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**Diagnostic Systems for Backing Calorimeter
and Low Level RF of VUV-FEL**

**Metody testowania i predykcji uszkodzeń systemów
elektronicznych w detektorze BAC i liniowym
akceleratorze cząstek elementarnych VUV-FEL**

Ph.D. Dissertation

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Acronyms

BAC – **B**acking **C**alorimeter

CAL – **C**alorimeter

CTD – **C**entral **T**racking **D**etector

DESY – **D**eutsches **E**lektronen-**S**ynchrotron

DOOCS – **D**istributed **O**bject **O**riented **C**ontrol **S**ystem

DUT – **D**evice **U**nder **T**est

FEL – **F**ree **E**lectron **L**aser

FLT – **F**irst **L**evel **T**rigger

FPGA – **F**ield **P**rogrammable **G**ate **A**rray

FSM – **F**inite **S**tate **M**achine

FTD – **F**orward **T**racking **D**evice

HEP – **H**igh **E**nergy **P**hysics

HERA – **H**adron **E**lectron **R**ing **A**ccelerator

ILC – **I**nternational **L**inear **C**ollider

LLRF – **L**ow **L**evel **R**adio **F**requency

LUT – **L**ook-**U**p **T**able

RTD – **R**ear **T**racking **D**evice

SASE – **S**elf-**A**mplification **S**pontaneous **E**mission

SLT – **S**econd **L**evel **T**rigger

SRAM – **S**tatic **R**andom **A**ccess **M**emory

TESLA – **T**eV-**E**nergy **S**uperconducting **L**inear **A**ccelerator

TLT – **T**hird **L**evel **T**rigger

TTF – **T**esla **T**est **F**acility

VAX – **V**irtual **A**ddress extension,

VHDL – **V**ery **H**igh **S**peed **I**ntegrated **C**ircuit **H**ardware **D**escription **L**anguage

VME – **V**ersa **M**odule **E**urocard **B**us

VMS – **O**pen **V**irtual **M**emory **S**ystem

VUV-FEL – **V**acuum **U**ltraviolet **F**ree **E**lectron **L**aser

VXI – **V**ME extensions for **I**nstrumentation

VXD – **V**ertex **D**etector

X-FEL – **X**-ray **F**ree **E**lectron **L**aser

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Chapter 1

Introduction

1.1 Work motivation and aim

Large and distributed electronic systems can be found almost everywhere. It is difficult to imagine industry, power stations, or even railroads working without electronic systems. They are responsible for control, exception handling and accident prevention. Electronic control systems can also be found in aircraft, cars, hospitals (e.g. in life support systems) and also in private homes, fire protection systems being one example. The electronic systems can be distributed over lengths ranging between a few meters like in cars, tens of kilometers in the case of high energy physics experiments [1], up to hundreds and thousand kilometers in case of railroads. In all cases, electronic systems play a vital role in system operation. Failure can cause danger to people, destruction of assets or to at least a significant loss of money. Hence an elaborate diagnostic and exception handling system has to be in place to ensure functionality of the system and detect malfunctions.

High energy physics experiments are a special class of scientific experiments, requiring highly specialized control systems. The primary task of these experiments is to study the structure of matter. Size and complexity level of high energy physics experiments can be compared to a big factory in size. Complexity is even increased as

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these experiments require leading edge technology at a reliability level of over 99 %. Requirements for availability, reliability and operability¹ exceed industry standard and goals are significantly different than in industry. It is necessarily to design and build a dedicated control system (hardware and software) for these experiments. High energy physics experiments rely on particle accelerators with length up to a few kilometers for beam production and detectors [15], [17] with hundreds of thousands analog and digital channels to detect collision events. Data streams from detectors are in the range of tens of Tbits per day. Electronic components are distributed all along the accelerator and detector, with connection lengths between certain subcomponents on the order of few hundred meters. An issue further complicating the design of electronics for accelerators and detectors is radiation exposure. During collisions, a significant amount of radiation is produced through particle showers This can cause Single Event Upset (SEU) in active electronic components, which can lead to unpredictable component failures.

The biggest accelerators [2] and detectors [3] are built by scientists, research institutes, and universities in international collaborations. Various groups provide subcomponents of the accelerator or detector with their own internal standard for hardware and software using different software platforms.. Usually only the interface between subcomponents is defined. But it is still necessary to provide a diagnostic system for the complete machine, dealing with all the different subsystems

Particle accelerators used in high energy experiments are not only used to produce particle beams used to study the subatomic world. Accelerators can also produce a wide spectrum of radiation which can be used in various other branches of science [16], e.g.:

- material analysis and modification,
- spectrometry,
- surface modification,
- sterilization,
- polymerization.,
- radiation surgery,

¹ These term will explained in chapter 3

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- cancer therapy,
- and others.

A few thousand electron and proton accelerators are used in hospitals around the world for radiation treatment of various cancers. Accelerators also produce radioactive elements that are used as tracers in medicine, biology and material science. Well-defined beams of photons find increasing use in lithography in order to fabricate the very small structures required in electronics.

A significant part of existing experiments (accelerators and detectors) is not equipped with diagnostic systems. There are some small custom systems for experts, but not available to the operators. In the past, uptime was not of prime importance. Usually, the lifetime for high energy physics experiments is about 10 - 15 years and during this time one or two upgrades are planned. The goal in an upgrade is to improve luminosity for accelerators and increase resolution of detectors, decrease the acquisition dead time for detectors and add new features made possible by advancement of technology. Therefore, requirements for upgraded systems become much higher and hence the electronics systems more complicated. To provide continuous operation, it is necessary to have fast and reliable diagnostics.

The motivation behind the work presented in this thesis was an attempt to define requirements and design diagnostic systems for electronic systems used in a high energy physics experiments. Another approach taken was trying to use an existing control system as diagnostic system to save money. Furthermore the diagnostic system would support maintenance; hence decrease maintenance cost and increase availability of machine for users.

The main contributions of the author are the following:

1. Requirement definition of a diagnostic system for accelerators and detectors
2. Design of a diagnostic system for the ZEUS-BAC detector [24],[28].
3. Design of a diagnostic system for the VUV-FEL accelerator [49].

4. Realization of a diagnostic systems for BAC detector and low-level subsystem of the VUV-FEL accelerator.
5. Result analysis of the designed diagnostic systems.

1.2 Theses

In this work following theses will be proven.

Thesis 1

It is possible to construct a diagnostic system for the control and measurement modules used in high energy physics experiments based on their data acquisition systems without crucial modification.

Thesis 2

The time needed for finding machine failures can be minimized using a developed diagnostic system; hence, availability for user operation of the device increases.

