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The beam test of anticoincidence scintillation detector prototype with SiPM readout and perspectives of GRBs studies for space-based gamma-ray telescope GAMMA-400

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Abstract. The GAMMA-400 project will be the new generation of satellite gamma-observatory. GAMMA-400 space-based gamma-ray telescope represents the core of the scientific complex intended to perform a search for signatures of dark matter in the cosmic gamma-emission, measurements of diffuse gamma-emission characteristics, investigation of extended and point gamma-ray sources, studying of high energy component of gamma-ray bursts and solar flares emission. Four fast plastic sub-detectors of the gamma-ray telescope are included in fast trigger logic in the main telescope aperture. This aperture expected angular and energy resolution are ~0.01° and ~1-2% respectively for gammas with the energy >100 GeV and electron/protons rejection factor $\sim 5 \cdot 10^5$. Prototype of anticoincidence detector based on long BC-408 scintillators with SiPM readout for gamma-ray telescope was tested on a 300 MeV secondary positron beam of synchrotron C-25P «PAKHRA» of Lebedev Physical Institute in Russia. The measurement setup, design concepts for the prototype detector and chosen solutions together with some test results are discussed. Two other apertures (additional and lateral) allow analyzing transient events not required precision angular resolution, for examples, GRBs and solar flares. Similar plastics sub-detectors included in their fast trigger logic. Using of all three apertures allows making more effective observations of GRBs (better signal to noise ratio), more detailed study of its high energy afterglow due long term measurements (because of high apogee orbit provides low background variations with time) and detailed analysis of the sources luminosity variability (spectral, angular and temporal).

1. Introduction

Scientific project GAMMA-400 [1-3] will be the new generation of satellite gamma-observatory. GAMMA-400 gamma-telescope represents the core of the scientific complex intended to perform a search for signatures of dark matter in the cosmic gamma-emission, measurements of diffuse gamma-emission characteristics, investigation of extended and point gamma-ray sources, studying of high

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energy component of gamma-ray bursts and solar flares emission in the wide energy range from several MeV up to TeV region, electron/positron and cosmic-ray nuclei fluxes with energies up to ~10^{15} eV. For gamma-rays with the energy >100 GeV expected angular and energy resolution are ~0.01° and ~1-2% respectively and electron/protons rejection factor is ~$5\cdot10^5$. The GAMMA-400 space observatory will be launched on the Navigator service platform [4] 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. The GAMMA-400 observatory is expected to operate more than 5 years, 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.

