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The trigger and data acquisition systems for space-based gamma-ray telescope GAMMA-400

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I. INTRODUCTION

Scientific project GAMMA-400 [1, 2] is one of the new generation of space observatories intended for 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 energy range from several tens of MeV up to the TeV region, electron/positron and cosmic-ray nuclei fluxes with energies up to ~10^{15} eV by means of the GAMMA-400 gamma-ray telescope that represents the core of the scientific complex. For gamma rays with the energy >100 GeV the expected energy and angular resolution are ~2% and ~0.01° respectively and the electron/protons rejection factor is ~$5\cdot10^5$. The GAMMA-400 space observatory is planned for the launch at the middle of the next decade on the Navigator service platform [3] designed by Lavochkin Association on an elliptical orbit with following initial parameters: an apogee ~300000 km, a perigee ~500 km, a rotation period ~7 days, and inclination of 51.4°. The apparatus is expected to operate more than 5 years, reaching an unprecedented sensitivity for the search of dark matter signatures and in the study of the unresolved and so far unidentified 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.

II. THE STRUCTURE AND DATA ACQUISITION OF THE GAMMA-RAY TELESCOPE

The under consideration variant of GAMMA-400 gamma-ray telescope includes following detecting modules (Fig. 1):

- a converter-tracker C consists of 13 layers of double (x, y) tracking coordinate detectors with total thickness about 1X_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 data from converter-tracker is used for high precision determination of the gamma-quanta conversion point coordinates and reconstruction of the trajectory of the primary and secondary charged particles;
- an ACS is a segmented anticoincidence system (135 scintillator strips) includes one top detector AC_{top} and four lateral detectors AC_{lat} surrounding convertor-tracker for discrimination between incoming charged particles and γ-quanta with an efficiency of ≥99.95%. All anticoincidence counters, as well as LD, S3 and S4 are made of two oriented in parallel layers of 1 cm thickness, 10 cm width BC-408 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 TOFS - time-of-flight system, consists of hodoscope of four oriented perpendicularly layers of 1 cm thickness, 10 cm width and 100 cm (top) and 80 cm (bottom) length BC-408 polyvinyltoluene scintillation counters combined in two detector planes S1 and S2 located at the distance of 50 cm between the convertor-tracker C and calorimeter CC. The TOFS provides a fast trigger to gamma-ray telescope readout electronics by measures the particles charge, crossing time and position, and separates upward from downward going particles within 10^{-3} level;
- an 80 cm x 80 cm, ~18X_0 thick coordinate-sensitive calorimeter CC to measure the incoming particles energy with resolution of ~2% for gamma-rays with E_γ≥100 GeV and separate e± and photons from hadrons at ~$5\cdot10^{-5}$ level. The CC includes preshower CC1 (consists of two CsI(Tl) planes with total thickness of ~ 2X_0, two layers of double (x, y) tracking coordinate detectors and fast plastic scintillation detector S3), the total-absorption calorimeter CC2, based on the set of CsI(Tl) crystals ~16X_0 thick, the anticoincidence LD and leakage S4 plastic detectors.

Four fast plastic detectors ACS, TOFS, S3 and S4 are included in fast trigger logic in the main telescope aperture. The construction and electronics of these detectors are similar. Each side of every plastic scintillation counter in gamma-ray telescope sub-detectors is viewed by photo sensor block on the basis of matrix of silicon photomultipliers (SiPM) - four SensL MicroFC-60035-SMT in current version of prototype detector.