Thesis 3

It is possible to tune detector parameters in the presence of real signals and noise that allow obtaining high efficiency of the detector.

First thesis will be proven if a diagnostic system for control and measurement modules used in high energy physics experiments is constructed without crucial modification in existing electronics system. If designed system will support the maintenance of an experiment and will provide higher availability for used operation then second thesis will be proven. Third thesis will be proven if it will be possible to tune detector parameters and obtain higher efficiency of the detector

Chapter 2

Detectors and accelerators in high energy physics experiments

This chapter presents general information about detectors, accelerators and their application in research and industry. Basic information about high energy physics experiments, their goals, measurement methods of collision products, and their meaning are presented. The ZEUS-BAC detector and VUV-FEL accelerator are presented and their principles of operation are explained.

2.1 Basic researches in High Energy Physics Experiments and their applications

In the last 30 years our understanding of nature's fundamental particles and the forces which act between them has advanced significantly. A theoretical model called the "Standard Model" describes the structure of matter in good agreement with our state of knowledge. During the XX century, the Standard Model has been improved, but it still contains theoretical postulates which are not yet confirmed by physical experiments. The Standard Model is one of the greatest intellectual achievements of particle physics.

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Any theory may only be verified by experimental results. Particle accelerators are devices producing beams of high energy electrons or protons. These probing particles are used in high precision electron microscopy to study atomic constituents. Based on de Broglie's equation, the corresponding wavelength of a probing particle defines the minimal object size that can be observed. The wavelength is inversely proportional to the particle momentum. Particles from accelerators colliding with target particles may lead to the creation of new particles. New particle will have a mass from the collision energy and according to equation $E=mc^2$, kinetic energy can be converted to mass. During collisions interesting and unknown particles can be created. Figure 2.1 shows the general products of collisions between elementary particles. Different elementary particles such as electrons, protons or hadrons are accelerated and collided.

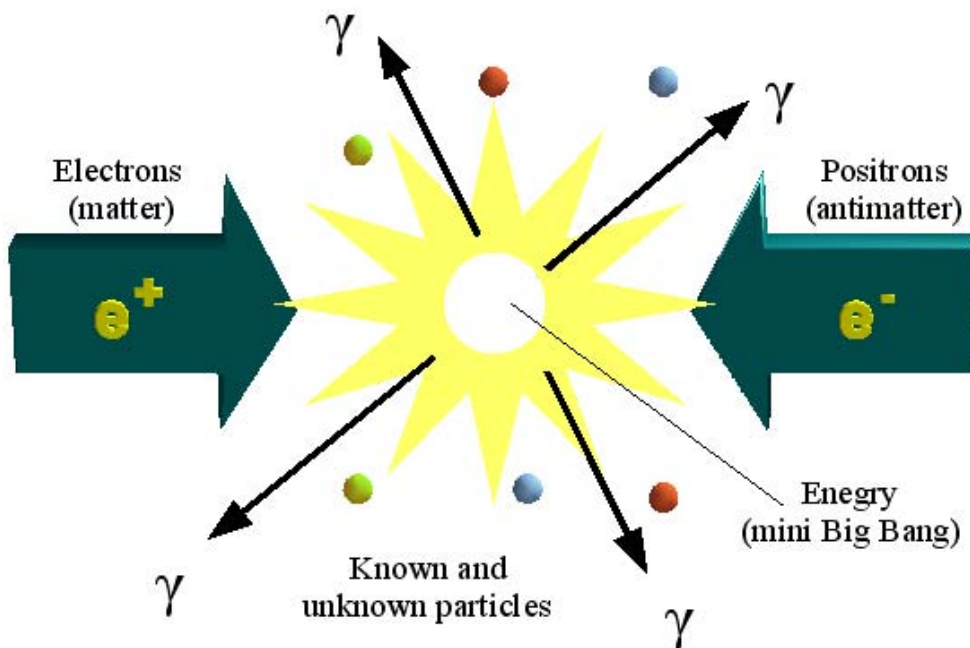


Figure 2.1. Products of collisions between elementary particles.

Different particles (electrons, positrons, neutrons) can be made to collide in different combinations and with different energies. The possible results are presented in Table 2.1. The biggest accelerators to date achieve energies on the order of a dozen TeV in the center of collision point. Experiments with accelerators are called High Energy

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Physics Experiments and the branch of physics High Energy Physics – HEP. The biggest accelerators are located in:

- CERN - Centre Europeen de Recherche Nucleaire, Switzerland
- DESY – Deutsches-Elektronen Synchrotron, Hamburg, Germany
- FNAL - Fermi National Accelerator Laboratory , Batavia, IL, USA
- JLAB - aka TJNAF, Thomas Jefferson National Accelerator Facility (formerly known as CEBAF), Newport News, VA
- SNS - Spallation Neutron Source, Oak Ridge, Tennessee, USA
- IHEP - Institute for High Energy Physics, Protvino, Moscow region, Russian Federation

<i>Particle Generations</i>		
electron	muon	tau lepton
electron-neutrino	muon-neutrino	tau-neutrino
up quark	charm quark	top quark
down quark	strange quark	bottom quark
<i>Antiparticles</i>		
positron	positive muon	positive tau lepton
electron-antineutrino	muon-antineutrino	tau-antineutrino
up antiquark	charm antiquark	top antiquark
down antiquark	strange antiquark	bottom antiquark

Table 2.1. Possible products of particle collisions.

An accelerator is the only device which produces a well defined beam of particles. Most important is, from the point of view of high energy physics, to be able to register the products of a collision. These are registered in multi-purpose detectors. Depending on particles used, detectors are different. A few different detectors can work

2.1 Basic researches in High Energy Physics Experiments and their applications

on one accelerator at the same time. A detector has to register trajectories and energy of the collision result, so it is possible to gather information about individual collisions. Each collision is called an event.