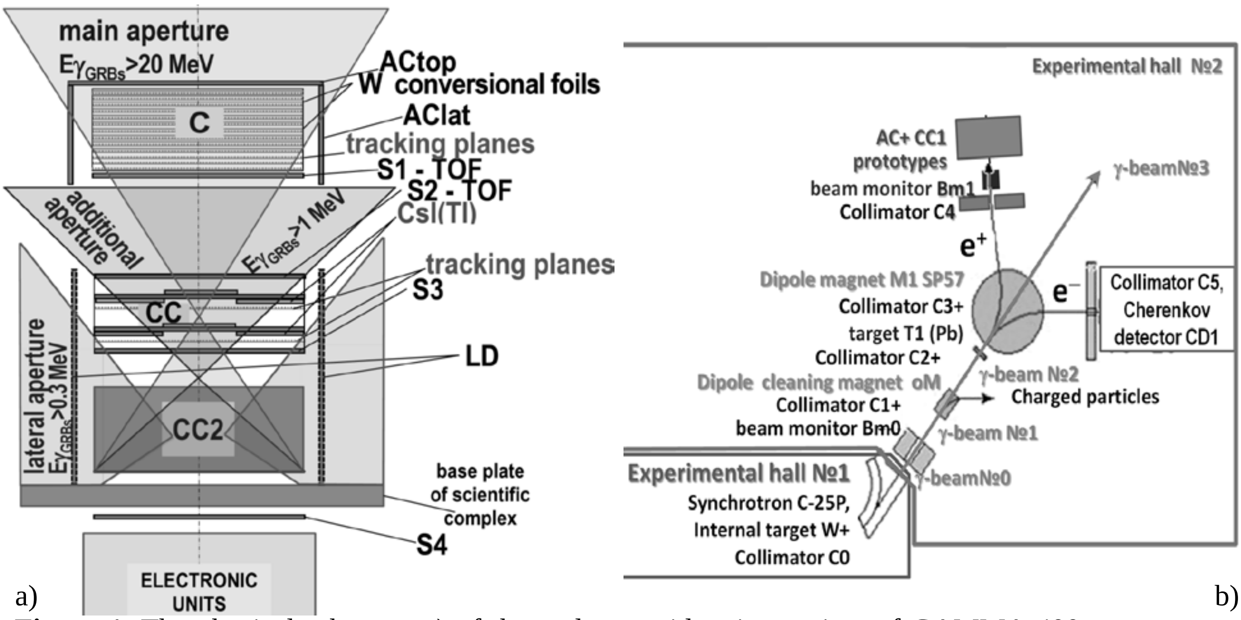

Figure 1. The physical schemes: a) of the under consideration variant of GAMMA-400 gamma-ray telescope construction and its three apertures for GRBs registration, b) positron beam formation setup and apparatus installation at C-25P synchrotron “PAKHRA”.

Three apertures provide events registration from both upper and lateral directions: main, additional and lateral ones [2] – see figure 1a. The main aperture created firstly due converter-tracker (C): gammas converted in tungsten conversion foils are registered. In the main aperture triggers will be formed using information about particle direction provided by TOF system and presence of charged particle or backsplash [2, 5]. Four fast plastic sub-detectors of the gamma-telescope AC, TOF, S3 and S4 are included in fast trigger logic in the main telescope aperture. The additional aperture provides to observe particles passes out of converter-tracker: no any signal from TOF system for such events, but S2 will be anticoincidence detector together with LD and S4 instead of AC top and lateral sections. The lateral aperture allows to register γ-quanta, electrons/positrons and light nuclei with energy E>10 GeV. Also it provides detecting of gammas in the energy ranges of 0.2 - 10 MeV and 10 MeV – 10 GeV. LD, S3 and S4 used as anticoincidence detectors. Additional and lateral apertures allow analyzing transient events not required precision angular resolution, for examples, GRBs and solar flares. Similar plastics sub-detectors included in their fast trigger logic.

2. The beam studies of light yield and time resolution of anticoincidence detector prototype

The primary beam of synchrotron “PAKHRA” of Lebedev Physical Institute consists of 0.3-1.2 GeV electrons with particle intensity up to $2\cdot10^{12}$ electrons/sec and repetition frequency of 50 Hz.

