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The application of digital techniques for spectrometric apparatus in space research

A.I. Arkhangelskiy*, A.S. Glyanenko, I.V. Arkhangelskaja

National Research Nuclear University MEPhI (Moscow Engineering Physics Institute), Kashirskoe highway 31, Moscow, 115409, Russia

Abstract

The application of digital methods for spectrometric observations by example of space projects executing at MEPhI is described. Some aspects of using schematic solutions and electronic component base are discussed. The example of realisation of space born spectrometer is presented.

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Keywords: ASIC; digital pulse processing; digital techniques; FPGA; gamma-ray spectrometer; PLIS; pulse shape discrimination; space research

1. Introduction

Modern devices for space research are impossible to imagine without devices that don`t use the digital data processing methods and specialized or standard interfaces and computing facilities. There are several approaches to implement this trend: the use of standard devices and components, development and use of application-specific integrated circuit (ASIC) and the creation of specialized units based on programmable logic integrated schemes (PLIS). Obviously, the use of standard components in comparison with PLIS and ASIC, has major flaws - notably the large size, weight and power consumption. In addition, it looks problematic the requirements of reliability (due to excess of functions and/or hardware interfaces) and radiation hardness or tolerance (RH/RT).

PLIS has some significant advantages versus ASIC: there is no time and cost in production of ready software implementation of the node; allows quick adaptation of the design to the requirements of the task; is usually cheaper in small and medium batches. There are two main classes of PLIS: complex programmable logic device (CPLD) and

* Corresponding author. Tel.: +7-495-788-56-99.
*E-mail address:*AIArkhangelskij@mephi.ru

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field-programmable gate array (FPGA). Leading PLIS vendors for space applications are Microsemi Corporation and Xilinx. Xilinx is a world leader in RAM based technology (multiple-programmable) whereas Microsemi Corporation in flash based technology (multiple-programmable) and antifuse technology (once programmable).

Unlike all other radiation-tolerant, space-flight PLIS, which use antifuse or RAM programming technology, devices in the RT Microsemi families use flash cells to store configuration information. Positive or negative charge stored on floating-gate transistors is used to hold pass transistors in either the on or off states, thereby opening or closing connections between routing tracks and logic resources. The use of flash-based interconnects presents some unique opportunities and advantages to designers of space-flight electronic hardware:

- The flash cells are reprogrammable. This allows the designer to change the design of the PLIS without removing the PLIS from the board, making prototyping easier. It also allows last-minute design change and code update to provide maximum design flexibility;
- The flash cells are nonvolatile. This means that flash-based PLIS are standalone devices, which do not require the provision of external code-storage devices, unlike RAM-based PLIS. This minimizes the board space used, and has an associated saving in mass;
- Some FPGA are operating almost at the instant of power-up, which is another advantage of the nonvolatility of the flash programming cells. There is no boot sequence required, as in RAM-based PLIS which need to download their configuration code from an external storage device;
- The flash cells do not exhibit single-event upsets in the presence of heavy ion radiation. Therefore, no triple-chip redundancy to mitigate configuration upsets is required, unlike RAM-based PLIS.

For the former projects, we used ProASIC+ Microsemi (Actel) flash-based family with maximum capacity up to 1500000 system gates. New generation ProASIC3 family with maximum capacity up to 3000000 system gates is available now.

2. Structure of electronic system

For CORONAS-PHOTON project [1] (satellite was launched from the Plesetsk Cosmodrome on January 30, 2009, to a low circular near-Earth orbit with altitude of ~550 km and inclination ~82.5°) at MEPhI were developed and manufactured following devices: NATALYA-2M high-energy gamma-radiation spectrometer [2], X-ray polarimeter PENGUIN-M [3], multi-channel monitor of ultraviolet radiation PHOKA [4] and fast X-rays Monitor BRM [5]. These devices were different in their internal structure, information flows and construction of their detectors. However, they have many common features – the need to accumulate information, synchronize their work, correlate the data to the reference onboard time, count the number of pulses in fixed time intervals (intensity) etc. To build these devices the cluster structure chosen, i.e. a use for all devices standardized parts, common for all devices and specialized units that implement special functions.

