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MULTITASKING MEASURING SYSTEM OF THE BACKING CALORIMETER FOR THE ZEUS EXPERIMENT AT THE HERA ACCELERATOR

The paper is devoted to the subject of application of a complex measurement system in HEP experiments. The measurement system is electronic, FPGA-based, multi-channel and distributed. The application is the Backing Calorimeter (BAC) located in an international ZEUS experiment at the HERA ring accelerator of counter-propagating particles, DESY Hamburg. The hadron-electron ring accelerator HERA is concisely characterized in the introductory part of the paper. Actually, the HERA accelerates electrons or positrons and protons. The particle collision takes place in detectors. One of them is ZEUS. The structure of ZEUS is presented with emphasis on the metrological requirements. These requirements are to obtain a good space and time resolution of measurements for numerable physical values. The measurements are taken from images of particle collisions. The measurement subsystems of the BAC detector are described. The BAC is equipped with over 40000 nondependent channels for position measurement, over 2000 channels for energy measurement. It possesses a local functional block of position and energy trigger, as well as modules for data acquisition. The functional structure of the system is presented in the context of task requirement superimposed by the ZEUS. These requirements are: global triggering system of the whole experiment, data acquisition and tests. The hardware solutions are included for particular parts of the measurement systems. Examples are presented of measurement results obtained from the ZEUS experiment. An original author's idea is debated to integrate the functional layers of the complex measurement system with a superimposed diagnostic layer. The aim is to have operator's access to the current on-line quality assessment of TRIDAQ measurement system for ZEUS. This includes the ability to detect, localize and prevent randomly appearing irregularities in system software and hardware.

Keywords: High Energy Physics, particle detector, data acquisition, trigger, metrological systems, data quality monitoring, FPGA, AHDL, Altera, HEP experiment

1. INTRODUCTION

A number of international long-lasting research programs are carried out on the structure of matter using large accelerators. A number of High Energy Physics (HEP) experiments are planned within these global programs [1]. In particular, new elementary particles are looked for [2]. The experimental results are compared with theoretical

research. These comparisons enable more and more precise measurements of known elementary interactions in matter. The research in HEP stimulates evidently the measurement science and technology. This area is a place of birth for new measurement methods. Following generations of HEP experiments require higher measurement accuracy, (space, time, signal), faster and more precise measurement signal processing, more measurement data acquisition. Contemporary large HEP experiments use over 100 mil of measurement channels. They register phenomena at the particle level every several tens of ns. To detect particles, a few tens of types of different chambers and calorimeters are used. The chambers cooperate with multi-channel, distributed and synchronous electronic measurement systems. The structure and functionalities of the measurement systems are strictly fitted to the sensory layers. The sensory layer is built of smartly distributed particle chambers, covering the whole space around the interaction point (vertex). The measurement system is also fitted to the specialized measurement tasks which have to be performed in a particular HEP experiment [3].

The paper presents the multi-tasking, multichannel and distributed measurement system for the Backing Calorimeter (BAC), in the ZEUS experiment at the HERA accelerator. The system is equipped with over 40000 measurement channels. Its functional layer is closely connected with the requirements of the experiment. In the introductory part of the paper there are presented the aims of the ZEUS experiment, research methodology, and organization of the measurement procedures. The susceptibility of such a big and distributed measurement system, which the BAC detector is, to software or hardware irregularities is comparatively large. The paper presents an idea, originally proposed by the author, to integrate functional layers with a diagnostic layer of novel construction [4]. The aim of the diagnostic layer is to secure the required reliability of the system by obtaining high quality data. The final aim is a continuous, uninterrupted (with time availability over 90%) participation of the BAC detector in the ZEUS experiment. There were debated examples of practical diagnostic layer implementations, introduced by the author. The original results of system work quality were quoted.

The research method on the internal structure of hadrons, and the interactions between partons relies on induced collision with other elementary particles (atoms or nucleons). Therefore the progress in particle physics is driven by construction of more and more powerful accelerators. One of such accelerators is HERA colliding electrons (or positrons) and protons [5]. The square of the momentum transfer Q^2 , which is carried by the intermediate bosons or the virtual photon [6], is the value describing the lepton-hadron interaction. It is given by equation (1):

$$Q^2 = (E - E')^2 - (\vec{p} - \vec{p}')^2, \quad (1)$$

where E , p is energy and momentum before the interaction and E' , p' after the interaction.

The primary spatial resolution $\Delta = \hbar/\sqrt{Q^2}$, determined by the Heisenberg rule, defines the resolution of the lepton-hadron interaction:

$$\Delta = \frac{\hbar}{\sqrt{(E - E')^2 - (\vec{p} - \vec{p}')^2}}. \quad (2)$$

The value of Q^2 , reachable in the collisions, is proportional to the E_{CM} of the accelerator. In the case of HERA, electron (or positron) energy is 30 GeV, whereas the proton energy is 920 GeV. The E_{CM} for two colliding particles of kinetic energies E_A and E_B (neglecting their rest mass) is:

$$E_{CM} \cong 2 \sqrt{E_A E_B}. \quad (3)$$

The HERA machine, with the $E_{CM} = 314$ GeV, increased this value an order of magnitude in comparison with the previous generation of the accelerators. Due to the high value of E_{CM} the transfer of Q^2 is 40000 GeV^2 [7]. The space resolution is 10^{-18} m, or three orders of magnitude smaller than the proton radius. The internal structure of nucleons can be effectively studied with a machine of these parameters.

All experiments use multilayer detectors built around the center of interaction. Particular detectors are specialized to the kind of expected measurements and observations of the collisions. The collisions lead to the new stationary states with new particles, among them many are transient. Full description of the final state includes characteristics of all involved particles – in the form of their identification and vectors of momentum [3]. The measurements and registrations are done by specialized electronic apparatus. The apparatus works with particle detectors, global triggering systems and data acquisition. The measurements and data registration in HEP experiments require multistage data selection and triggering [8]. This paper presents an electronic triggering and data acquisition (TRIDAQ) measurement system for the Backing Calorimeter (BAC), which was integrated with global systems of the ZEUS experiment¹.