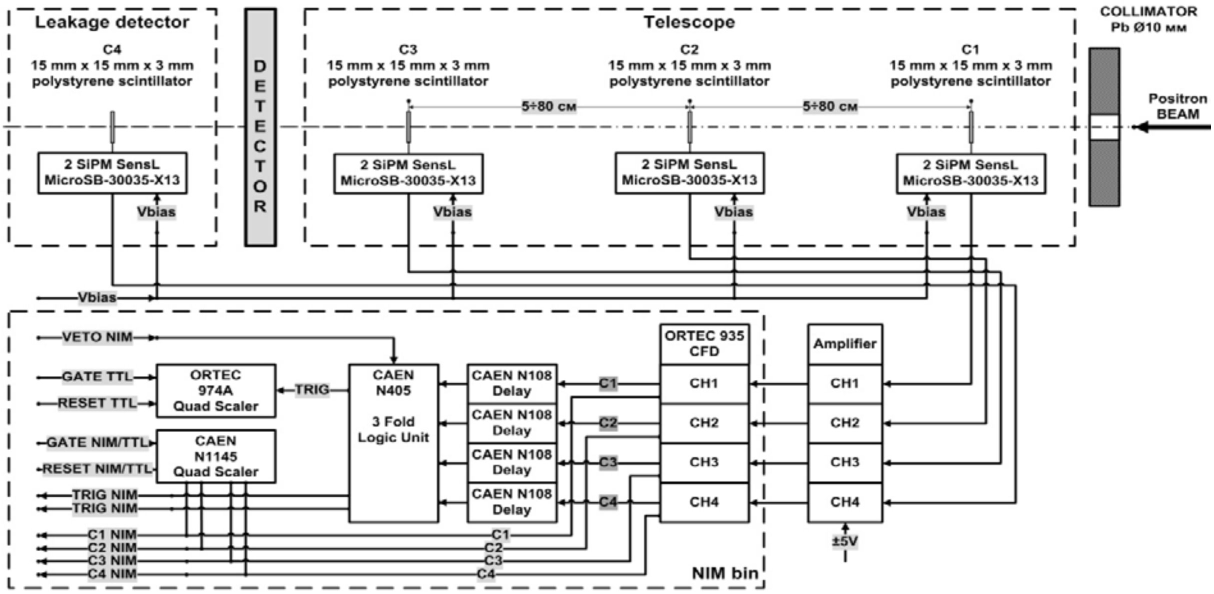

Figure 2. Experimental setup, including beam monitor. The dash-dotted line represents the beam line.

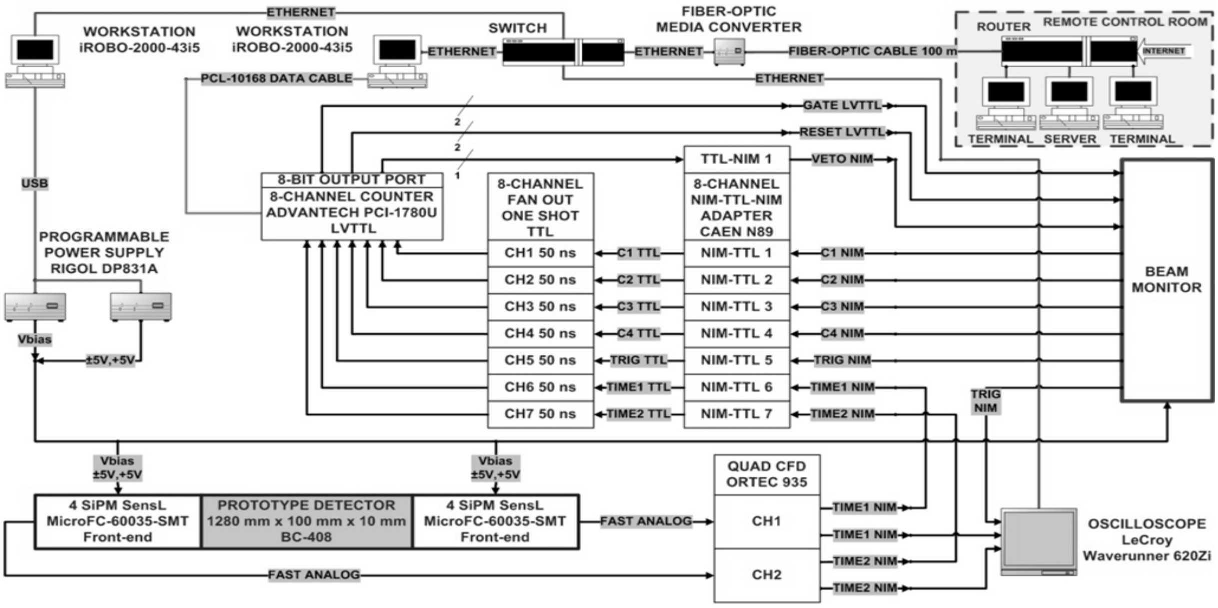

Figure 3. Functional diagram of the data acquisition.

For described tests this beam was used to create a secondary positron beam by two-stage bremstrahlung → e± pair beam production. A secondary beam with particle momentum of 300 MeV/c is selected using dipole magnets (see figure 1b). The studied detector was installed on remote controlling platform permits to horizontally moving the detector with respect to beam position in the range of ±40 cm. The origin of *x* coordinate is defined as the center of the scintillation strip. A beam monitor for secondary positrons selection consists of four 3 mm thick polystyrene scintillation counters C1-C4 with dimensions of 15 mm × 15 mm wrapped with Al film and coupled with silicon grease BC-630 from one side with two connected in parallel 3 mm × 3 mm SensL MicroSB-30035-X13 silicon photomultipliers (SiPM). The SiPM units are installed on the high-precision horizontally and vertically moving platforms for accurate positioning of scintillation counters with respect to positron beam. The signals from each SiPMs pair are amplified by four two-stage fast shaper-amplifiers with pole-zero cancellation circuits, produced output signals with rise-time of ~3.5 ns. The amplified and shaped signals are fed into four constant fraction discriminators (CFDs, ORTEC Model 935). The CFD outputs are connected through the set of delay lines (CAEN Model N108) to CAEN Model N405 3 FOLD LOGIC UNIT for coincidence whish generate the reference start time for positron registration. The reference time resolution was measured to be 104±2 ps. The experimental setup is shown in figure 2.