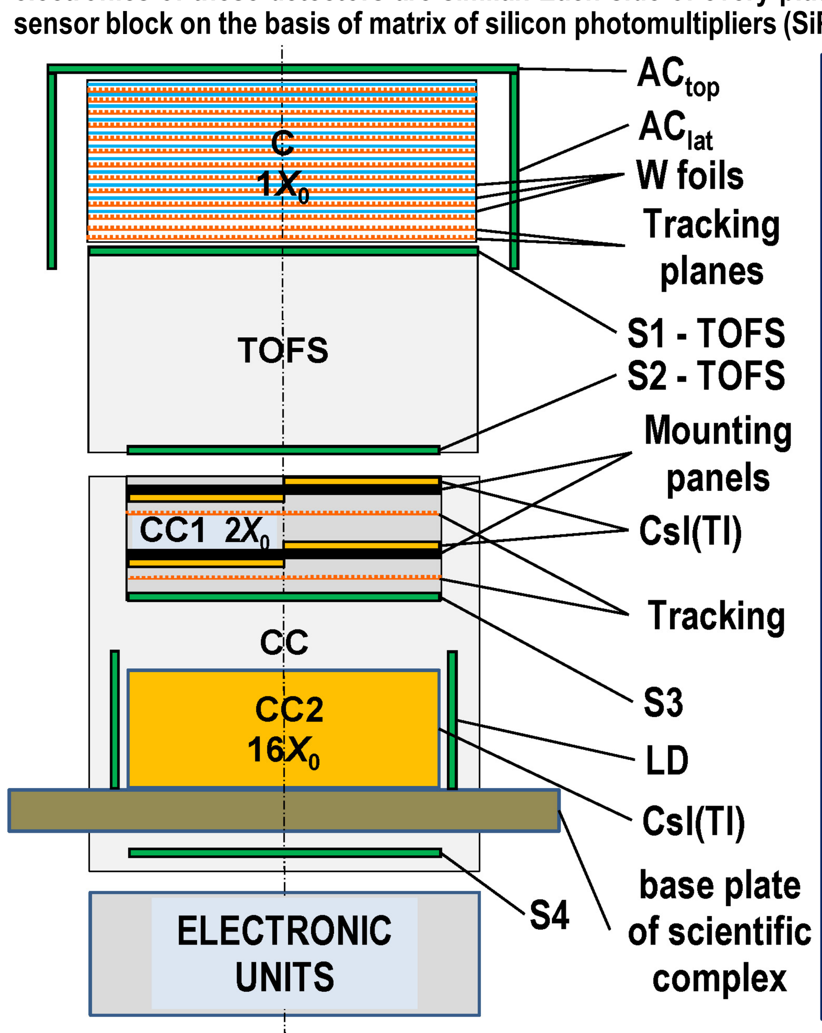

Fig. 1. The sketch of the GAMMA-400 gamma-ray telescope

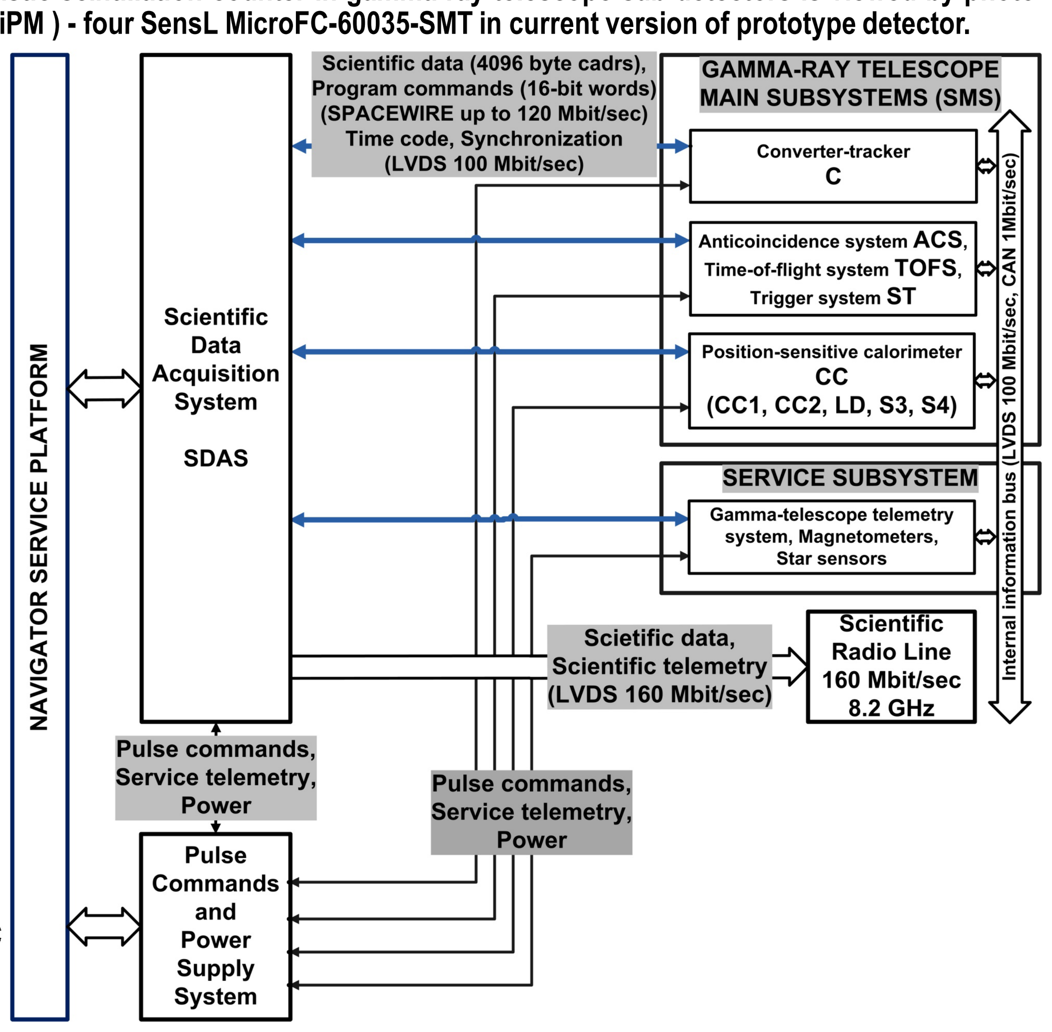

Fig. 2. Functional diagram of the data acquisition system

The GAMMA-400 gamma-telescope can be subdivided into a following subsystems (Fig. 2):

- the main scientific measuring subsystems (SMS) of gamma-telescope – ACS, C, TOFS, CC;
- service subsystem, including two magnetometers for measuring the magnetic field along the satellite trajectory, two star sensors for determining the GAMMA-400 axes with accuracy of approximately 5" and scientific complex telemetry system for cyclic registration up to 65535 housekeeping parameters of scientific complex;
- scientific data acquisition system (SDAS) [4] for acquisition and pre-processing data from SMS and service subsystem, storage it in non-volatile mass memory (1 TByte), scientific data and telemetry transfer into high-speed scientific radio line (up to 160 Mbit/sec) for their transmission to the ground segment of the project and control information reception from spacecraft onboard control system via multiplexed channel MIL-STD-1553B, its decoding and transfer into SMS;
- pulse commands and power supply system PCPSS, providing secondary power supply for scientific complex, one-time pulse radio commands sharing and their transmitting to SMS and transmit of the most important telemetry parameters directly to the satellite onboard telemetry system.

A series of Navigator service platform systems are used for direct providing the functioning of scientific measuring subsystems:

- command radio line - for receiving one-time pulse radio commands and 16-bit program control commands from control ground station and transmit them through onboard control system to SMS. Precise timing of scientific data is maintained in SDAS by using onboard time code OTC from onboard control system, forming a 32-bit serial time code transmitted to each SMS via LVDS interface along with a set of reference synchronization signals SYNC;