2. MEASURING PROCESSES IN BAC DETECTOR

The Backing Calorimeter (BAC) is a large multifunctional detector. Its basic function is to measure high energy hadron cascades flowing from the central uranium calorimeter, and to supplement the identification and determine the direction of movement of the muons [9]. The BAC supplements the energy balance of the measured e-p collisions. It may additionally work as a VETO type calorimeter, or check if the whole energy was registered by the basic calorimeter. It may also efficiently work as VETO detector for parasitic phenomena like detector of the cosmic muon streams [10].

The BAC detector has 5200 proportional chambers with the aggregated surface of 3500 m^2 . It is the largest volume and independent component of the ZEUS spectrometer

¹ Because of the confined volume of the paper the description of ZEUS detector is not included here [9].

[9]. Its structure is presented in Fig. 1. The BAC consists of four parts: 2 covers (FORECAP and REARCAP), the central area (BARREL) and the lower area BOTTOM (not visible in Fig. 1). It has a multilayer structure. It consists of several detector and iron (absorbing) layers positioned one over another. The energy measurement adds all electrical signals inside the calorimetric pad towers (1692) and wire towers (178). The position measurement uses 40000 wire channels [11].

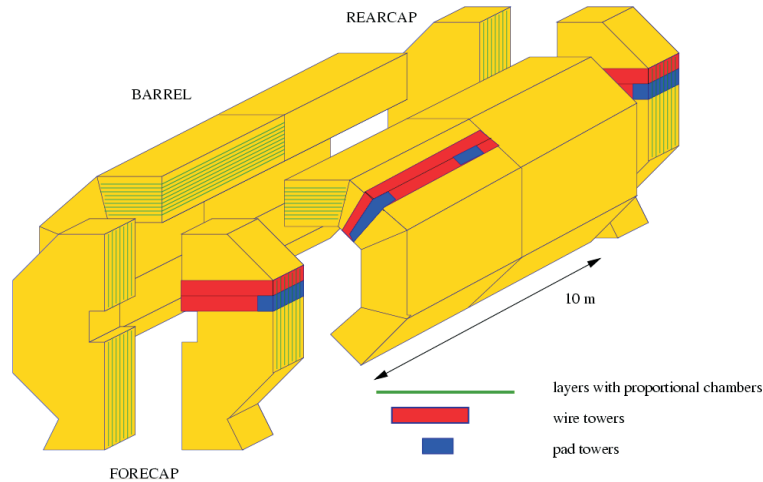


Fig. 1. Structure of BAC detector.

The basic task of the Backing Calorimeter is measurement of energy flow from the central ZEUS spectrometer every 96ns (for each bunch crossing). The range of energy measurement was optimized for low energy band of 2–20 GeV at the energy resolution of $\Delta E/E = 100\%/\sqrt{E (GeV)}$ [11]. The passage of a particle generates an electrical pulse of $\sim 20\text{ns}$ at the output of the chamber. The pulse represents charge which is proportional to the energy of the particle. The BAC detector enhances the muon identification process and determination of their directions. The detection properties of cathode layers and anode wires were used for this purpose. This process is enabled by geometric division of the detector to pad, strip and wire towers (Fig. 1). These measurement tasks are realized by several parallel and correlated measurement processes. The processes were grouped in two separate categories, because of different character of generated results and further processing:

1. Measurement processes resulting in data registration synchronously with the first level trigger of ZEUS [9, 11] They concern:
 - Position identification using wires (P_{WI}), each of 40000 wires is used as individual passage detector of a minimally ionizing particle. The space resolution perpendicularly to the wire is 1 cm and longitudinally 2–5 m.

- Energy from the calorimetric pad tower (E_{PT}), which is calculated from the accumulated cathode charge. A typical pad tower is built of three or four cathode planes (dimensions $0.5 \times 0.5 \times 1$ m) in the cross-section of all BAC layers. The pad towers provide the best energy resolution in the BAC detector. Their number is 1962.
 - Energy from the calorimetric wire tower (E_{WT}), which is determined from the accumulated charge from anode wires. All wires of three or four adjacent chambers in the cross-section of BAC detector are building a typical wire tower (dimensions $0.5 \times 1 \times 5$ m). The number of wire towers is 178. The wire towers do not provide a good space resolution in comparison with the pad towers (P_{WI}). The measurement results are used for calculation of the local trigger decision of BAC.
 - Energy from calorimetric strip tower (E_{ST}), which is determined from the accumulated charge from cathode planes formed into skew towers. The skew polar angle is constant against the interaction point. Their number is 133. The strip towers are used for calculation of the local trigger for BAC.
2. Measurement processes resulting in generation of the local trigger for BAC for each consecutive e-p interaction. They embrace [12]:
- Total energy in detector (E_S) determined from measurement of partial energies from wire towers (E_{WT}) or strip towers (E_{ST}).
 - Total transverse energy in detector (E_{TS}) determined from measurement of partial energies from wire towers (E_{WT}).
 - The biggest two energy deposits (E_{FD} , E_{SD}) chosen appropriately from partial energy measurements from wire towers (E_{WT}) or from strip towers (E_{ST}) together with information about topology.
 - Number and type of discovered muons (M_{CT}) obtained from position readout (P_{WI}) and partial energy measurements from wire towers (E_{WT}).

All of the above major measurement processes and a few tens of auxiliary measurement diagnostic processes (partial results, statistical measurements, D_{TS}) are realized by a triggering and data acquisition (TRIDAQ) measurement system [9–15]. It was designed to serve the BAC detector and to cooperate with the global systems of ZEUS [9, 16].