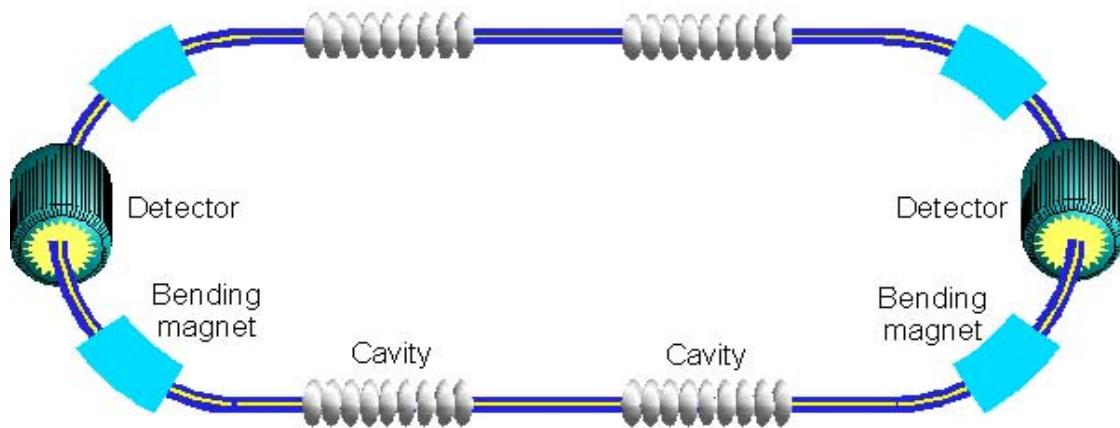


Figure 2.2. An accelerator and detectors

2.1.1 Accelerators

The first accelerator was built at the end of the 19th century and was called a ray tube. Particles were accelerated by a high voltage applied over the gap between a cathode and an anode. Using cathode ray tubes, X-rays were discovered in 1895 by Wilhelm C. Roentgen. Also using ray tubes, the first elementary particle, the electron, was discovered by Joseph J. Thomson in 1896. The discovery of the electron started a new era, the electronic age, which rapidly changed the world in the next few decades. All existing types of accelerators were invented during the first few decades of the XX century. New concepts for accelerating particles, such as a time-varying potential across a series of gaps, a high frequency voltage applied over the gaps, and others have been developed. The most important accelerator types are listed and shortly described below.

Cyclotron – acceleration is achieved by means of a time-varying voltage. The charged particles circulate in a strong magnetic field and are accelerated by electric fields in

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gaps. After a gap, the particles move inside an electrode and are screened from the electric field. When the particles exit from the screened area and enter the next gap, the phase of the time-varying voltage has changed by 180 degrees and the particles are again accelerated. The process is repetitive. After many turns of acceleration, resulting in an outward spiral trajectory, the particles circulate near the boundaries of the strong magnetic field. Here, the field is shaped so that the beam of circulating particles can emerge and be formed into an external beam. Ions which are accelerated by a voltage of fixed frequency equal to the ion frequency of rotation in the magnetic field. The ionization of a gas is limited in the centre. The magnetic field lines are directed towards the lower magnet pole. The positively charged ions circulate in the clockwise direction. The ions are accelerated when they move in the gap between the electrodes. When the beam of ions reaches the magnetic field boundary it is extracted from the cyclotron and formed into an external beam. A cyclotron is used to produce artificial radioactive elements for industry, medicine, etc., provide beams for radiation surgery and therapy. Cyclotrons are needed for the production of radio nuclides as tracers for positron emission tomography (PET), a technique for mapping the functioning of the human body.

Synchrotron –particles are accelerated along a ring-shaped orbit and the magnetic fields bending the particles increase with time so that a constant orbit is maintained during the acceleration. The particles are accelerated by high voltages across one or several gaps along the circumference. Basic focusing element is a quadrupole magnet with four iron poles where the magnetic field is excited by currents in surrounding coils. Two north poles are opposite to each other and each of them has neighboring south poles. At the centre axis the magnetic field is zero and it increases linearly with increasing distance from the centre axis. Electrons orbiting in a magnetic field lose energy continually in the form of electromagnetic radiation (photons) emitted tangentially from the orbit. This phenomenon is called synchrotron radiation.

Linear Accelerator – in this accelerator, the gaps are placed along a straight line. A great many electrodes are separated by small gaps and placed along a straight line. There is no magnetic field that changes the direction of the particles being accelerated. When

2.1 Basic researches in High Energy Physics Experiments and their applications

particles move inside the field-free region of a given electrode, the direction of the accelerating electric field is reversed so that particles are always accelerated in the gaps between the electrodes, see Figure 2.3. In the synchrotron, the magnetic field is increased during the acceleration so that particles move in rings of essentially constant orbit. In these accelerators, particles are accelerated in a repetitive way and the energy is limited by the size of the accelerator and not by the maximum voltage that can be reached.

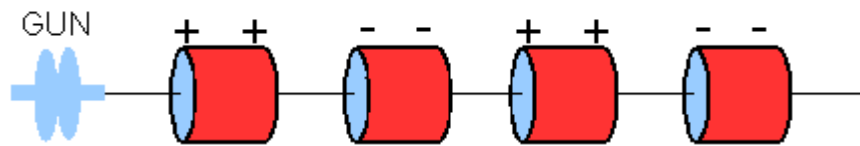


Figure 2.3. Principle of operation of a linear accelerator.

Colliders – this accelerator consists of one or two storage rings in which bunches of particles are accelerated in opposite directions, clockwise and counter-clockwise. When the particles have attained the required energy they are stored and made to collide at specific points along the circumference of the rings, where detectors are placed to register particles scattered and produced in the collisions. Protons, antiprotons, electrons and positrons can be made to circulate in opposite directions and collide in the same synchrotron ring. Colliders are also used to produce mesons.

2.1.2 Detectors

Detectors enable us to register particles passing through a certain point in space. Depending on the kind of detector, particles passing through leave visible traces or generate electrical signals. These devices can register either charged or uncharged particles. The most important detector parameters are resolution and sensitivity. Both parameters depend on the construction of the detector.

2.1 Basic researches in High Energy Physics Experiments and their applications

The *resolution* of a detector is the smallest distance between two particles which can be distinguished. If the resolution is too low, a detector will only register one particle when in reality there were more particles close together. The *sensitivity* of a detector is the minimum energy of a particle required to produce an electrical signal or leave visible trace. If the particle energy is lower than the sensitivity of a detector, the detector will not register that particle. More than 20 basic types of particle detectors are known, e.g.: calorimeter, dosimeter, drift chamber, photodiodes, scintillators, semiconductor detectors, Wilson cloud chambers and many more. The most important types of detectors and their principle mode of operation are described below.

Gaseous detectors – a common name for a big class of detectors designed to seek the presence of particles [40]. Their principle of operation is based on the fact that if a particle has enough energy to ionize a gas, the resulting electrons emitted can cause a change of gas conductivity, which can be observed as a current flow. Gas detectors have the ability to detect radiation and determine particle energy levels. Depending on their construction, test gas used or associated electronics [12], detectors have different names (proportional counters, wire chamber, etc.).

Wire chamber - is a gaseous detector for particles of ionizing radiation. Construction of the multi wire chamber is shown in Figure 2.4. Multi wire chambers consist of a set of single wire chambers. A gas-filled metal tube is held at ground potential. Isolated wires are connected to a high voltage. Any ionizing particle that passes through the tube causes the flow of current (change of gas conductivity). The instruments amplify this current flow and measure it.