The electronics of the scientific instruments based on Modular Electronic System (MES) developed at MEPhI comprising set of crates. Each crate contains identical for all crates hardware units collection: crate backplane with a set of system buses; power supply module and control module. Each crate backplane is being subdivided in several clusters consists of special unified System Controller (SC) module to control the operation of each cluster and set of functional modules (amplifiers, counters, base line restorers, ADC, DAC etc.), providing interface to scientific measuring systems (SMS), connected to the system bus. The functions of the System Controller module are:

- the data acquisition from the functional module (modules) in a cluster;
- preprocessing and packing of the obtained data with reference time recording;
- the data transfer to Scientific Data Acquisition System (SDAS) [6];
- receiving of the control code words (CCW – 16-bit program commands for control of SMS operation) and 32-bit onboard time code (OTC) from SDAS and transfer of control actions to the SMS units.

In CORONAS-PHOTON project were used several configurations of crates: from one to three clusters in 12 or 17 - positional crates for different SMS. Fig. 1 demonstrates an example of two-cluster crate functional diagram.

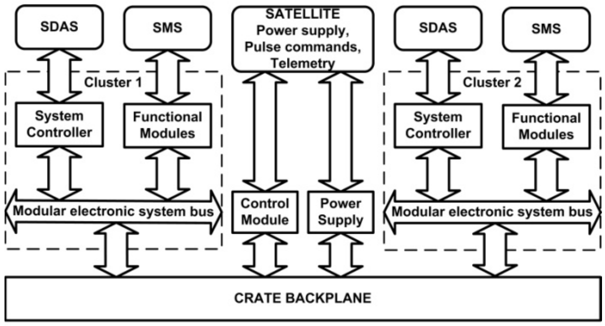

Fig. 1. Functional diagram of two-cluster configuration.

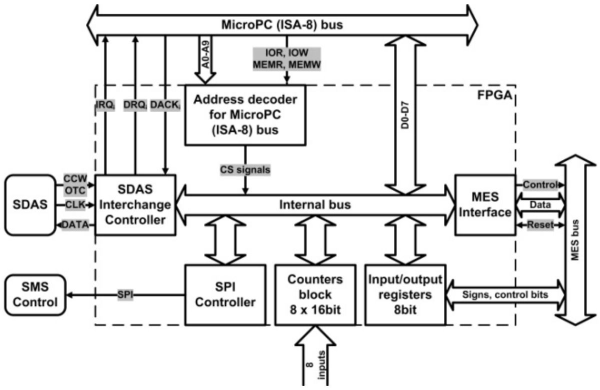

Fig. 2. Functional diagram of system controller module.

The computational core of the System Controller in this project is a single board industrial processor module Octagon Systems 4020. It is based on the 25 MHz Intel 386EX processor. This module distinctive features consist of: DOS 6.22 in ROM; three serial ports (including one RS-485 port); multifunctional LPT1 parallel port; watchdog timer; 1 MB of DRAM; 1 socket for optional 512kB of flash memory with internal programmer unit or 1 MB of standard EPROM; 128kB of SRAM; keyboard and speaker ports; 3 solid–state disks; 8-bit ISA interface (MicroPC and PC-104 bus); 48 lines of digital I/O; 8 lines of high current drive I/O; 3 counter/timer channels; opto-isolated reset; 2 opto-isolated interrupts.

All special functions of SC were realizing in FPGA APA600 from ProASIC+ Microsemi (Actel) flash-based family with capacity of 600K system gates, installed on the printed circuit board (PCB) in MES format. Functional diagram of SC is presented at Fig. 2. The main components of SC are six groups of registers combined by their functionality. The information exchange with the microcontroller implemented as a program mode and/or via DMA channels. Address decoder realizes access for all SC registers in accordance with MicroPC (ISA-8) protocol. For data transfer to SDAS and receiving of the control code words and onboard time code from it the SDAS interchange controller is intended. It consists of three register groups including special control registers for each group. SDAS interchange controller generates one of three interrupt requests IRQ_i in accordance with the type of operation (output the data to SDAS, input of CCW or OTC) after its completing.