3. MEASUREMENT LAYER OF TRIDAQ SYSTEM FOR BAC DETECTOR

The electronic TRIDAQ system for the BAC detector realizes measurement processes listed in chapter 2. From the functional side it is a fast, multi-channel, synchronous pipeline data selector and concentrator of a distributed modular structure [9]. The fast processing rate is determined by the frequency of e-p collisions in HERA detectors, which is 10.1 MHz. The TRIDAQ measurement system realizes measurement processes independently for each collision of particle bunches. The multi-channel system ability

stems from the presence of 40000 position readout channels and over 2000 energy readout channels in the BAC. Each channel processes the input signals with the e-p collision frequency. The synchronous character of the system provides time correlation for particular e-p bunch crossing for all stages of the measurement data processing and for all channels. The structure of the pipeline data concentrator is justified by the needed fast processing rate for particular processes and their synchronous character. The pipeline processing is realized by successive functional blocks and results in the increase of TRIDAQ measurement system efficiency. The system has to calculate the trigger which is based on numerable partial data which results in functional concentration. The integration and synchronization of numerable distributed modules results in the hardware concentration.

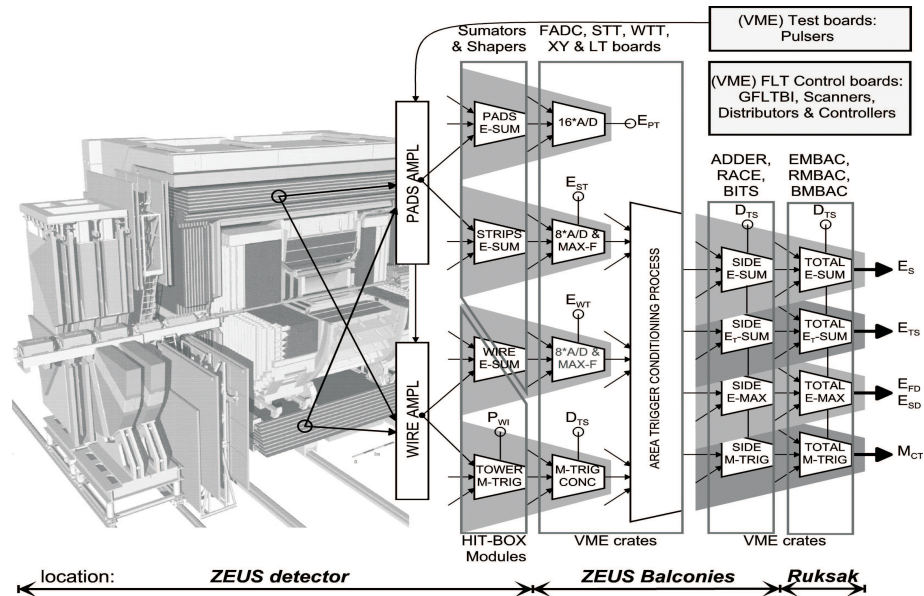


Fig. 2. General functional structure of TRIDAQ measurement system for BAC detector with major stages of data concentration and basic hardware classification.

The TRIDAQ system for BAC detector was designed, fabricated and tested [16]. The system is integrated with global systems of the ZEUS. Its overall structure is presented in Fig. 2. There are shown main concentration stages of data and basic classification of hardware to functional levels of modules. The positions of data acquisition for FLT were marked with circles. The positions of local trigger calculations were marked with names and arrows. The TRIDAQ measurement system for BAC realizes five basic functional tasks:

1. Energy readout for the first level trigger (FLT) of ZEUS experiment [9]. There are registered 2352 analog channels from the pad towers (E_{PT}), strip towers (E_{ST}) and

wire towers (E_{WT}). Some of the signals are amplified by 10, to increase the dynamic range of the amplitude. The signals are read out in parallel channels. The analog channel embraces pad amplifiers (PADS AMPL) wire amplifiers (WIRE AMPL), analog signal summators from the towers (respectively: PADS E_SUM, STRIPS E_SUM and WIRE E_SUM.), and signal shapers. The signals from particular towers are AD converted with 8-bit resolution, synchronously with the ZEUS system clock. Then, they are saved for FLT respectively with the usage of the following PCBs: FDAC for pad towers, STT for strip towers, and WTT for wire towers. The cooperation with GFLT of ZEUS is realized by GFLTBI board SCANNER boards cooperate with the Global Data Acquisition System.

2. Position readout embraces almost 40000 binary identification channels (P_{WI}) [13, 17]. The passage of a particle is amplified (WIRE AMPL), and registered as a positive logical state. The position readout uses more than 330 modules HIT-BOX positioned on ZEUS detector. The cooperation with GFLT of ZEUS is realized by DISTRIBUTOR boards. CONTROLLER boards cooperate with the Global Data Acquisition System.
3. Calculation of local trigger for BAC for the FLT of ZEUS experiment [12]. Calculation of trigger decision is done in stages. Part of the BAC energy trigger (components: E_S , E_{TS} , E_{FD} and E_{SD}) uses energy maxima from strip towers (modules MAX-F on STT boards) and wire towers (modules MAX-F on WTT boards). The muon part of the trigger uses local muon triggers calculated inside wire towers in blocks TOWER M-TRIG (modules HIT-BOX) and concentrated in blocks M-TRIG CONC (boards XY). The energy maxima and trigger decisions from 16 towers are mutually correlated and are conditioned in the AREA TRIGGER CONDITIONING PROCESS (boards LT). The calculated results are concentrated in two groups for two sides of the detector (boards ADDER, RACE, BITS) and finally in the blocks TOTAL (board EMBAC calculates the components E_S and E_{TS} , board RMBAC provides the components E_{FD} and E_{SD} , board BMBAC determines E_{CT}).
4. Diagnostics provides continuous on-line physical data monitoring and system work parameters. It is to discover the work irregularities and carry out service tests [18–20]. A method to excite the pad amplifier (PADS AMPL) and wire amplifiers (WIRE AMPL) was applied with the stimulus pulses for particle passages or with digital test sequences. The programmable pulse generators were used positioned on PULSER boards and diagnostic blocks distributed in different parts of the TRIDAQ measurement system [17, 21].