- high speed scientific radio line - for scientific data transmitting to the data-acquisition ground stations at a frequency of 8.2 GHz. The nominal data transfer rates are 160/118.8 Mbit/sec without/with coding respectively. Data encryption is used to reduce the quantity of transmission failures (level of 10^{-9} of malfunction probability in the downlink data transmission) by means of the cascade coding technique involving the Reed-Solomon and convolution codes;
- onboard telemetry system - for direct (bypassing of gamma-telescope telemetry system and SDAS) monitoring of the most important analog and digital parameters, contacts and resistance of thermo sensors (up to 100 parameters for operational diagnostics of the scientific complex health);
- onboard power supply system – for providing overall power supply for scientific complex (+28 V, 2000 W).

For the control and fine tuning of scientific measuring systems functioning one can use:

- up to 100 one-time pulse radio commands in the form of either voltage pulse with duration ~0.1÷0.3 sec with amplitude equal to satellite power or "dry contacts" – switch on/switch off;
- up to 65535 programming control commands (16-bits control words) for each SMS.

The scientific data is transferred in the form of 4096 bytes length digital arrays from scientific measuring systems to the SDAS, which maintains data reception from eight (seven for gamma-telescope subsystems and one for service subsystem) sources of digital arrays via high-speed SPACEWIRE (120 Mbit/sec) channels. Data are loaded upon a request for service from SMS.

Two main operating regimes can be specified for GAMMA-400 scientific complex:

- event registration regime, corresponding to the registration of incoming particles according to the master trigger signals generated by system of triggers and counting signals formation. In this regime the data acquisition from all detecting system of the gamma-telescope is performed;
- patrol regime, realized continuously, independent of event registration. In this regime the periodic data acquisition from detecting system of gamma-telescope is performed. The period and the set of interrogated detecting systems can be changed by the control commands.