Often, the chamber is put into a homogeneous, strong magnetic field. Charged particles are led into spiral paths due to Lorentz force. By measuring the direction of the curves, one can calculate the particle charge. Big detectors can consist of hundreds of multi wire chambers with many parallel wires arranged as a grid.

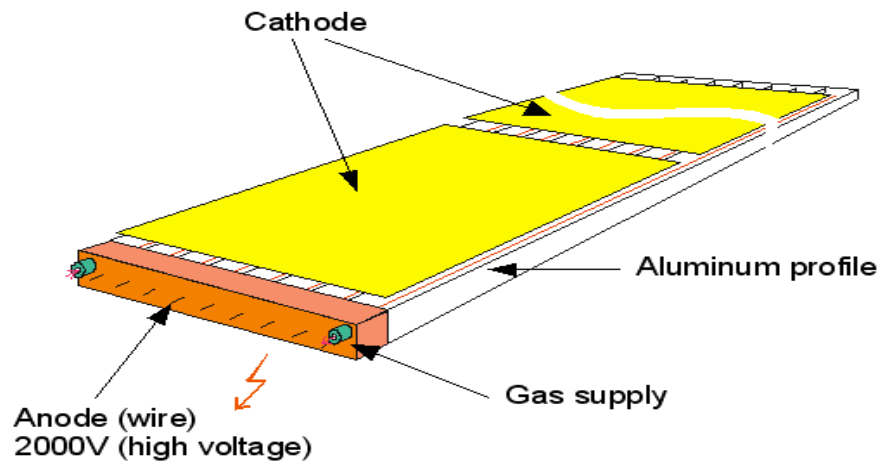


Figure 2.4. Wire chamber used in the BAC detector.

Scintillation counter – measures ionizing radiation. Scintillators consist of a transparent crystal (usually phosphor), plastic (usually plastic containing anthracene) or organic liquid that fluoresces when an ionization particle strikes it. A sensitive photomultiplier tube, equipped with an electronic amplifier, measures the light from the crystal.

Calorimeter – device designed to detect particles and measure their energy. Particles enter the calorimeter and initiate a particle shower. The particle's energy is deposited in the calorimeter and may be measured in its entirety or sampled. Calorimeter detector consists of alternately absorber and sensor layers. Additionally, calorimeters are segmented transversely and longitudinally. Transverse segmentation may provide information about the direction of the registered particle, as well as the energy deposited. Longitudinal segmentation may provide information about the identity of the particle based on the shape of the shower as it develops.

Semiconductor detector - is a device that uses a semiconductor (usually silicon or germanium) to detect traversing charged particles or the absorption of photons. These detectors are based on semiconductor diodes formed in strips [18]. Particles passing through these strips cause a small ionization current which can be measured. Silicon detectors [13] have high resolution (size of diode) Semiconductor detectors based on germanium are mostly used for spectroscopy in nuclear physics, while silicon detectors are used for particle detectors. Silicon detectors can not be thicker than a few

2.1 Basic researches in High Energy Physics Experiments and their applications

millimeters, germanium can have a depleted, sensitive thickness of centimeters, and therefore be used as a total absorption detector for gamma rays.

HEP experiments require high performance detectors, which consist of different types of detectors in one device. Detectors designed for modern accelerators are huge, both in size and in cost. To achieve high resolution, hundreds thousand and more analog and digital channels are available. Analog channels are used to measure energy leaved by particle, digital channels register its trajectory. Detectors are placed at collision point of accelerator, and have to be able to register products of the collision which appear every few nanoseconds. The typical structure of a detector for accelerators is shown in Figure 2.5. Particular components form a sphere around the interaction point. Different components have different parameters and usually are devoted to various products of collisions. Only 0.01% of events are interesting and acquisition system has to be equipped with an advanced trigger system, which can select events which meet the assumed requirements. Each HEP detector is designed for a given accelerator and as such unique.

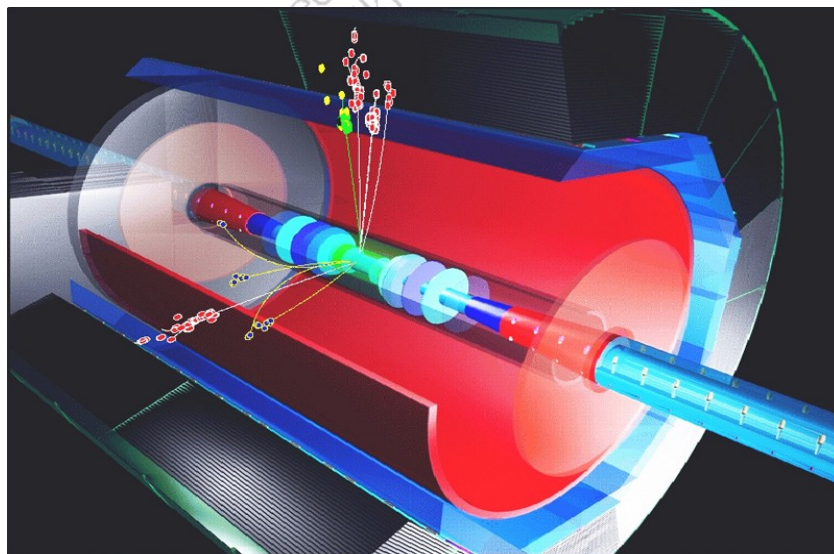


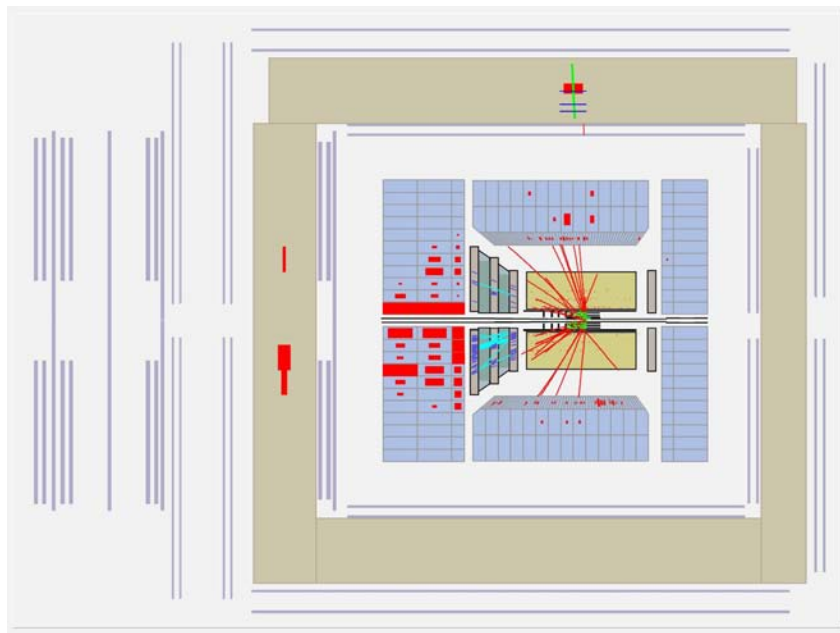
Figure 2.5. A detector for HEP experiment. (Source: DESY)