The TRIDAQ measurement system of the BAC detector is a very large, pipeline distributed network of functional blocks. The hardware and functional concentration of a few tens of thousands of readout and trigger channels required the modules and the boards to be positioned directly on the ZEUS detector and in large 22 VME crates outside the detector and in the adjacent hardware building called “Ruksag” [9, 11].

The position readout of the BAC detector is used by all experiments, where there is a need for identification and reconstruction of muons [10, 11]. There are also other cases

to use the data for full reconstruction of muons, even not considering the BAC detector. The examples showing the cases of J/ψ produced in DIS and PhD are presented in Figs. 3 and 4. For these examples, a single muon is not detected in the uranium calorimeter but is reconstructed in BAC. The possibility to reduce the background is important for the physical analysis. This is done via the muon reconstruction from the position readout. Figure 5 shows a case of a cosmic muon. This muon was seen only in the FCAL and in BAC. This particle may cause erroneous interpretation of the real e-p collision. The position readout is useful for elimination of muon background. Figure 6 presents the muon background with a muon reconstructed at both sides of the BAC detector.

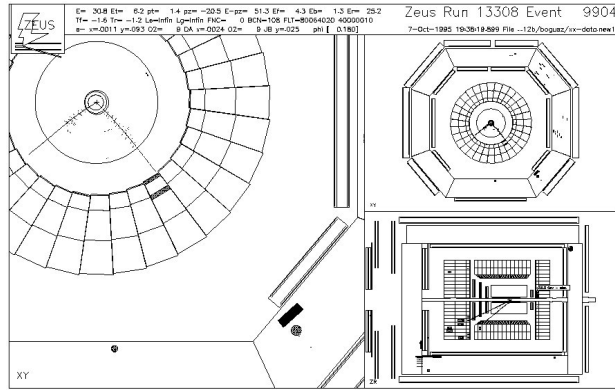


Fig. 3. Event of J/ψ production in DIS with a single lost muon.

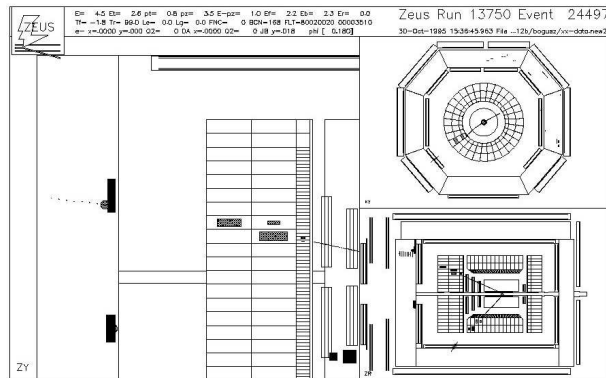


Fig. 4. Event of J/ψ production in PhD with a single lost muon.

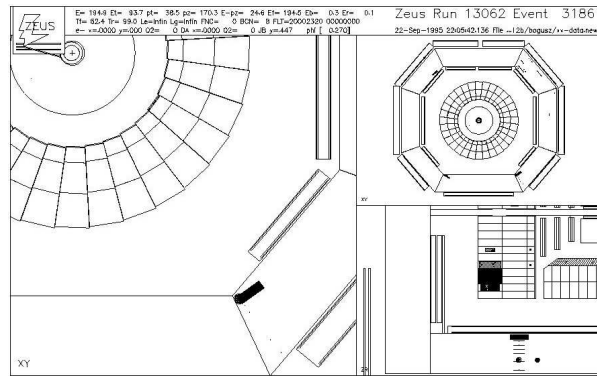


Fig. 5. e-p collision event with registered cosmic muon.

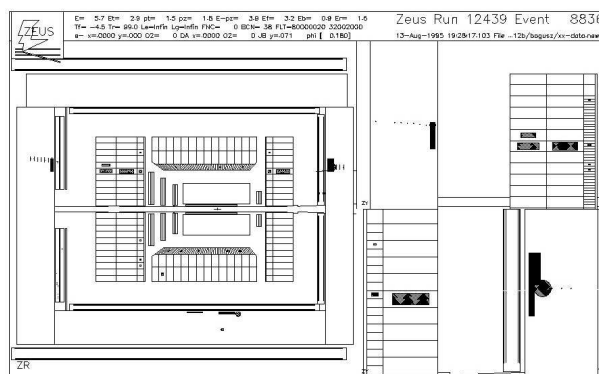


Fig. 6. Muon background event registered in BAC detector.

Example of the measurement result of energetic leakage from Uranium Calorimeter was presented in Fig. 7. It is done to improve the measurement accuracy of high energy hadron cascades. The position of leakage was marked with a circle. An example of cosmic jet discovery by the local trigger in BAC, and registering its image by the position readout system is presented in Fig. 8. Experimental results were described in [22].

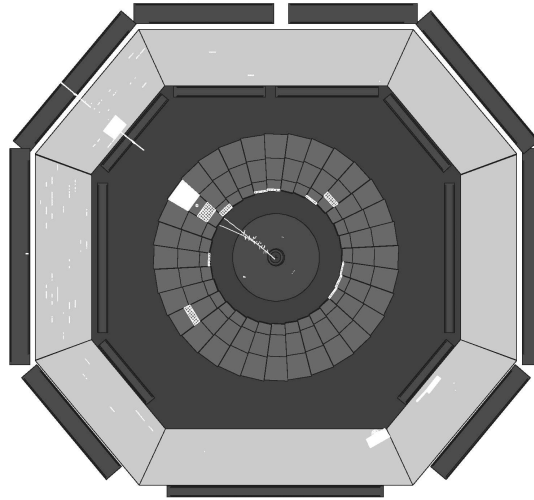


Fig. 7. Image of e-p collision with measurement of energy leakage in BAC calorimeter.