III. THE SYSTEM OF TRIGGERS FORMATION

The system of triggers and counting signals formation (Fig. 3) represents the electronic structure consists of the set of programmable front-end detector units, trigger logic module for triggers signals formation based on signals from detecting subsystems, power and telemetry module and control and interface module, provides communication with scientific data acquisition system SDAS and the final level of events data reduction and processing. In order to increase the reliability, the system is designed using a scheme with two hot- and cold-reserved subsystems. Data exchange signals are double redundant and each redundant line assigns with its own allocated data transceiver. All front-end units of ACS, TOFS, S3 and S4 detectors, providing incoming information for triggers generation, are similar and consists of two parts for time and charge measurements (Fig. 4). Each time analysis channel includes preamplifier AMP, fast shaper FS with pole-zero cancellation circuit to select the leading-edge part of the signal (shaped signal rise time ~5 ns) and to quickly restore a stable baseline, and constant fraction discriminator CFD. The CFD outputs FT_j are fed to fast trigger formation logic and time analysis circuit with 20 ps resolution, based on four 4-channels ASICs ACAM TDC-GPX2 and FPGA based processing unit (Microsemi ProASIC3 in current prototype version). Each charge measurement channel, based on 16-channel ASIC IDEAS IDE3380 includes attenuator with adjustable gain ATT, current integrator CI, slow shaper SS, leading edge discriminator LED and track-and-hold unit T/H. The "slow" shaped signals are memorized into T/H and transmitted sequentially via analogue multiplexer MUX 16-1 to the 12-bit analogue-to-digital converter ADC for total light released in the counters measurement. The fast amplifier and current integrator gain, shapers parameters, hold delay, CFD and LED thresholds and output pulse duration are programmable by the set of controlling commands. The CFD thresholds are set at ~40% of the minimum ionizing particle (MIP) signal, relates to Z≥1 particles, forming FT_j signals (j=0..9 is scintillator strip identifier for each of four TOFS layers) used in LVL0 and LVL1 triggers logic. The LED thresholds are set at ~200% MIP, relates to Z≥2 particles, forming ST_j signals used in LVL1 trigger logic. The FT_j and ST_j signals are stored in a pattern registers, and in a set of scalers of front-end electronics unit for counting how many FT_j and ST_j signals are presented in a predefined by controlling command time interval of up to 2 s. The LVL0 trigger signal initiates the transfer of pattern registers information into trigger formation logic module through high speed LVDS data link for subsequent LVL1 trigger formation.

The GAMMA-400 trigger system is based on three levels of triggers: two fast, hardware levels LVL0 and LVL1, and slow software level LVL2:

- the level 0 trigger LVL0 is generated by TOFS when a charged particle passing through the gamma-ray telescope acceptance, when at least one counter side in each TOFS plane produces a signal above a threshold within predefined time gate, and provides, in about 50 ns, the reference time label for the time measurements. For this purpose, all "fast" and "slow" outputs of each TOFS counter side are combined in OR to form the TOFL and TOFH signals, according to the threshold that has been passed. Indeed in the TOFS readout electronics both a low ~40% MIP and a high ~200% MIP threshold are implemented for signals from each counter side. Then the signal originated from one plane side is matched in OR or AND with one coming from the other side (depending on a programmable settings). The coincidence of TOFS planes with a trigger mask enables TOFL and TOFH signals. The TOFL signal corresponds to the transit of a particle with Z≥1, passing the low threshold, whereas TOFH is related to higher Z ions with Z≥2, passing the high threshold (see. Table.1). The TOFL signal is send to TOFS, ACS, S3 and S4 sub-detectors as LVL0 trigger;
- the level 1 trigger LVL1 formation begins with the TOFS particle hit counters pattern analysis and crossing time one for acceptance checking and upward/downward particles selection. Then the ACS hit counters pattern is considered, taking into account backsplash events suppression by time analysis method [5, 6]. The S3 preshower response is also included in the trigger for hadronic and electromagnetic showers separation, and the S3 signal is enabled if the conditions on a defined combination of the S3 hit counters pattern with enough energy deposition are fulfilled. The signal of