The tested detector consists of strip of polyvinyltoluene scintillator BC-408 with dimensions of 1280x100x10 mm^3, wrapped with Tyvek reflective material. The strip is viewed from opposite shortest ends by two independent photosensor blocks consists of front-end electronics and mounted on PCB four silicon photomultipliers SensL MicroFC-60035-SMT coupled to scintillator with silicon grease BC-630. The functional diagram of data acquisition is presented in figure 3.

The time resolution and the average photoelectron yield per incident positron for one end of the scintillator strip are shown in figure 4 as a function of the 300 MeV/c beam position along the strip relative to strip centre. The number of incident positrons is about 10^4 for each point. As expected, the time resolution worsens with the increase in distance of the beam position from respective SiPM block. For separation of upward from downward going particles at 10^{-2} level the time resolution of about 0.5 ns or better is required. As seen in figure 4 this condition is fulfilled for scintillator strips with length of ~100 cm or less (all gamma-ray telescope GAMMA-400 detectors except for top anticoincidence counters). For anticoincidence detector one should increase the number of SiPMs at the detector ends up to 8 instead of currently used four SiPMs and utilize of new silicon photomultipliers with improved photon detection efficiency and dark count rate parameters for obtaining of more photoelectrons. This work is under realisation now in the frame of preparation for the next beam test session.

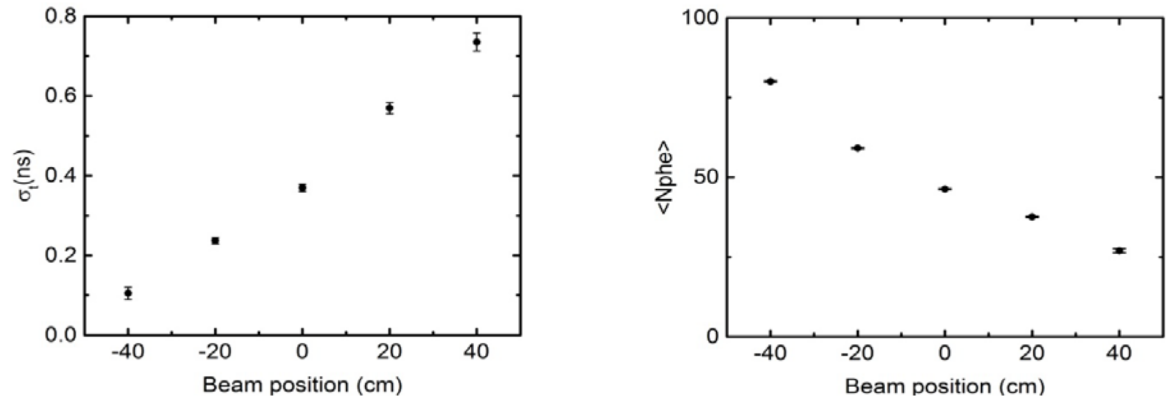

Figure. 4. Time resolution – left figure, and average total number of photoelectrons per incident positron – right figure, as a function of 300 MeV/c beam position relative to the detector centre.

3. GRBs observations: several unresolved questions

The first GRB670702 was registered by detectors onboard Vela-4A satellite on July 2, 1967 [6]. Gamma-emission during this burst observed in energy range 0.1-1 MeV and its duration was ~1s. Several tens of experiments onboard satellites in interplanetary and near-Earth space detected more than 10000 such bursts – one of GRBs catalogues described in [7]. GRBs are varying widely in its characteristics intervals. Thus, bursts duration and its observed near the Earth fluencies changes within ~5 orders of magnitude and lies in the ranges $10^{-2}–10^{3}$ s and $10^{-8}–10^{-3}$ erg/(cm^2×s) correspondingly [7].