Usually at the collision point, a high resolution (silicon detector with resolution tens of microns) detector is installed. Further from the collision point, the required resolution is lower, a few centimeters up to tens of centimeters. A strong magnetic field

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(e.g. 4T) is applied. Measuring the curvature of the trajectory of a particle deflected in an electric or magnetic field, a physicist can determine the charge and mass of the particle and thus identify it. An example of reconstructed registered tracks in a detector is shown in Figure 2.6. In the presented graph not all components (detectors) were able to register all tracks. For some of them the particle energy could be too low or a part of a detector did not work properly.

a)



b)

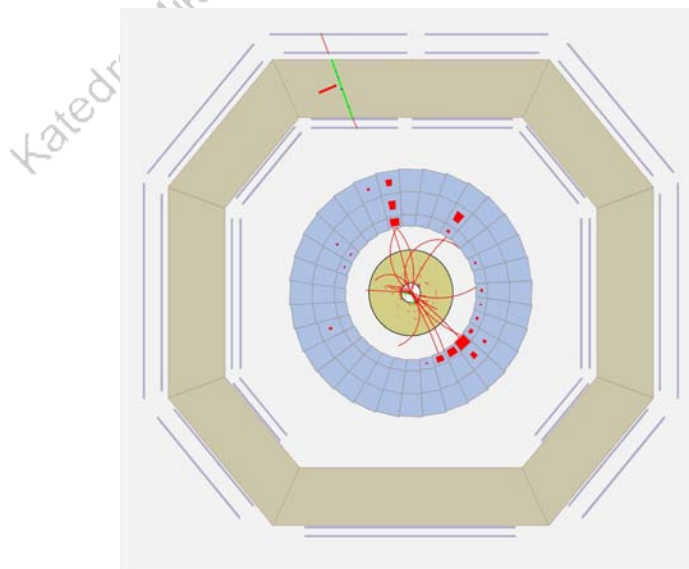


Figure 2.6. Particle paths registered by detector. (Source: DESY)
a) longitudinal-section, b) cross-section

2.1.3 VUV-FEL

VUV-FEL (Vacuum-Ultra-Violet Free-Electron-Laser) is a superconducting linear accelerator [49] with a free electron laser for radiation in the vacuum-ultraviolet and soft X-ray range of the spectrum. The VUV-FEL is based on the TTF (TESLA Test Facility), which was built in 1997 to test the superconducting cavity technology, called TESLA technology. This technology will be used for European X-FEL. A sketch of the tunnel layout of the VUV-FEL is shown in Figure 2.7. The facility makes it possible to carry out tests of different subsystems like: cryogenic, vacuum, control and data acquisition system and the super-conductive cavities. The installed cavities, based on TESLA technology [49] are grouped in 5 cryogenic modules and accelerate the electron beam up to 0.73 GeV. A further increase of the beam energy up to 1.2 GeV is planned when further acceleration modules will be installed. The 30 m long undulator was installed to supply vacuum ultraviolet radiation from 10 to 200 nm according to the SASE principle.

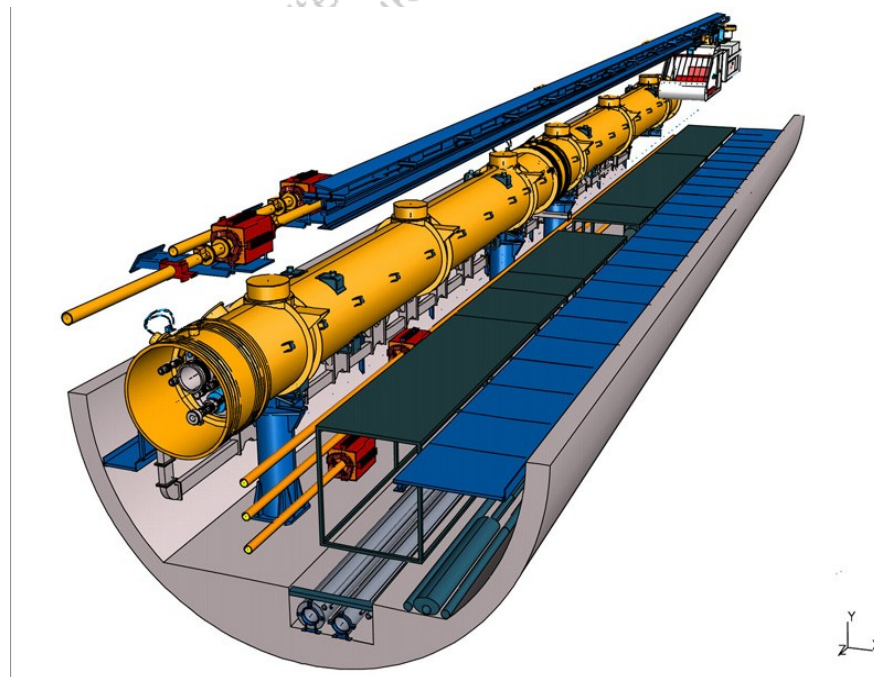


Figure 2.7. The layout of the VUV-FEL tunnel. (Source: DESY)

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The modules are installed along a 260 meter long tunnel with their electronics. Cavities work with a 1.3 GHz radio frequency field, each module is supplied by a 10 MW klystron. Power to each cavity is distributed by a wave-guide distribution system. A FEL consists of a high-energy electron beam passing through periodic transverse magnetic fields with alternating directions. These fields cause the electrons to bend and perform a wavy motion. At each bend, very short pulses of synchrotron radiation are emitted by the electrons as they perform a large number of bends. The emitted synchrotron radiation at each bend is added coherently and in this way, a pulse of short-wave nearly monochromatic radiation builds up successively. The wavelength of the radiation is dependent on the energy of the electron beam and on the periodic magnetic fields causing the wavy motion. By increasing the energy of the electron beam, the wavelength of the radiation can be made shorter. Compared to a conventional laser, a FEL can be tuned continuously to any wavelength, only dependant on the electron energy. The goal is to be able to produce monochromatic radiation down to wavelengths of one tenth of a nanometer (nm). That light will be used in biological and chemistry experiments, but also in research on solids.