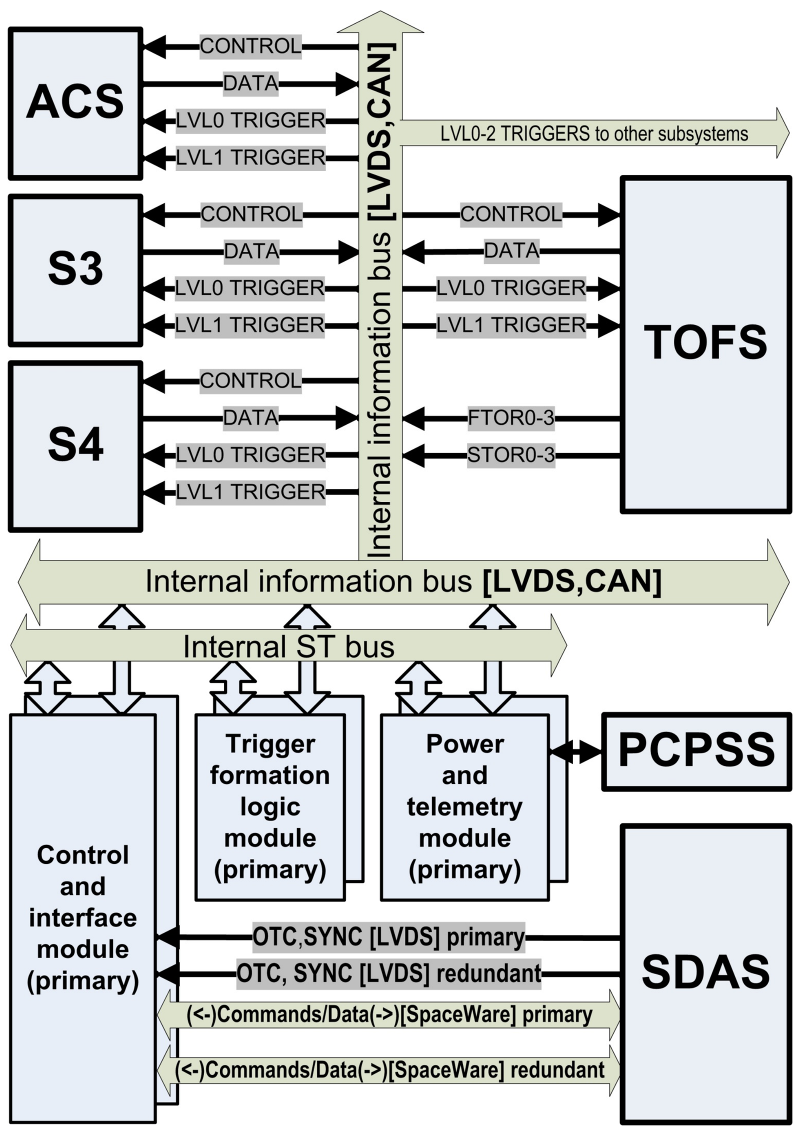

Fig. 3. The functional diagram of the trigger system

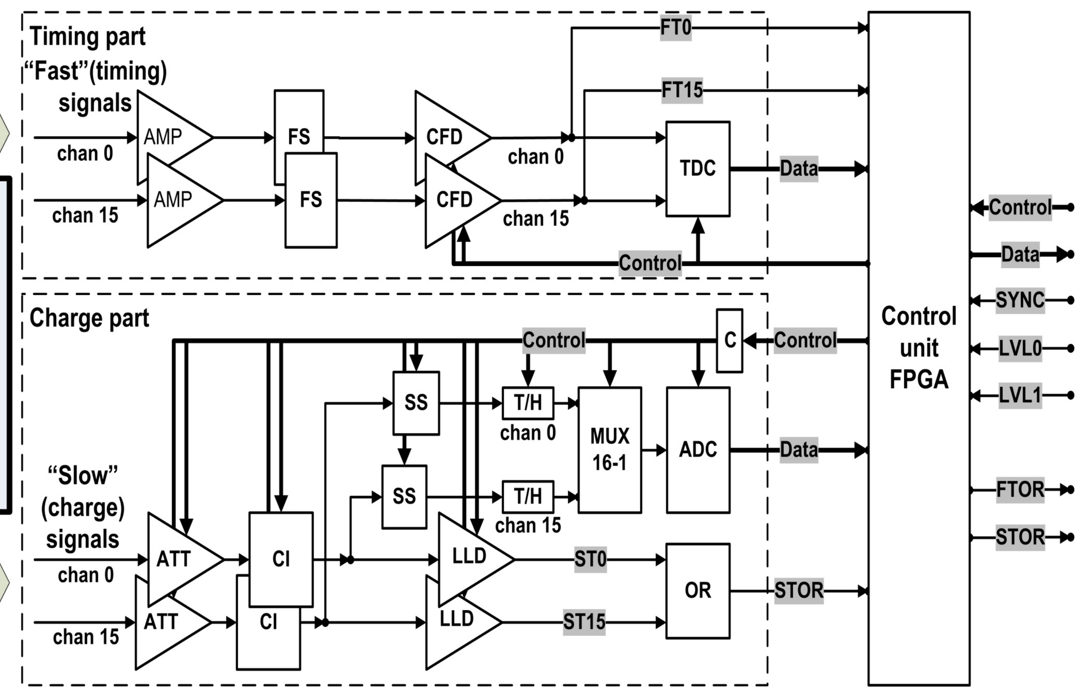

Fig. 4. The simplified functional diagram of the front-end electronics

Table 1. The simplified set of level 1 trigger LVL1 conditions used for selection of different types of events