For the first time the catalogues with more informative GRBs characteristics were published based on results of four experiments: BATSE, COMPTEL, OSSE and EGRET, onboard Compton Gamma Ray Observatory (CGRO) [8]. Some tens GRBs were detected simultaneously by all these detectors [4] and the widest energy range for gamma emission registration on satellite experiment for the some GRBs was ~10 keV ÷ ~20 GeV. 15 GRBs had E>120 MeV [9] but 3 bursts of these events had no emission with E>200 MeV. Bursts spectral parameters typically decreasing monotonically while the flux rises and falls or its behavior corresponds to flux temporal profile. Usually GRB spectra (both time resolved and time integrated) are well described by two-component Band function [10] where first component is proportional to combination of power law with index α and exponential cutoff defined by E_1= Epeak/(2+α) and second one is proportional to power law with index β up to high energies. Spectral evolution for GRB910927 is shown at figure 5a. But new additional spectral component was observed diring some bursts (GRB920902, GRB 941017 and GRB980923) – see figure 5b and characteristic energy E_2 was separated [11]. Mostly common structure of temporal profiles is similar in various energy bands (exluding several GRB with no-Band component in the spectra): the same amount of global peaks, approximate ratio of relative peaks intensity are the same too. But during some GRB extended high energy emission was observed by EGRET (for example up to E_{max} ~18 GeV for GRB940217). Moreover, there is some evidence of TeV emission from GRB 970417a using data from MILAGRITO: photons with energies above 650 GeV were detected by results of preliminary data analysis [13].

The GRBs duration distribution analysis based on CGRO data had shown long and short bursts classes existence separated by t_{90} = 2 s [33]. But analysis results of similar distributions for bursts observed by other detectors have shown shifting of boundary between short and long events. For example, Swift/BAT GRBs subset analysis gives the value of ~1 s for this separator point [12]. Mostly other characteristics of now observed GRBs are similar one registered by detectors onboard CGRO and earlier experiments, although third characteristic energy was separated in several bursts spectra [11] because of very low energy component (tens of keV) observations by Fermi and Agile – see, for example, figure 5c. Several GRBs has precursors – see figure 6. It is possible to separate two main classes of GRB with high energy tails of temporal profiles: first with energy spectra in low band

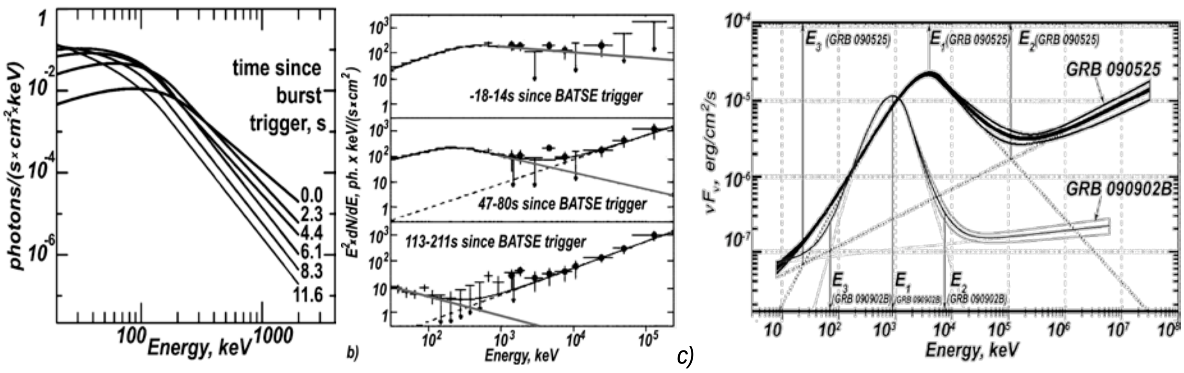

Figure 5. The spectra of GRB910927 (a), GRB941017 (b), GRB 050525 and GRB090902B (c). Additional component is presented in GRB941017, GRB050525 and GRB090902B but it lasts from 8 keV up to 300 MeV for GRB050525.