2.1.4 ZEUS Detector

ZEUS [20], [37], [44] is a particle detector in operation at HERA (Hadron Electron Ring Accelerator) [2],[42] at DESY, Hamburg. The detector is about 12 x 15 x 14 meters big and weighs 3600 tons. It is an example of a multi-purpose detector used in high energy physics experiments. The major components of the ZEUS detector are the inner tracking detectors [43], situated in the 1.4 T magnetic fields of a superconducting solenoid, the uranium-scintillator calorimeter, muon detection chambers and the luminosity monitor. In addition various dedicated detectors extend the measurement of very forward or very backward going particles. A cross sectional view of the ZEUS detector is given in Figure 2.8. The layout of the detector is shown in Figure 2.9. The essential elements are a vertex detector (VXD, semiconductor detector) [31], a central track detector (CTD) [46] plus transition radiation detector (TRD), and planar drift

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chambers (FTD, RTD) in the field of a thin magnetic solenoid (SOLENOID), an electromagnetic (EMC) and a hadronic calorimeter (HAC) surrounding the coil over the full solid angle, a backing calorimeter (BAC) [24], barrel and rear muon detector (MU), and a forward muon spectrometer (FMU).

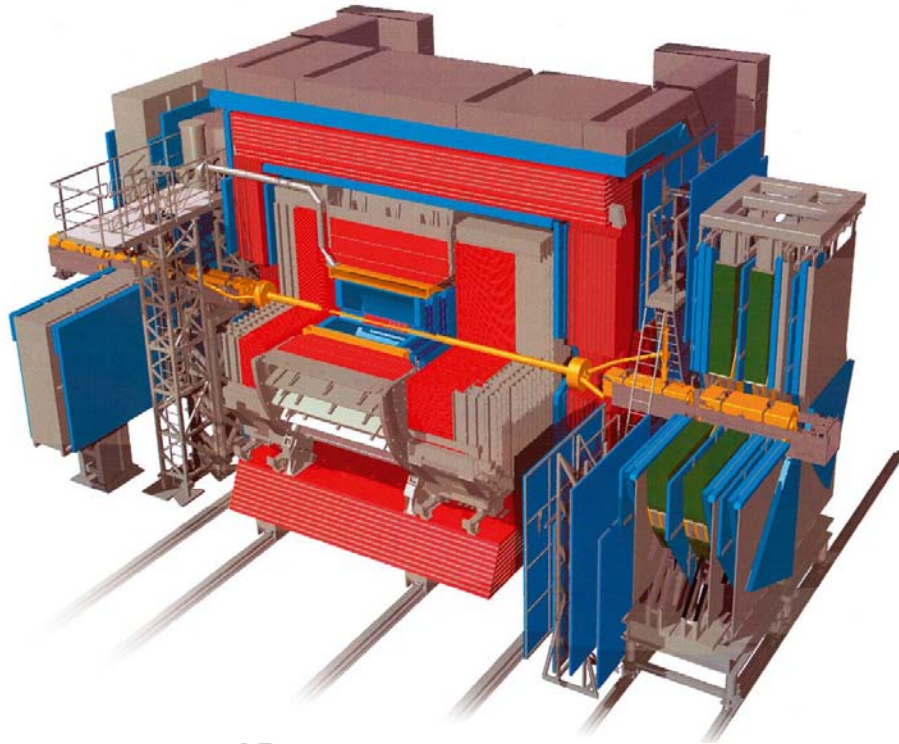


Figure 2.8. The ZEUS detector. (Source: DESY)

The heart of the ZEUS detector is the uranium scintillator calorimeter (CAL) which measures energies and directions of particles and particle jets with high precision. VXD, CTD, FTD, and RTD are surrounded by a thin superconducting solenoid coil producing an axial magnetic field of 1.8 Tesla to determine the momentum of charged particles from their track curvature. Energy not fully absorbed in the uranium calorimeter is measured in the backing calorimeter (BAC) which uses the 7.3 cm thick iron plates of the return yoke as absorber and proportional tube chambers for observing penetrating particles.

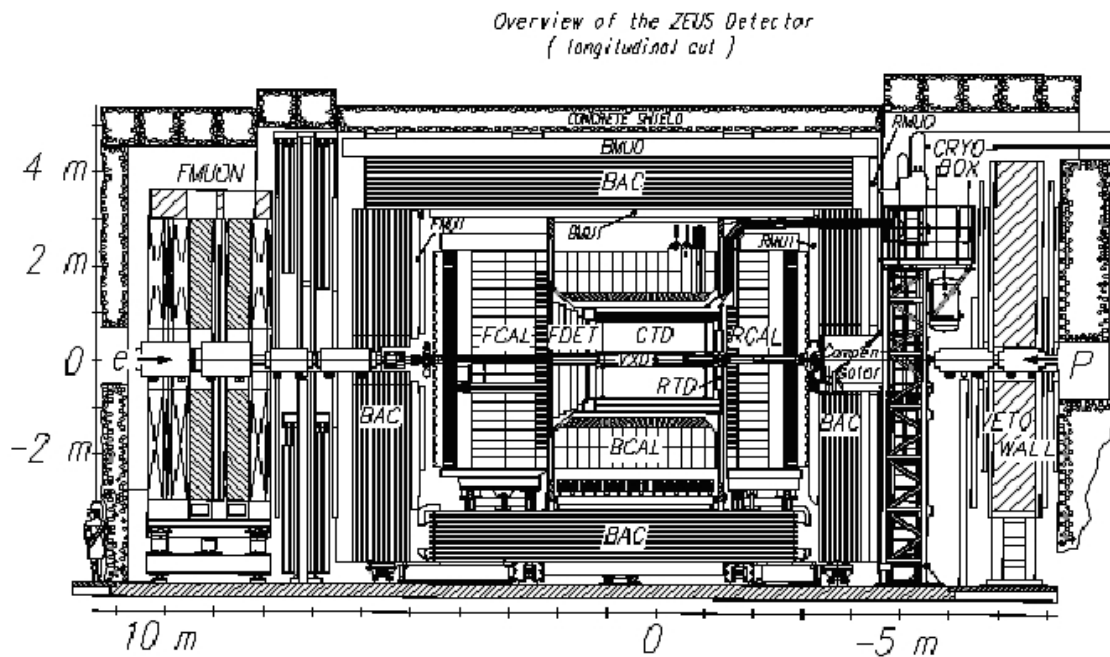


Figure 2.9. Longitudinal section of the ZEUS Detector. (Source: DESY)

Particles which are not absorbed in the substantial material of the uranium scintillator and backing calorimeter are typically identified as muons. Their tracks are measured before and after the iron yoke by limited streamer tube chambers (MUON). The muon momenta are determined by the deflections of their paths by the solenoid and by the iron yoke which is magnetized toroidally up to 1.6 Tesla by copper coils. In the forward direction, magnetized iron toroids fitted with limited streamer tubes and drift chambers can measure very energetic muons (up to 150 GeV/c). An iron wall equipped with two layers of scintillation counters (VETOWALL) is placed near the tunnel exit for detection of background particles produced upstream by the proton beam. The goal of the ZEUS detector is to determine with high precision the energies, directions and nature of single particles and particle jets created in the interactions.