Level 1 trigger LVL1	Selected events
TOFL & (not AC) & S3	γ
TOFL & AC & S3	e±
TOFL & AC & (not S3)	p, d
TOFH & AC	He, heavy ions

leakage detector S4 indicates that some part of incident particle energy is not absorbed in CC2 calorimeter. In this case the subsequent analysis of the shower spatial profile in calorimeter is needed for energy reconstruction. The LVL1 trigger initiates the process of data acquisition from the gamma-ray telescope subsystems and storing it into intermediate buffer memory. Two counters in trigger logic module count how many LVL0 and LVL1 signals are presented in a time interval of up to 2 s. In Table 1 some examples of simplified LVL1 trigger conditions are presented;

- the level 2 trigger LVL2 suppress spurious fast triggers, finds preliminary tracks on the convertor-tracker, analyzes energy deposition in position-sensitive calorimeter CC by using stored on the level 1 stage data, and makes a final decision about transmitting or not registered information to the ground segment of scientific complex.

The collected event information is compressed, structured, combined with the service data by means of the control and interface module, based on the 100 MHz Milandr 1986VE8T 32-bit RISC-microcontroller and sent to the scientific data acquisition system SDAS for temporary storing in the non-volatile mass memory or for direct transferring into the high-speed scientific radio line. The power and telemetry module represents interface with the pulse commands and power supply system PCPSS of gamma-telescope, providing secondary power supply for the trigger signals formation system, the one-time pulse radio commands receiving and transmission of the telemetry parameters to the satellite onboard telemetry system.

IV. THE BEAM STUDIES OF THE PROTOTYPES

The primary beam of the synchrotron C-25P «PAKHRA» of Lebedev Physical Institute consists of 300-850 MeV electrons with particle intensity up to $2\cdot10^{12}$ s^{-1} and repetition frequency of 50 Hz. Bremsstrahlung photon beam is formed by interaction of accelerated electrons with an internal tungsten target with a thickness of 0.22X_0 placed inside the accelerator vacuum chamber. This beam is used to create a secondary positron beam by e± pair production on copper converter with 0.1-5 mm thickness. Secondary positrons with particle momentum of 300 MeV/c and intensity up to ~100 $s^{-1}cm^{-2}$ are selected using dipole magnet. The studied detector was installed on a remote controlling platform which allows horizontally and vertically moves the detector with respect to the beam position in the range of ±40 cm with accuracy of 1 mm. A beam monitor (Fig. 5) for secondary positrons selection installed behind 10 mm diameter lead collimator consists of four 15×15×3 mm^3 polystyrene (IHEP_SC-301) scintillation counters *M1-M4* wrapped with aluminized mylar film and coupled with silicon grease BC-630 from one side with two 3×3 mm^2 SensL MicroSB-30035-X13 SiPMs connected in parallel. These counters are installed on high-precision horizontal and vertical slide positioners for finely polishing of monitor counters with respect to positron beam. The signals from each SiPM pair are amplified by two-stage broad-band shaper-amplifiers with pole-zero cancellation circuits based on fast AD8000 operational amplifiers, produced output signals with rise-time of ~3.5 ns and width of T_{90}~10 ns. The amplified and shaped signals are fed into four-channel CFD (ORTEC Model 935). The CFD outputs are connected through the set of delay lines (CAEN Model N108) to coincidence logic unit (CAEN Model N405) which generate the reference start time pulse $M = M1 \wedge M2 \wedge M3 \wedge M4$ for the positrons registration. Two quad scalers are used for counting *M1-M4* and *M* pulses. The beam monitor time resolution was measured as 104±2 ps.