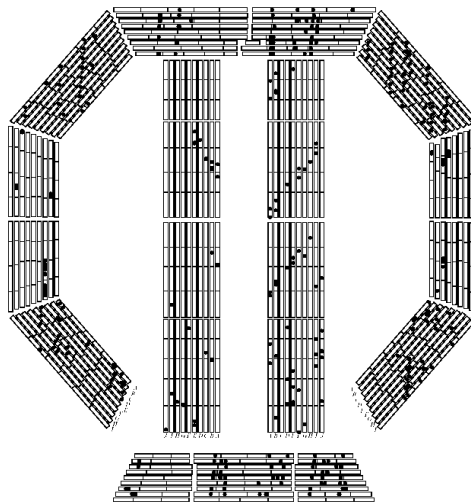


Fig. 8. Data acquisition for a cosmic jet discovered by the local trigger system of BAC.

4. DIAGNOSTIC LAYER FOR TRIDAQ MEASUREMENT SYSTEM OF BAC DETECTOR

The TRIDAQ measurement system for the BAC detector is a very large, distributed and complex electronic system. It consists of more than 200 EURO boards placed in VME crates and more than 1000 electronic modules distributed all over the ZEUS. The aggregated cabling length is over 10km. Due to this complexity, the susceptibility of the system to lose synchronization or to breakdowns is relatively large. It is impossible to predict all potential problems which may be generated during nominal work conditions of the TRIDAQ measurement system. It is impossible to carry out all tests of its behavior due to time confinements. An increase in system reliability was obtained via application of hardware solutions enabling in the TRIDAQ measurement system the following features [4]:

- monitoring during regular work in the ZEUS experiment. The physical and test data are analyzed to discover and register potential system malfunctioning like irregularities and calibration errors;
- tests and simulations during the cool down periods of ZEUS. Tests of synchronization, calibration, particular functional modules are done. Irregularities are discovered and localized to be removed by a technical team.

Gathering of diagnostic data is not confined only to the analysis of physical, position and energy readouts taken during the nominal work conditions of the ZEUS. These data have a confined character and sometimes are not correlated with phenomena which have to be subject to the diagnostic processes. Thus, the regular functional layer of the TRIDAQ measurement system for BAC was supplemented with a diagnostic layer in key places of the system. This layer provides additional on-line data concerning the processes of data acquisition and local trigger status. These data are calculated from the stream of physical data or test data. A general structure of diagnostic layer is presented in Fig. 9. The following types of diagnostic processes were additionally implemented in the TRIDAQ measurement system for BAC [18]:

- continuous diagnostics analyzing the status of a monitored module for each successive collision of particles. The following parameters are subject to continuous quality control: data signals (measurements of frequency, histograms, value distributions, etc.) and control signals (synchronization, data formats, etc.),
- selective diagnostics realized via the data acquisition mechanism in the FLT of ZEUS. The data registered in the TRIDAQ measurement system are subject to further analysis in an external PC system and separately stored.

A dedicated, distributed, multithread software layer was realized for diagnostic purposes. It consists of the following functional parts connected into a network of cooperating blocks via the Ethernet [19, 20]:

- control, embracing programs residing in transputers. They control the electronic hardware via VME interfaces and perform data acquisition. In the case of data

acquisition for ZEUS this role is done by the data acquisition channel and local trigger. In the case of tests, a specialized diagnostic software was installed,

- database, the major role of which is fast gathering and releasing of data stored in complex structures imaging the construction of the BAC detector. The data base provides safety of data archives and enables data aging,
- application, basing on a group of application servers and object oriented software for various operational platforms. The software realizes partial diagnostic tasks in parallel and provides result processing according to preset conditions and releases the final results,
- client, basing on standard web browsers and Java applets, PHP etc. This solution enables free access for many users, according to their level of authorization.

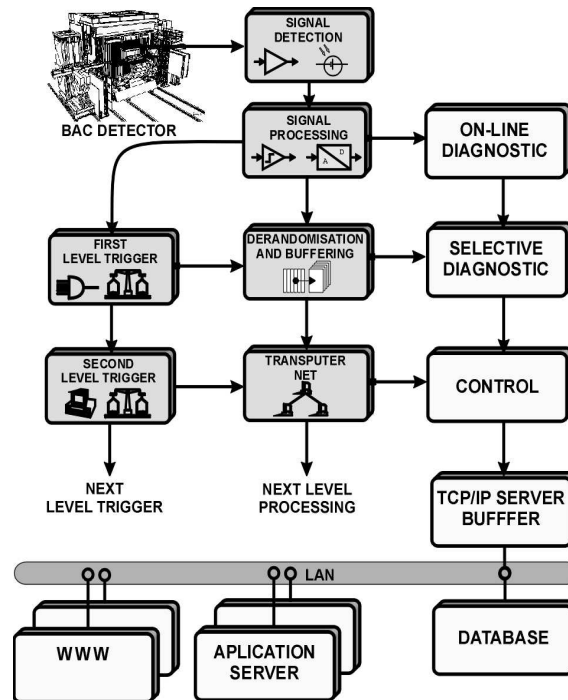


Fig. 9. Functional structure of energy readout.

The designed and realized diagnostic layer for BAC TRIDAQ measurement system provides many tests and automatic monitoring procedures. The programmable digital simulators may be used as well as complex test pulse sequences or real data from particle interaction (like cosmic muons). Depending on the method by which the diagnostic process is done, one can distinguish the following work mode of the system:

- data quality monitoring (DQM) during the time the BAC participates in ZEUS or during the stand-alone mode of work (using local trigger or simulators) [23–26].