From the electronics point of view, the ZEUS detector can be treated as a set of several hundred thousand analog channels connected to the data acquisition system [39]. The conversion from analog to digital signals is performed in a synchronous, parallel way driven by the common clock source and other control signals. The most challenging issue of the data acquisition system designed for all HERA experiments was the high (10

2.1 Basic researches in High Energy Physics Experiments and their applications

MHz) rate of electron-proton bunch crossings. The principal goal of the trigger system is to recognize and on-line reject events produced by other causes than the electron-proton collisions. Main sources of such background events are the proton (or electron) interactions with residual gas inside the vacuum beam pipe (beam gas events), events induced by the beam halo and cosmic rays. The ZEUS detector consists of more than 250 000 analog and digital channels.

Trigger System

The ZEUS data acquisition system has to deal with the HERA bunch crossing rate of over 10 MHz (The time interval between bunches crossings at the interaction point is 96 ns). The corresponding rate of non-zero signals produced in the detector lies between 10 and 200 kHz. Of these events no more than 10 per second are accepted by the ZEUS trigger chain and stored on tape. In the ZEUS detector, the selection of events [8] and the reduction of background events is achieved by the three-level system presented in Figure 2.10.

The First Level Trigger (FLT) [11],[23],[32, [47]] has to deal with the HERA bunch crossing rate of ~10 MHz, corresponding to 96 ns per bunch crossing. Data from every bunch crossing is stored in pipelines. These pipelines are 46 bunch crossings deep. The FLT is a hardware trigger reducing the event rate to about 1 kHz. The local decisions are future sent to the Global FLT (GFLT).

The Second Level Trigger (SLT) is a software trigger, which reduces the events rate to below 100 Hz. The time available at the SLT allows more complex data analyzes [14] including the calculation of energy deposit and the event timing in the calorimeter. Each component uses the transputer network [35], which makes the local SLT decision and sends it to the Global SLT. In case the GSLT makes a positive decision, the data is sent to the Event Builder (EVB)[8]. The EVB combines information from different components into one data block, allowing the data processing at the next trigger level.

2.1 Basic researches in High Energy Physics Experiments and their applications

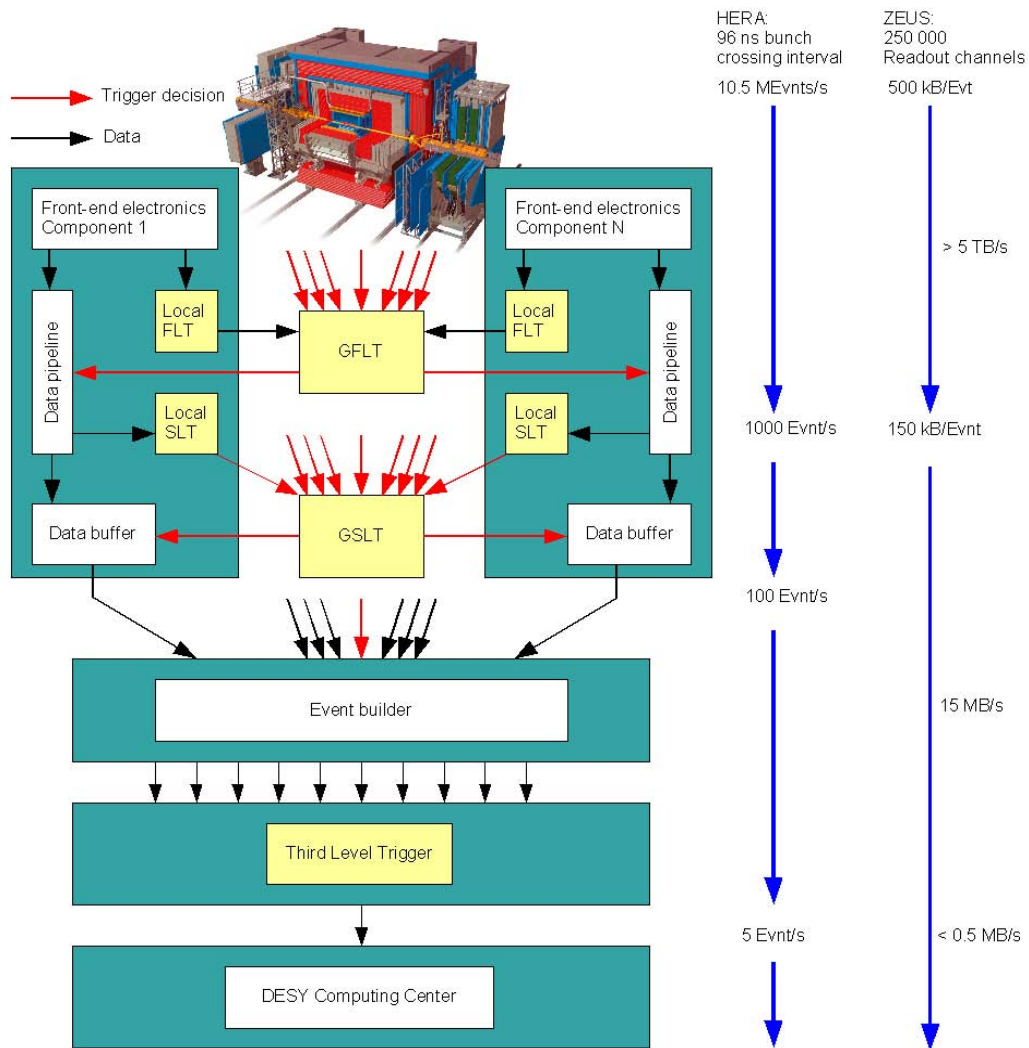


Figure 2.10. The schematic diagram of the ZEUS free-level trigger and data acquisition system

The Therd Level Trigger (TLT) [45] is a software trigger reducing the event rate to $\sim 5\text{Hz}$. The TLT is a computer farm, which runs the simplified version of the off-line event reconstruction code, including track and vertex reconstruction algorithms. The TLT is based on the physics filters, which reduce the background events. Data satisfying the TLT requirements are sent to the DESY computing center and recorded on the magnetic tapes for future off-line analysis.