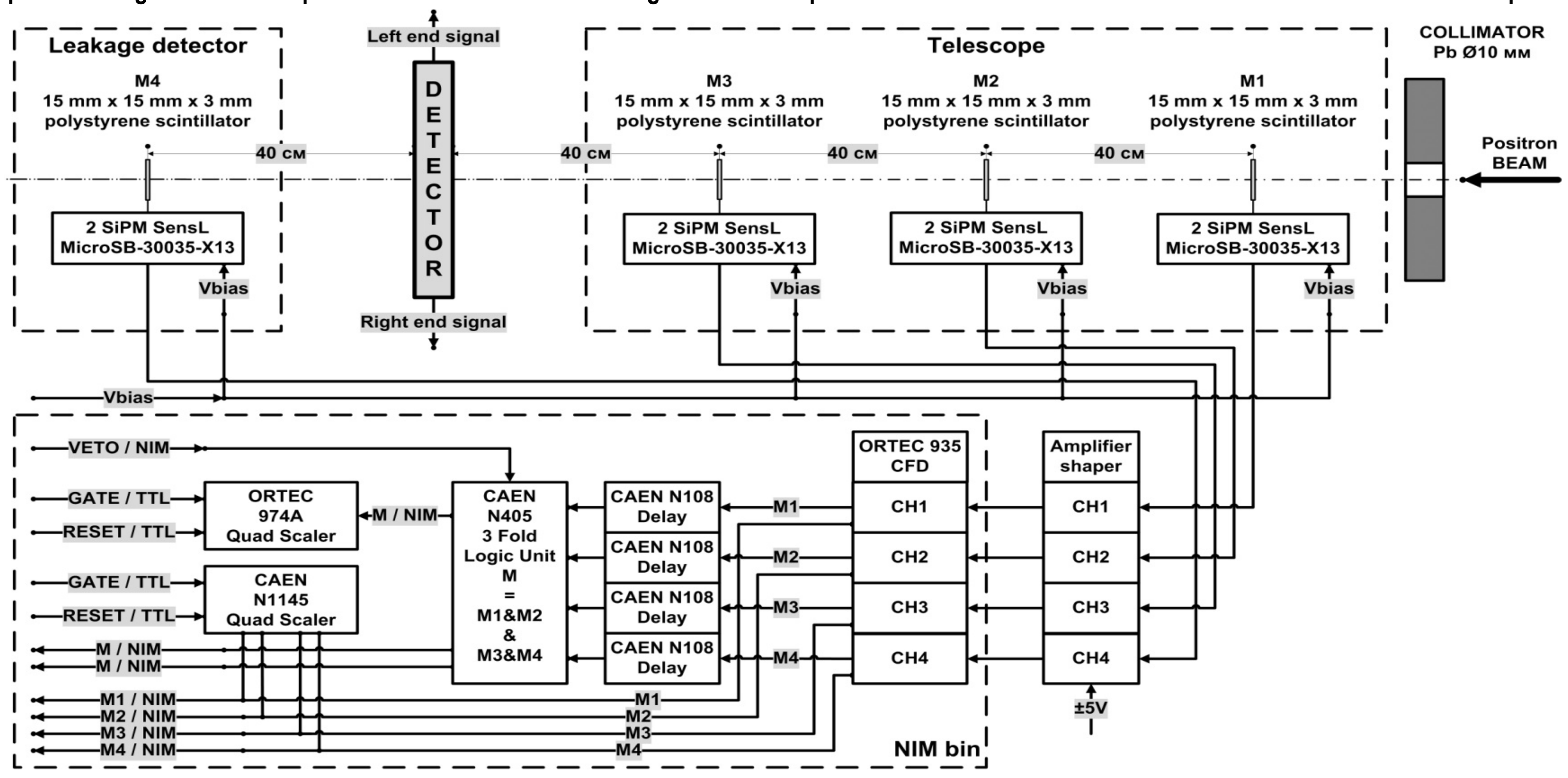

Fig. 5. The experimental setup, including beam monitor. The dash-dotted line represents the beam line