The physical or test data are registered on line, processed and analyzed by the TRIDAQ measurement system. Collected information is used to calculate the measurement data quality and regularity of processes – data acquisition, calculation of the BAC trigger, discovery of process irregularity, lack of synchronization, or low data quality enables removal of these data from further physical analysis and avoidance of large errors. A particularly critical situation may lead to switching off a part or the whole BAC detector from ZEUS.

- Calibration and tests of TRIDAQ measurement system done periodically during the ZEUS system cool downs [24, 27]. The following parameters are measured and the following calibrations done: electrical parameters of particular analog channels (amplification, pedestal, nonlinearity, dynamic range etc.), discrimination thresholds for position channels are set, the filling of LTM modules is corrected in particular blocks of local trigger, synchronization states are checked (data consistency from various areas of BAC detector), etc. Single modules are tested and calibrated as well as larger functional parts of the TRIDAQ measurement system. There is generated an automatic diagnostic status report which is taken into account during the real physical data analysis. The configuration file is modified, taking into account the current status of hardware.
- Technical service of the TRIDAQ measurement system is referenced to breakdown situations, which require additional diagnosis of failures, repairs, hardware blocks or cabling change. An expertise is called for in such situations or the presence of a technical team is involved. Some situations require direct access of the technical team to the TRIDAQ measurement system hardware. The regular service tests are done under the supervision of an expert team.

The basic task of the diagnostic layer is to provide the high efficiency and quality of the TRIDAQ measurement system. A consequence of this is a regular participation of the BAC in ZEUS. This requirement is fulfilled by continuous on-line monitoring of the work status of all hardware/software modules of the system as well as collected physical and control data. However, when an irregularity occurs, the diagnostic layer enables fast discovery of a breakdown, localization and finding the underlying cause. Chosen examples of the diagnostic layer activity are described in the following chapters.

4.1. Analog channel calibration using a programmable test pulse system

A system of test pulses was installed in the BAC. It allows to set in a programmable way the pulse length (from 20ns to 100ns with step of 10ns), polarization, amplitude (from 0 to 5V with 8-bit resolution). Chosen channels may be programmably masked. The signals from pulsers are transmitted to test inputs of pad and wire [11]. The calibration process enables data synchronization for particular parts of the BAC (data consistency) and investigation of linearity, amplifications, dynamic range of particular

channels [27]. An example of test pulse readout from a chosen local trigger of BAC is presented in Fig. 10.

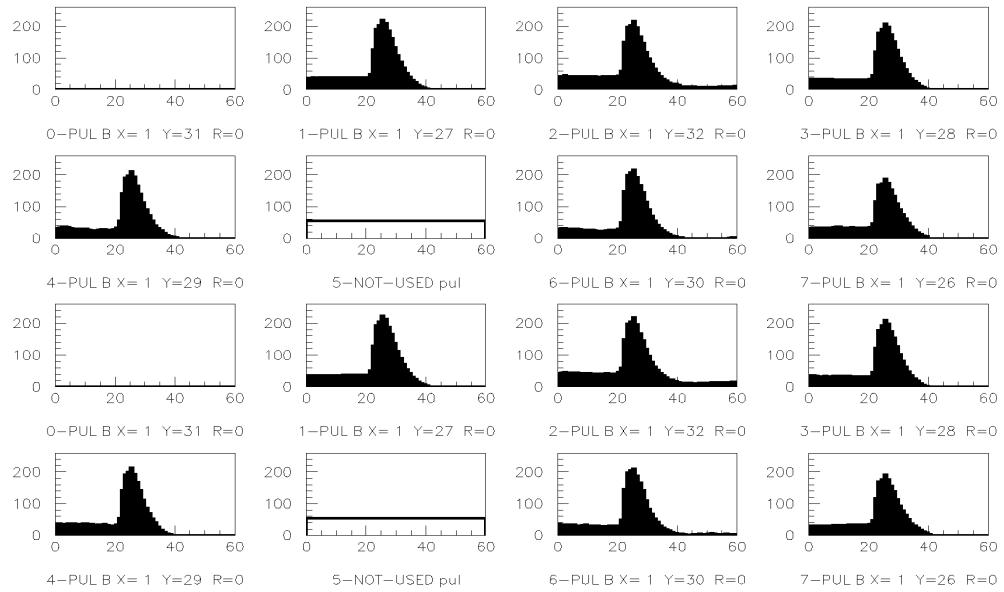


Fig. 10. Example time responses to test pulse excitations registered by local trigger of BAC.

The obtained data are subject to further numerical analysis. As a result, the characteristic identification parameters for all channels are obtained. These parameters are inserted to the data base and used during the analysis of physical data.

4.2. Energy readout calibration with use of cosmic muon detection by local trigger

The local trigger of BAC, in cooperation with the GFLTBI board, enables independent physical data acquisition for position and energy readout. These properties of the TRIDAQ measurement system allow to use the cosmic muons as a precise source of test signals [15]. The passage of a muon, which is a very penetrating particle, leaves behind an image of the full trajectory in the detector (layers of chambers in BAC). This can be used for investigation of chamber efficiency, space alignment, monitoring of particular readout channels, channel synchronization. An example of cosmic muon passage, registered by the position readout system is presented in Fig. 11.

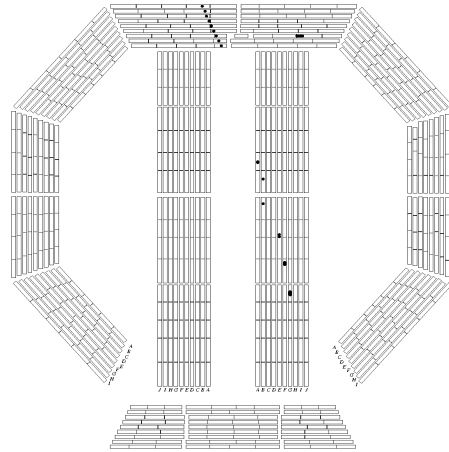


Fig. 11. Image of cosmic muon passage registered by position readout system.