First group realizes the data transfer to SDAS through 8-bit output data register, accessible in both program mode and via DMA channel. To transfer data block on SDAS first byte of the packet data writes in this register in program mode, then the program command writes in control register for beginning transmission of the data packet. Device using synchronization signals (CLK) from SDAS to converts the data into serial code for transfer to SDAS. The data are automatically updated in output data register via DMA channel.

Second group realizes the receiving of OTC from SDAS. OTC represents the 32-bit serial code accompanied with synchronous pulses (CLK). The period of OTC arriving is 1 ms. For receiving of OTC a 32-bit data register is used; for operation controlling - 8-bit control register. The data are transferred via DMA channel.

Third group realizes receiving from SDAS of control code words (program commands). The control code word represents 16-bit serial code, transmitted with synchronous pulses (CLK) in pauses of OTC transmitting. Control code word arrival is automatically identified and corresponding interrupt request is generated. The control code word arrived is written in 16-bit register accessible in program mode.

Control over hardware that are located in or outside the electronics crate is carried out by means of using of the serial control interface SPI. The special SPI-controller is intended for this purpose. It consists of 16-bit data register, 3-bit register of SPI channel number and 8-bit control register. Access to this group of registers is implemented by program mode.

The block of counters is intended to measure the count rate of pulses in various channels of SMS. It consists of eight 16-bit binary counters-registers. Their management is carried out through a special 8-bit control register. Data are accessible in program mode.

Group of input/output registers allows the reception of 8-bit digital data. It can generate an interrupt request. The data is accessible in program mode.

3. Spectrometric system

In this section, we demonstrate the application of digital techniques by example of NATALYA-2M gamma-ray high-energy radiation spectrometer. The spectra and temporal profiles of the gamma quanta count rates are measured in four subranges: R (0.2–2 MeV), L (1–18 MeV), M (7–250 MeV), and H (50–1600 MeV). Observation of solar-origin neutrons with energies of ~20–300 MeV was the scientific task for this apparatus too.

The discrimination between neutron and γ-ray events is performed using the selection of events by the shape of the light pulse emitted by a scintillation detector based on the dependence of the ratio of the light-output components intensities with different fluorescence decay times on the average ionization density produced by charged particles in the CsI(Tl) detector (pulse shape discrimination - PSD method) [7]. When neutrons with energies of ~5-1000 MeV interact with Cs and I nuclei, highly ionizing particles are produced: hydrogen and helium isotopes with average energies of ~10 and ~15-20 MeV, respectively. Because of γ-quanta interactions, electrons and positrons are generated, for which the specific ionization produced in the substance at energies of several hundred keV and higher is close to its minimum. A scintillation flash in CsI(Tl) consists of two main fluorescence components with decay time $\tau_{fast}\approx 0.5$-$0.7\mu s$ and $\tau_{slow}\approx 7\mu s$, and the ratio of the slow component intensity Q_{slow} to the fast component intensity Q_{fast} depends on the specific ionization of the interacting particles. This ratio changes from ~1 for relativistic particles down to ~0.25 for α-particles with energies of ~10 MeV. The method employed is based on the integration of the signal from detector for two different time intervals: T_1 lasts from 0-0.2 μs after the pulse leading edge to ~10 μs (in which the total charge $Q_{tot}= Q_{slow}+ Q_{fast}$ is collected), and T_2 lasts from 1-1.2 μs after the pulse leading edge to ~10 μs (in which the slow fluorescence component Q_{slow} is almost full collected) [8-10]. Values of Q_{tot} and Q_{slow} for each registered event are numerically calculated and appropriate spectra are accumulated.