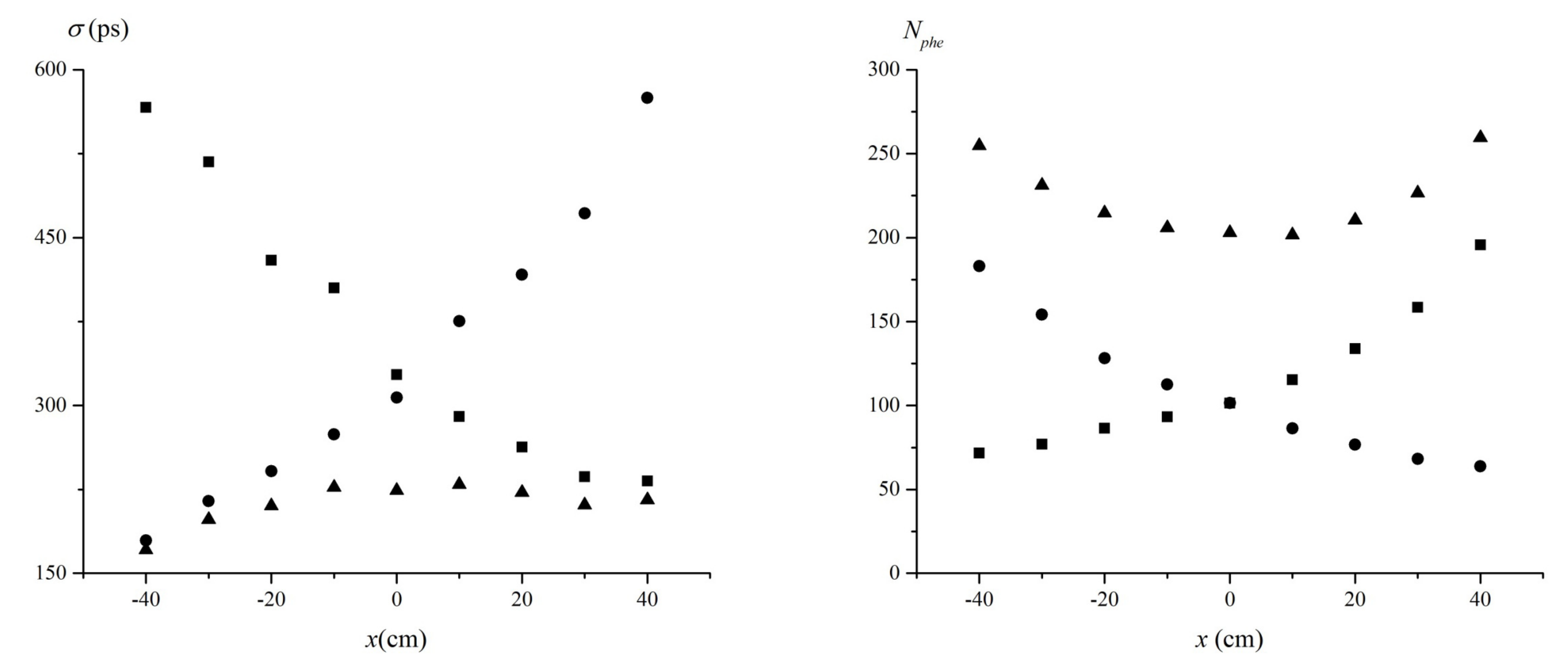

Fig. 6. The time resolution – left figure, and average total number of photoelectrons per incident positron – right figure, as a function of positron beam impact position relative to the detector centre. Squares are data for the left strip end, circles – for the right end, triangles – for left and right ends sum. Error bars are smaller than the points on the plot

To characterize the prototype detector, the measurements of the following parameters were carried out: attenuation length, photostatistics, effective light velocity and intrinsic time resolution. The tested detector presents two strips of BC-408 scintillator with dimensions of 1280×100×10 mm^3, wrapped with Tyvek reflective material and placed into 1.5 mm thick aluminum cover. At the middle of each strip the FC-type fiber optic adapters are situated for optic cables connection from laser monitoring system. Each strip is viewed at opposite shortest ends by two photo sensor blocks which consist of four 6×6 mm^2 SiPM of the type SensL MicroFC-60035-SMT connected in parallel and front-end electronics. Only "slow" SiPM outputs were used in this prototype variant. The amplified and shaped signals from both sides of the detector are split into two paths: the first signal goes to the LeCroy WaveRunner 6Zi digital oscilloscope directly, for amplitude and charge analysis, and the second signal goes through CFD ORTEC Model 935 for timing analysis. Threshold of CFD was set at about 25% of the most probable energy deposited by minimum-ionizing particles crossing the whole thickness of scintillator (10 mm). The bias voltage for SiPMs was set at 29.5 V level (~5 V above SiPM breakdown voltage). The intrinsic time resolution of the prototype detector is found to be not worse than 230 ps which is enough for reliable suppression of the backsplash events (the self-veto of the ACS by products of the high energy photon interactions in the instrument's calorimeter) and the upward/downward particles selection. The measured effective scintillation light velocity is 13.1±0.1 cm·ns^{-1}. The measured attenuation length is 91±1 cm. For further improvement of the prototype parameters the number of SiPM at each detector end was increased up to 8 instead of currently used 4 SiPM and the new type of silicon photomultipliers SensL MicroFJ-60035-TSV with enhanced photon detection efficiency and lower dark count rate were employed for obtaining the better photoelectron statistics and time resolution. The "fast" SiPM outputs were used as a source of signal for timing measurements too.

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