4.3. Efficiency monitoring of local trigger with usage of cosmic muons

Cosmic muons may be a stable decision-initiating source for the local trigger of BAC. The average number of cosmic passages is $150 \text{ [m}^{-2}\text{s}^{-1}\text{]}$. Figure 12 presents distributions of cosmic muon passage frequencies for particular energy towers in the BAC barrel registered by XY boards of local trigger of BAC. It is possible to estimate the predictable number of interactions taking into account the angular distribution of cosmic muons defined by particular tower geometry [21]. From these results it is possible to optimize the values of discrimination voltages for analog signals from wire readout, in order to reduce the noise and increase the efficiency of the local trigger for BAC. The monitoring detects considerable deviations from the expected values, as too large excitability of the area *SWTYA8part1*. Due to the diagnostic layer working during the nominal conditions of BAC in ZEUS, it is possible to estimate the quality and efficiency of the local trigger.

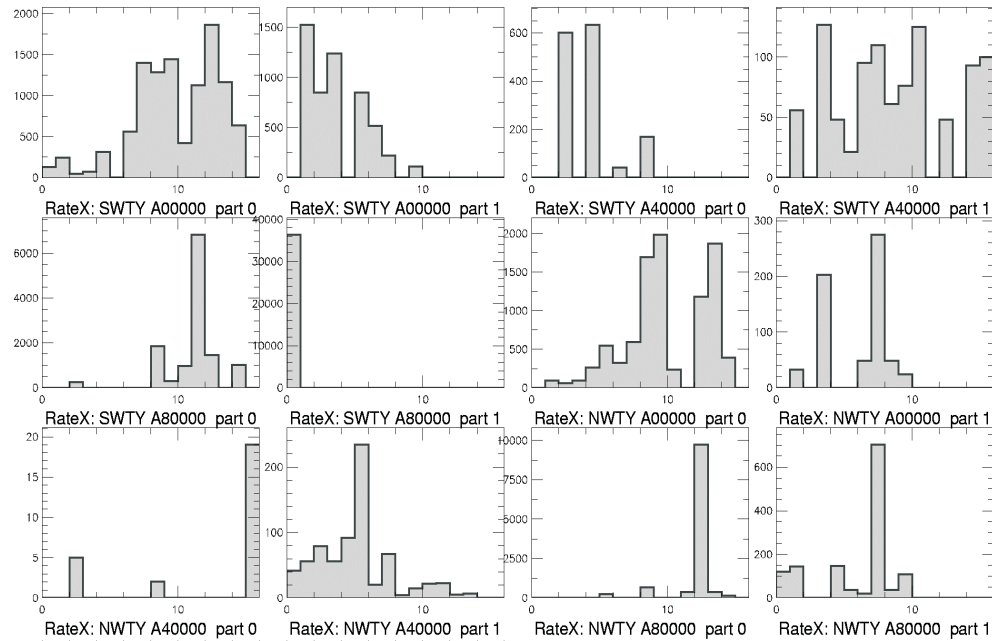


Fig. 12. Example time response functions to test pulse excitations, registered by the BAC local trigger.

4.4. Hardware tests of position readout

Detailed hardware tests are performed with the HIT-BOX modules which are positioned directly on the ZEUS spectrometer. Over 300 independent modules serve 40000 position readout channels. Control and data acquisition required the realization of a complex cabling system and external power supplies. These systems are susceptible to frequent failures in cabling (lack of connections) or in power (voltage level fluctuations). Figure 13 presents an example of an application which gathers the state of position-readout modules on the northern side of the BAC [25]. Information on the current hardware status are gathered directly from the data base [18]. The left drawing of the detector images positions of the electronic modules and their technical status (marked with colors). The left side is a reference to the physical position of the readout channels. The navigation tools allow the operator to obtain precise data about each HIT-BOX module.

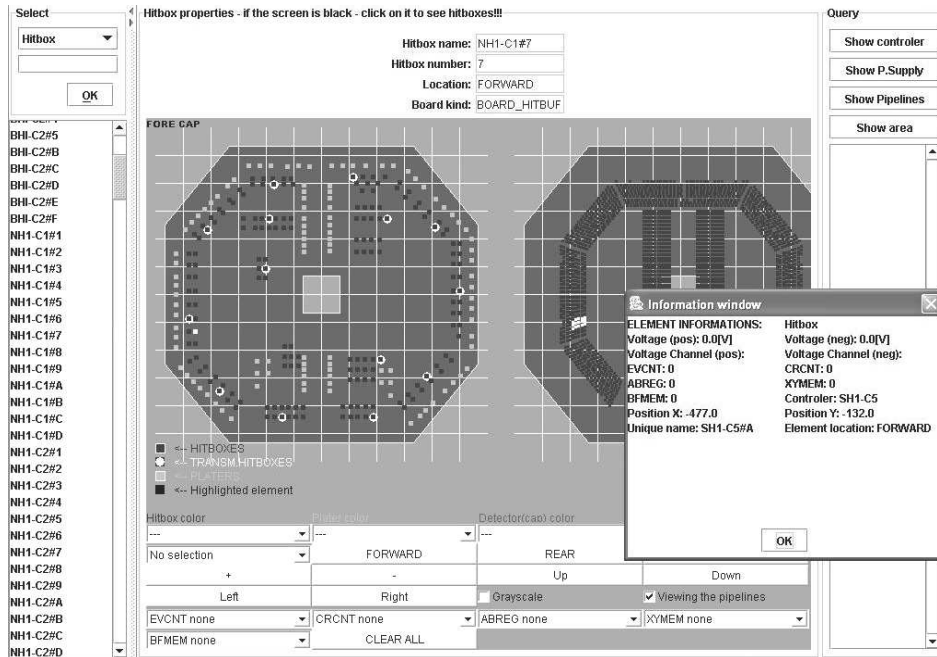


Fig. 13. Presentation of the status of position readout for the northern side of BAC detector.