Gamma radiation is registered using a spectrometer (SE) based on 16 inorganic single crystals CsI(Tl) with a total area of 32×38 cm^2 and total thickness of 18 cm comprising two sections (SE-1 and SE-2) positioned one above other. Each section consists of two planes, consisting of four CsI(Tl) crystals each viewed by two photomultipliers from their butt-ends. The events related to the background of charged particles excluded by polystyrene scintillation detectors operated in the mode of anticoincidence with the spectrometer (a “dome” AK covering the assemblage from the top and a flat detector AC from the bottom of SE-1). Fig. 3 shows the block diagram of NATALYA-2M electronics.The system of data collection and processing divided into six clusters. Each of them includes the microprocessor system controller (SC) and a set of process execution functional modules. Depending on the energy range and the function of the cluster it can includes the base line restorers module (BVNU) and either two-channel amplitude-digital converter (ADCM) or master trigger system block (BOSM) or two-channel neutron/gamma separation module (NGRM). The device combined in two of three-cluster MES crates (SOVI-3 and SOVI-5).

All signals from detectors arrive to the base line restorers. For the low energy range, signals from each four CsI(Tl) crystals of upper SE-1 plane (R1-R4 signals) are used separately. All analogue signals for other energy ranges (L, M, H) and for neutron channel (N), as well as all anticoincidence and trigger signals for all energy ranges are formed in BOSM module by the set of program controlled preamplifiers, analogue and digital comparators, multiplexers and adders. The cores of BOSM, ADCM and NGRM modules are FPGA APA600 from ProASIC+ Microsemi (Actel) flash-based family with capacity of 600K system gates, installed on the PCB in MES format.

For fine detectors control there were used a set of SPI control channels (from all clusters of NATALYA-2M electronic system). An additional feature, transmission of control code words, enables one to form adaptive digital control of instruments parameters, thereby considerably expanding the potential of “thin” adjustment of instruments (as compared, for example, with the control of instruments characteristics by means of program pulse control commands). Each cluster forms their own output data formats for SDAS. All data synchronized with the OTC from SDAS. The ADCM module (NGRM module is fully identical by construction but working in special mode of n/γ separation by means of input signals PSD analysis), developed at MEPhI, represents a two-channel digital pulse processor for spectrometry of charged particles, neutrons, X-ray and γ-ray in a wide energy band. It is intended for processing of pulses with duration of 250-10000 ns arrive from semiconductor and scintillation detectors. All special functions of ADCM realized in FPGA Actel APA600. Functional diagram of ADCM is presented at Fig. 4.