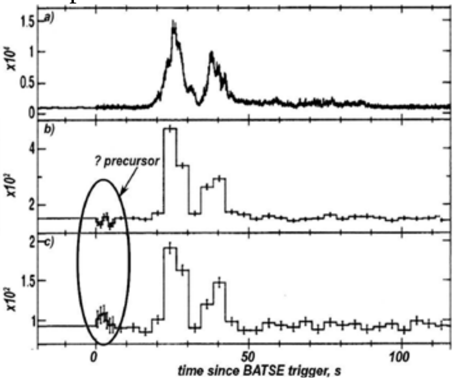

Figure 6. GRB 090510 observation by Fermi [31]

similar to usual GRB (Band, power law or broken power law) and second with presence of new additional component. Both types of GRB observed since CGRO mission beginning and can have extended high energy emission including component with E>500 MeV for some events and low energy precursors. Also both types of temporal profiles can be similar in the various energy regions during some bursts or differs in other cases. Thus, some GRB with presence of high energy component (more than some MeV) within low energy t_{90} intervals were detected by experiments onboard CGRO and up to now such events were registered both in space and ground experiments. Up to the middle of October, 2018 seven instruments provides GRBs registration [14] in the energy bands from ~2 keV (MAXI [15], 104 bursts [16]) up to several hundreds of GeV (Fermi/LAT [17], 146 events [18]). Catalogue of WIND/KONUS [19] consist of 2992 GRBs [20], ones of Swift/BAT [21] and Fermi/GBM [22] contain 1255 [23] and 2432 [24] bursts correspondingly). Also INTEGRAL/SPI-ACS [25] registered 934 GRBs triggers [26], CALET/GBM [27] detected 363 ones [28] and Agile [29] observed ~150 bursts [30]. But several unresolved questions occur after summarizing of experimental results, firstly in difference between other characteristics of GRBs grouped relatively:

- similar and different temporal profiles in various energy bands especially if their maxima are not coincide (for example, events like GRB930131 and GRB 050525);
- appearance of high energy spectral component which contradict Band model or its absence;
- presence of high energy extended emission or its nonexistence;
- high and low energy precursors existence for several events.

4. Background structure influence to long events registration

There are three components of the gamma background: gammas themselves with diffuse cosmic and atmospheric origin, ones formed in prompt interactions and activation produced γ-emission – see, for example, [34]. Thus, the background conditions in the energy range with E>0.1 MeV differ due to frequency of Earth Radiation Belts (ERBs) and South Atlantic Anomaly (SAA) regions passes and cosmic rays rigidity depends of orbits parameters (perigee Hp, apogee Ha and inclination I). Prompt interactions caused due magnetosphere electrons, charged particles originated in cosmic rays, solar flares and ones trapped in ERBs including SAA. Activation component occurs during ERBs and SAA passing and its influence lasts correspondingly life-time of nuclei formed in trapped particles interactions with detectors and construction elements. If orbit parameters like Fermi, i.e. Hp = 500 km, Ha = 500 km, I~20^{o}, satellite rotation period is ~1.57 hour and background has periodic structure with the same period caused by trapped protons and particles rigidity variation in the Earth magnetosphere.

Such satellite passed through ERB and SAA once per several days and then activation component occur. The possibility to lost part of multi episode event due background complex structure takes place in such case – see figure 7. Moreover, question about registered events duration widely discussed [35]:

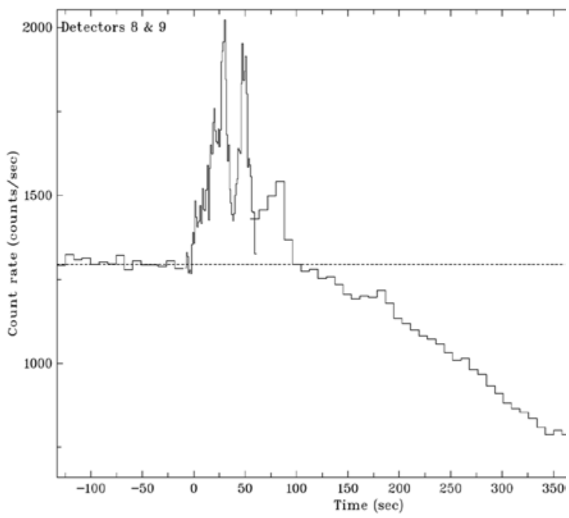

Figure 7. Temporal profile of GRB170405A (18:39:48 UT) [13]. Dashed line show calculated background without taking into account its periodic complex structure. Unfortunately this event last peak was located at more than 50 s from main three-peak episode and its intensity is only about 50 counts/s over background count rate 1200 counts/sec against ~2000 counts/s over background count rate ~1300 counts/s during first peak. Thus Fermi/GBM burst table doesn't contain data about this episode of GRB170405A and its duration t_{90}= 78.593 ± 0.572 s [13] in energy band 50-300 keV sufficiently differ t_{90}=165 ± 32 s in energy range 15-350 keV on Swift/BAT data [12].

how to predict that an event will be an ultra long GRB, i.e. duration more than 3 hours, while high-energy detectors are recording only the first tens of seconds?

But the orbit of GAMMA-400 satellite will be high apogee with following initial parameters: the apogee will be 300 000 km, the perigee will be 500 km and the inclination will be 51.4^{o}. In this case it enter in ERB and SAA once a week at ~ 2 hours and it occur only at firsts 5 month from start, then orbit will transform to circular with a radius of ~150 000 km and will be outside radiation belts. It provides stable background conditions without influence of Earth magnetosphere during long periods and possibility of analysis of very long events with complex temporal profile.

5. Conclusion

The properties of a time-of-flight scintillation bar BC-408 with SiPM readout, wrapped with Tyvek reflective material were studied on a 300 MeV/c positron beam at the test beam of C-25P synchrotron "PAKHRA" of Lebedev Physical Institute in Russia. The time resolution worsens with the increase in distance of the beam position from respective SiPM block and to average about 400 ps at the centre of the tested AC detector prototype.

Four analogues fast plastic sub-detectors of the gamma-telescope AC, TOF, S3 and S4 are included in fast trigger logic in the main telescope aperture. Similar plastics sub-detectors included in their fast trigger logic of additional and lateral ones. Obtained light yield, time and coordinate resolution of the AC detector prototype allow provide backsplash rejection and event recognition in all GAMMA-400 apertures. Using of all three apertures allows making more effective observations of GRBs (better signal to noise ratio), more detailed study of its high energy afterglow due long term measurements (because of high apogee orbit provides low background variations with time) and detailed analysis of the sources luminosity variability (spectral, angular and temporal). Thus we conclude wide possibilities of the GRBs advanced studying contain following items:

- energy spectra detailed investigation in the wide energy band:
    - definition of maximum energy of γ-quanta registered during GRB;
    - check of no-Band component presence during the burst;
    - E_1 and E_2 spectral breaks positions definition;
    - spectral indexes evolution investigation and hard to soft tendency check;
    - high energy γ-quanta spatial distribution studying for particles with E>100 MeV;
    - search of possible correlations between E_2 and E_3 spectral breaks positions, burst spectral indexes and other GRB characteristics;
    - search of spectral features could be associated with mesons decay lines and possible processes in black holes;
- temporal profiles detailed investigation in the wide energy region:
    - characteristic and minimum variability times definition;
    - burst temporal profile shape variation investigation in dependence of energy bands (comparison temporal profiles and characteristic and minimum variability times in the energy bands $E > E_2$, $E_2 > E > E_1$ and $E_1 > E > E_3$) ;
    - GRBs duration distribution studying;
    - temporal profiles in various source parts studying if angular resolution allow to recognize any spatial features at burst image in the energy band with E > 20 MeV;
    - temporal profiles in lines investigations if several spectral features will be separated;
- GRBs precursors spectra and temporal profiles investigation
- high energy afterglow spectra detailed investigation:
    - definition of registered γ-quanta maximum energy;
    - possible spectral break position definition;
    - spectral indexes evolution investigation;
    - high energy γ-quanta spatial distribution studying for particles with E>100 MeV;
    - search of possible correlations between various GRB and its high energy afterglow spectral characteristics;

    - search of spectral features;
- high energy afterglow temporal profiles detailed investigation:
    - characteristic and minimum variability times definition;
    - temporal profiles in various source parts studying if angular resolution allow to recognize any spatial features in burst image in the energy band with E > 100 MeV;
    - temporal profiles in lines investigations if several spectral features will be separated.

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