5. FPGA TECHNOLOGY IMPLEMENTATION

During the first decade of exploitation of the BAC TRIDAQ measurement system in the ZEUS experiment there were numerous experiences gathered. As a result, there was an increase in the functional requirements and diagnostic needs. Since 1998 the realization of new modules of the TRIDAQ measurement system relied on novel technologies, as in particular usage of *Field-Programmable Gate Array* (FPGA) [28].

For realization of ADDER, RACE, BITS, EMBAC, RMBAC, BMBAC and GFLTBI boards (see Fig. 2) chips by Altera were used FPGA ACEX-K50 [29]. These chips possess several thousand configurable four-input logical blocks (LCELLs) and above 100 kb of programmable SRAM memory blocks. The possibility of multiple reconfiguration of FPGA chips enabled successive implementation of new firmware versions. Using these features the author effectively designed the functional and diagnostic part of the BAC local trigger. This was described in detail in the chapter 4.

The author used *Altera Hardware Description Language* (AHDL) to describe the hardware. Universal, parameterized diagnostic blocks were created. They were used to measure the frequency of the position signal (M_{CT}), distribution of energy signals (E_S , E_{TS}) and to store BAC local trigger decision on consecutive levels of processing. These solutions are working in real-time. They enable the analysis of consecutive events every

96ns. Application of parametrization gave the possibility to implement functionally integrated diagnostic blocks in each FPGA circuit. The blocks were automatically optimized against the number of input measurement signals and effectively used the resources of FPGA circuits.

6. SUMMARY

The multichannel, distributed data acquisition and local trigger (TRIDAQ) system for the BAC detector is a representative example of a multifunction measurement system [9]. This system is integrated with over 2000 proportional gas chambers and the global system of the ZEUS experiment [16]. It services over 2000 analog channels designed to measure energy leakages and 40000 channels for the measurement of muon trajectories [11]. It calculates the energetic and position local trigger integrated with the global trigger system of ZEUS experiment [12].

During the period of 1991–2003 the author has participated in the design of a large part of the measurement system of the BAC detector. In particular, he designed the functional and hardware structure and implemented in ZEUS the following subsystems (see Fig. 2):

- Position readout system – modules HIT-BOX, CONTROLER and DISTRIBUTOR boards [13, 17]
- Control system for energetic readout – GFLTBI and SCANNER boards [14]
- Part of the BAC local trigger realized in FPGA technology ADDER, RACE, BITS, EMBAC, RMBAC and BMBAC boards. Author designed the hardware configuration (*firmware*) of FPGA circuits using AHDL coding. The project was implemented in the form of parameterized functional blocks. The blocks realize particular processes of the local BAC trigger [12].

The measurement system of the BAC detector is a unique device realized strictly to fulfill the research and technical requirements of the ZEUS experiment. The design, construction, testing and commissioning process had many stages and lasted over 10 years. The required resources embraced over 1 M\$, several experts and over 20 technicians. A prototype solution was applied practically in which then the current state of technology was frozen. The performance of the system was checked after the ZEUS experiment was launched. At this time there were no possibilities, neither technical nor financial, to introduce considerable changes or improvements. These factors, though unfavorable, influenced the final shape of the system.

A key factor while designing a very large measurement system is to determine a proper functional structure of the whole electronic layer. The structure should provide high quality and reliability of the system. A functional layer is understood by the tasks defined in chapter 2. The functional layer consists of elementary logical processes realizing certain measurement, processing and data acquisition functions. These func-

tions are unambiguously defined and precisely imaged in hardware in the early stage of system design.

Partial results of all implemented processes in the functional layer contribute to the final performance of the very large BAC measurement system. On-line analysis of TRIDAQ system may be conducted via the monitoring of particular processes and data distribution. The discovery of irregularities is strictly determined [4]:

- *Functionally*, when the kind of irregularity is known;
- *Topologically*, when the place of the irregularity is known;
- *Time resolved*, when the precise moment of irregularity generation is known.

From practice it is known that large distributed, multichannel measurement systems, which work autonomously in the hostile areas of large ionizing radiation levels and EMI are subject to numerable and impossible to predict work irregularities and fatal failures. This was the main reason behind undertaking by the author this work on a measurement system with embedded monitoring and diagnostic layer with separate test tools for BAC:

- checking of data integrity from position measurement – situated in HIT-BOX modules [13, 17],
- diagnostic layer of local BAC trigger – implemented in separate FPGA circuits on ADDER, RACE, BITS, EMBAC, RMBAC and BMBAC boards. The author designed the diagnostic firmware in AHDL code [21],
- testing system for programmable pulses exciting the monitoring inputs of analog pad (PADS AMPL) and wire (WIRE AMPL) – amplifiers of PULSER board [11, 12],
- programmable modules of work simulators for particular parts of the BAC system, situated on GFLTBI, SCANNER and DISTRIBUTOR boards [13, 14],
- monitoring of work status of particular functional blocks implemented in all devices designed by author.

The chapter 4 presents examples of practical application of the described design method. The diagnostic layer in this design turned to an indispensable part of any large measurement system, which is the TRIDAQ of the BAC detector. The diagnostic layer provides not only current information of work quality in particular ZEUS processes but also useful measurement data, which are used for the calibration and physical analysis. A considerable development of the diagnostic layer became possible due to the fast advances in FPGA technology offering large logical and memory resources. The presented hardware diagnostic layer for the local BAC trigger undertook a lot of functionalities realized earlier by computer software basing on the experiment data. This early solution prevented precise on-line analysis of the system status and data quality. An objective indicator of the usefulness of this layer is a considerable balance in the number and functions of diagnostic blocks and BAC trigger signal calculation blocks in favor of the monitoring sub-system [21]. This proportion is approximately as great as 3:1.

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