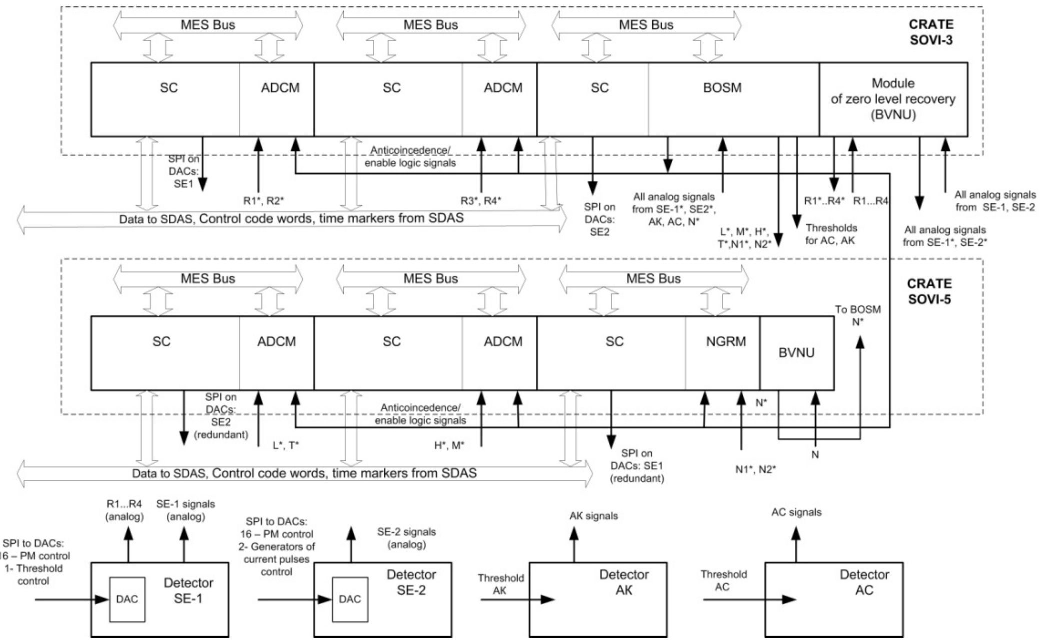

Fig.3. Block diagram of NATALYA-2M electronics (output signals from BVNU are marked by symbol *).

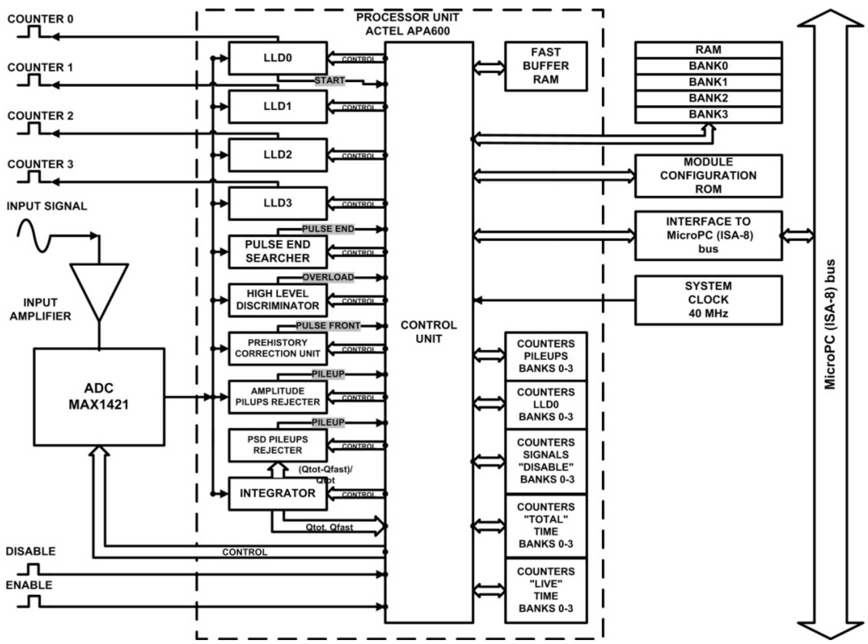

Fig.4. Functional diagram of ADCM module channel (only main counters are shown). Output signals COUNTER 0-3 arrive to external counters.

The functionality of ADCM based on continuous sampling of input signal by 12-bit ADC MAX1421 with discreteness of 25 ns and subsequent real time processing of samples sequence by special purpose processor based on FPGA APA600. Data processing of pulses takes into account “prehistory” of pulse – up to 1024 samples (number is set by means of programming) before low-level discriminator trigger moment, stored in “fast” internal

RAM of the module. Spectral information is accumulated in one or two pairs (depending of operating regime) RAM banks with total capacity of 64 kByte/channel. At each moment, the information is stored in one bank of pair. After finishing of spectrum accumulation in one bank of pair, the processor sets out the interrupt request on the system bus and system controller SC initiates the transfer of spectral information from this bank via DMA channel. In this time, the spectrum accumulation is continued in the second bank of pair. This algorithm guarantees the lossless uninterrupted measurements. The main parameters of ADCM module are presented in Table 1.

Table 1. The main parameters of ADCM module.

