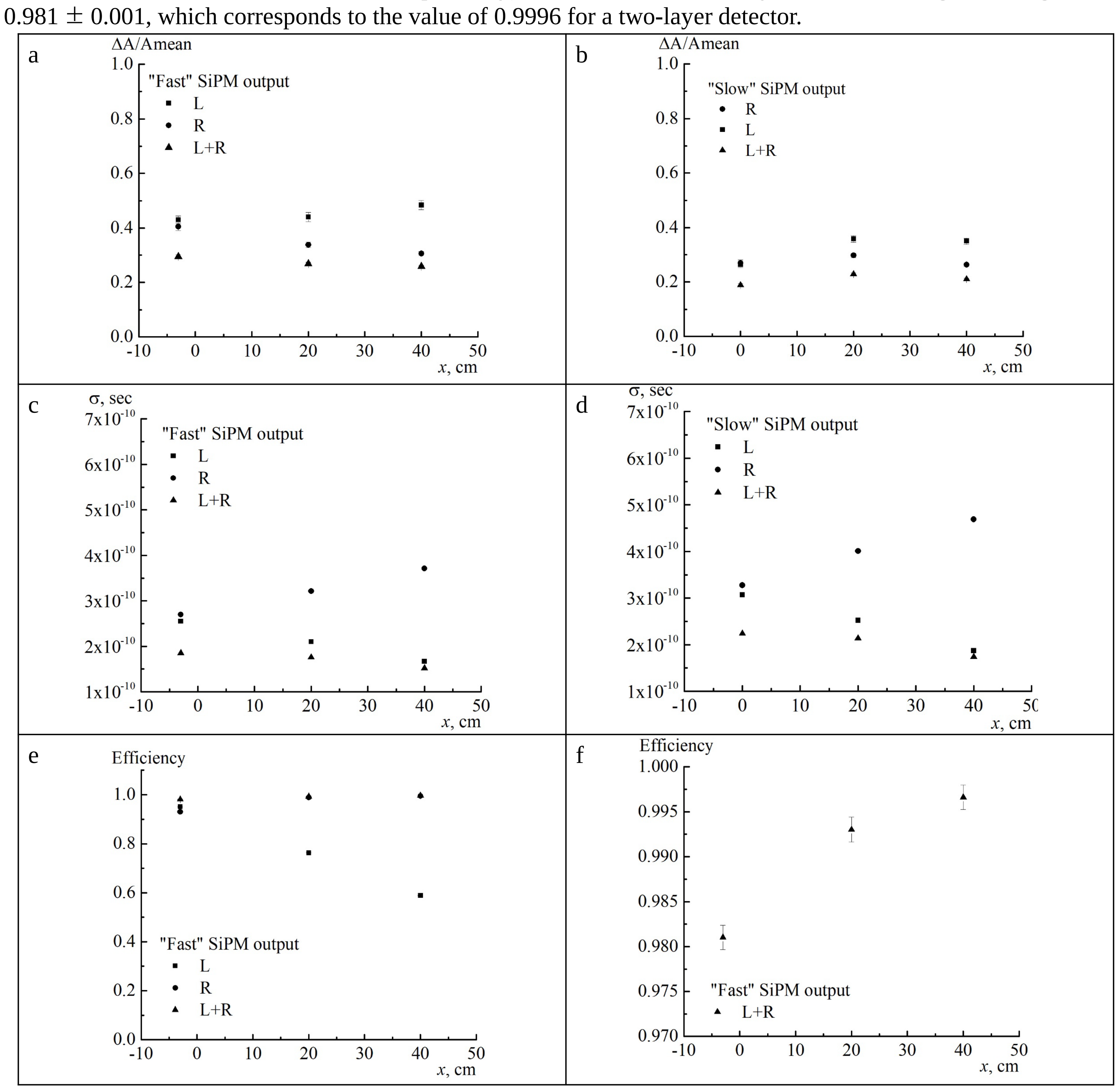

Fig. 2. The amplitude resolution (a, b), time resolution (c, d) and detection efficiency (e, f) of the prototype detector as a function of the beam impact position *x* relative to the detector center for “fast” (a, c, e, f) and “slow” (b, d) SiPM output, respectively. Fig. 2f shows the overall L+R efficiency from Fig. 2e on an enlarged scale. ΔA – FWHM of the amplitude distribution, A_{mean} – mean value of the amplitude. The designators L and R correspond to the left and right ends of the scintillator strip, respectively. L+R – combined resolution σ^2_{LR} at both ends obtained as $1/\sigma^2_{LR} = 1/\sigma^2_L + 1/\sigma^2_R$ for Figs. 2a-2d and logical sum (by OR) of signals from both strip ends for Figs. 2e-2f. Error bars are less than some points on the plots.

III. CONCLUSIONS

The work presents the main characteristics of the prototype of anticoincidence system of the space-based gamma-ray telescope GAMMA-400 with light readout at both ends of scintillation strip (BC-408, 1280 mm x 100 mm x 10 mm) by modules of photodetectors consisting of six SiPM type OnSemi MicroFC-60035-SMT-C1 using both «fast» and «slow» outputs of SiPM. The measurements were performed on the beam of secondary positrons of the C-25P «PAKHRA» synchrotron of Lebedev Physical Institute with an average energy of ~250 MeV. The using of «fast» output of SiPM gives the intrinsic time resolution of the prototype by ~20% better compared to one obtained with «slow» shaped SiPM output but the amplitude resolution is worse by ~30% at the same time. The approach with simultaneous utilization «fast» SiPM output for time measurements and «slow» SiPM outputs for amplitude measurements allows us to reach the optimal result. In this case the scheme of the front-end electronics of time analysis channel becomes simpler and this approach can simplify the development and tuning of the system consisting of hundreds identical channels. The reached values of time resolution (185 ± 1 ps for the «fast» SiPM output) and amplitude resolution (22 ± 1% for the «slow» one) in conjunction with obtained value of detection efficiency (≥0.9996 for two-layer detector) shows that this approach is well suitable for using in anticoincidence detectors of space-based gamma-ray telescope.

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