Parameter	Value
Number of Channels	2 (Differential or Unipolar)
Differential/Unipolar Input Range	±5 V/0 ÷ +5V or -5V ÷ 0
Input Resistance	10 kΩ
Sampling Frequency	40 Msps
Bandwidth	400 MHz
Resolution	12 bit
Effective Number of Bits	10.7
Differential Nonlinearity	±0.5 LSB
Integral Nonlinearity	±0.5 LSB
Module Spectra RAM	64 kB/channel
Module “FAST” Prehistory Storage RAM	2 kB/channel
Time of One Pulse Processing	≤1 mks
Input Amplifier Amplification Coefficient	0.5, 1, 2, 5, 10 (programmable switching)
Number of Spectral Channels	256, 512, 1024, 2048, 4096 (programmable)
Spectral Channels Capacity	8, 16, 24, 32 bit (programmable)
Number of Programmable Counters	20/channel (16,24 and 32 bit)
Pileups Rejection	Amplitude and PSD (programmable)
Overloads Rejection	Programmable
Time of Spectra Accumulation	100 mks – 100 sec (programmable, discreteness 25 ns)
Time of Pulse Integration (Q_{tot}, Q_{fast})	0-100 mks (programmable, discreteness 25 ns)
Operating Temperature Range	-40°C to +85°C
Power Consumption	≤1 W

Each ADCM channel can be independently programming for operating in one of three regimes:

- Regime 1: “OSCILLOSCOPE” - continuously accumulation of digitized input pulses. All 2048 samples per pulse with discreteness of 25 ns from low-level discriminator trigger moment, taken into account “prehistory” are stored. This regime is intended for testing. In this regime one pair of RAM banks is used;
- Regime 2: “SPECTROMETER” - continuously accumulation of Q_{tot} spectra and one of the following additional spectra – either signal amplitude A_{max} spectra or Q_{fast} spectra or PSD=(Q_{tot} - Q_{fast})/Q_{tot} spectra for fixed time interval or fixed number of events per spectrum. The mode of “manual” (by means of START and STOP command) control of spectra measurements is available too. In this regime two pairs of RAM banks is used;
- Regime 3: “SINGLE EVENTS RECORDER” - continuously accumulation of information for each pulse registered. For each pulse two measured values is stored: Q_{tot} and one of the following additional values – either A_{max} or Q_{fast} or PSD=(Q_{tot} - Q_{fast})/Q_{tot} for fixed time interval or fixed number of events per RAM bank. The mode of “manual” (by means of START and STOP command) control of spectra measurements is available too. In this regime two pairs of RAM banks is used.

Each ADCM channel consists of:

- programming controlled input amplifier;
- 12-bit ADC;
- special purpose processor that implements:
  - “prehistory” storage;
  - finding of the beginning and the end of current pulse;
  - discrimination and digital integration of input signals (values Q_{tot}, Q_{fast} are calculated) with correction of pulse front duration by “prehistory”;
  - input signals PSD analysis;
  - pileups and overloads rejection by amplitude and/or PSD analysis;
  - timing of spectra accumulation and filling of RAM banks BANK 0-3 by spectral or single events information;
  - counting of “total” and “live” time of spectra accumulation, number of pileups, overloads, low-level discriminators LLD 0-3 triggers and external control signals “ENABLE” and “DISABLE” that enables and disables input pulses processing;
- RAM for spectra accumulation (64 kB/channel);
- ROM for module configuration storing (3 x 128 kB - triple-chip redundancy);
- MicroPC (ISA-8) bus interface;
- 40 MHz system clock generator.

The most part of ADCM parameters can be reprogramming in real time through system bus by writing 8, 16, 24 or 32-bit control codes into appropriate internal registers of the module (36 registers per channel). At that, settings of thresholds of discriminators, pileups and overloads rejecters, input signals integration time intervals, spectra accumulation time etc. can be perform. Output of spectral and service information, counters content implemented through the system bus MicroPC (ISA-8) via DMA channel.

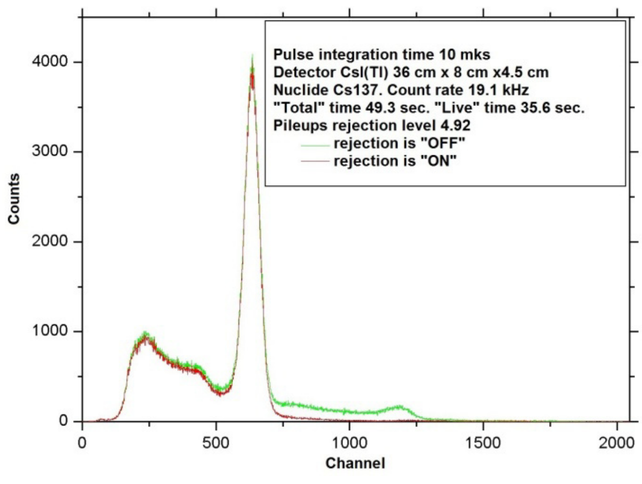

Fig.5. Example of ^{137}Cs spectrum, measured by ADCM module in Regime 2 with and without amplitude pileups rejection.

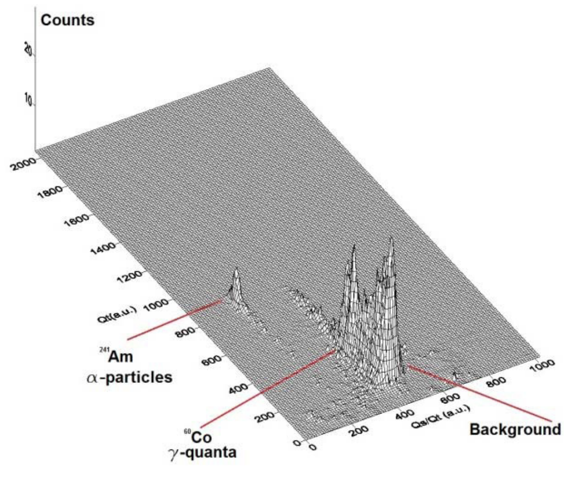

Fig. 6. Example of ^{241}Am+^{60}Co 3D Qslow/Qtot versus Qtot distribution, measured by ADCM module in Regime 3.

Fig. 5 and Fig. 6 demonstrate the examples of real time accumulated spectra, measured by single cluster of NATALYA-2M apparatus in different regimes. Spectrum on Fig. 5 was measured in spectrometric regime 2 with and without amplitude pileups rejection. Three-dimensional distribution on Fig. 6 presents an example of n/γ separation mode by input signals PSD analysis. Peaks corresponding to γ-quanta from ^{60}Co and α-particles from ^{241}Am are clearly seen.

For estimation of particle`s discrimination quality the figure of merit M defined as:

$$M=(A_{\alpha} - A_{\gamma})/0.5*(W_{\alpha} + W_{\gamma}) \quad (1)$$

where A_i and W_i – height and FWHM of peaks corresponding to different particles is usually used. For data presented at Fig. 6, value of M=3.26. For reliable particle identification the figure of merit value, have to be ≥ 3.

At present, the new space project GAMMA-400 [11] for measurements of characteristics of cosmic γ-emission in the energy band from ~20 MeV up to several TeV, electrons/positrons fluxes from ~1 GeV up to ~10 TeV and cosmic-ray nuclei fluxes with energies up to ~10^{15} eV is developing at MEPhI. The core of this project is the γ-telescope [12] of new generation for a broad range of scientific goals, such as search for signatures of dark matter, studies of Galactic and extragalactic γ-ray discrete sources and diffuse emission, gamma-ray bursts and solar flares. All the mentioned above principles and experience are used during design stage of this experiment with employment of up to date methods and electronic components base. In particular, the implementation of the next generation ProASIC3 Microsemi flash-based family, new system and data transferring buses – PCI-Express, Serial RapidIO, SpaceWire and up to date Russian made high-reliable and radiation-tolerant electronic component base [13].

4. Conclusion

The application of digital techniques in spectrometric systems allows drastically reduce time and cost of the development of newly designed apparatus and sufficiently simplify the adaptation of currently exploiting devices to changes of the scientific task requirements. The advantages of digital system for gamma-ray spectroscopy in comparison with classical analog system are reflected in the possibilities of complex algorithms implementation and simple modification of algorithms used for signal processing. In this way, the highest quality of measurements is achieved at both low and high counting rates using various radiation detectors. Other advantages of digital spectrometers as a spectrum real time processing, simple storage, analysis and presentation of results are evident.

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