2.2 Backing Calorimeter

BAC is a sampling calorimeter assembled using aluminum proportional drift chambers. The typical structure of an electronic readout [20], [21] and principles of operation are presented in Figure 2.11. The iron yoke of the ZEUS detector, covering the uranium calorimeter, serves as a mechanical support for the whole construction. The chambers, made from an aluminum extrusion of typically 5m length, are inserted into the gaps between the iron plates of 7:3 cm thickness which are used as a calorimeter absorber material. A gas mixture of Ar and 13% CO₂ is used as an active gas medium. The forward region (Forecap) is instrumented with 10 layers, the Barrel with 9 and the

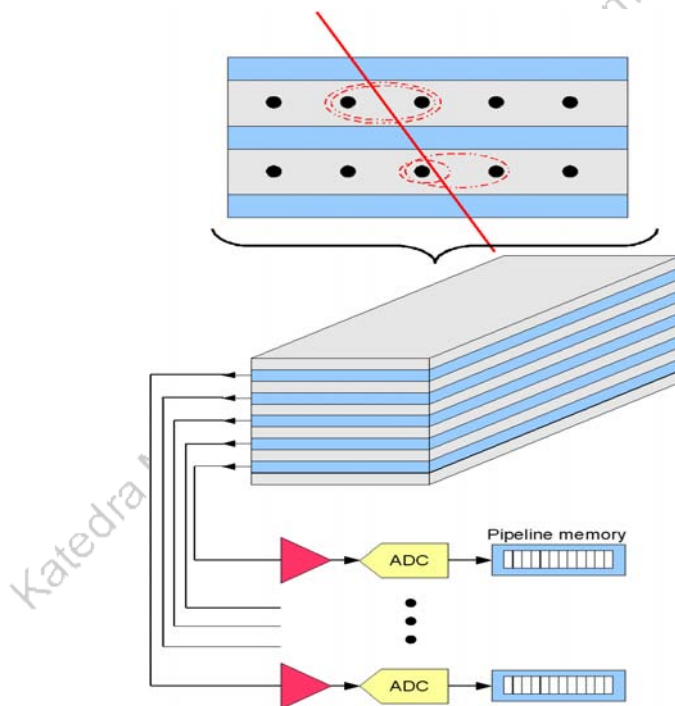


Figure 2.11. Gas chamber of the Backing Calorimeter, principles of operations

Rearcap with 7 layers of chambers. All regions of BAC are shown in Figure 2.12. Such detectors are very sensitive to ionizing particles they are also characterized by relatively long drift time of the collected charge. In case of the BAC, the drift time to the anode wires is on the order of 100-150 ns, which is comparable to the time interval between

2.2 Backing Calorimeter

two consecutive HERA beam crossings. Collisions of electrons and protons occur at the frequency of 10 MHz and this defines also the frequency of the clock used in the experiment. In order to deliver on time trigger decisions associated with a given bunch crossing, the jitter of the signals must be very well controlled. Moreover taking into account the geometrical volume, BAC is the biggest ZEUS component and in terms of cable lengths different detector areas are separated by several tens of meters. This requires a perfect transmission and synchronization of trigger signals coming from different parts of the detector.

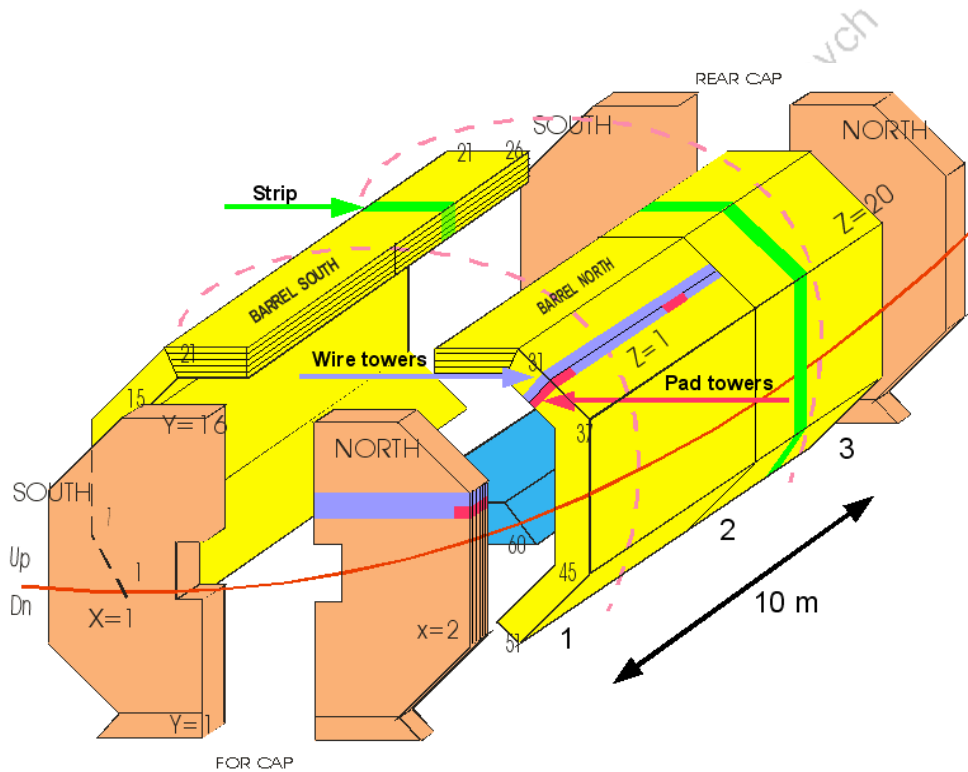


Figure 2.12. Main units of the Backing Calorimeter detector.

2.2.2 Data acquisition

The BAC detector is equipped with large, distributed, electronic measurement and acquisition system, which receives data from over 5 thousands gas chambers with over 40 thousands position (digital) [22], and over 2 thousands of energy (analogue)

2.2 Backing Calorimeter

channels every 96 ns. Its components are located all over the detector and some links are up to 100m long. Most of the data acquisition electronics is located inside the ZEUS detector (analogue front-end electronics and position readout modules [30]) and outside the detector in 22 VME crates. Distribution of electronics modules is shown in Figure 2.11. The complete system consists of more than 200 different types of VME boards and 150 different power supplies.

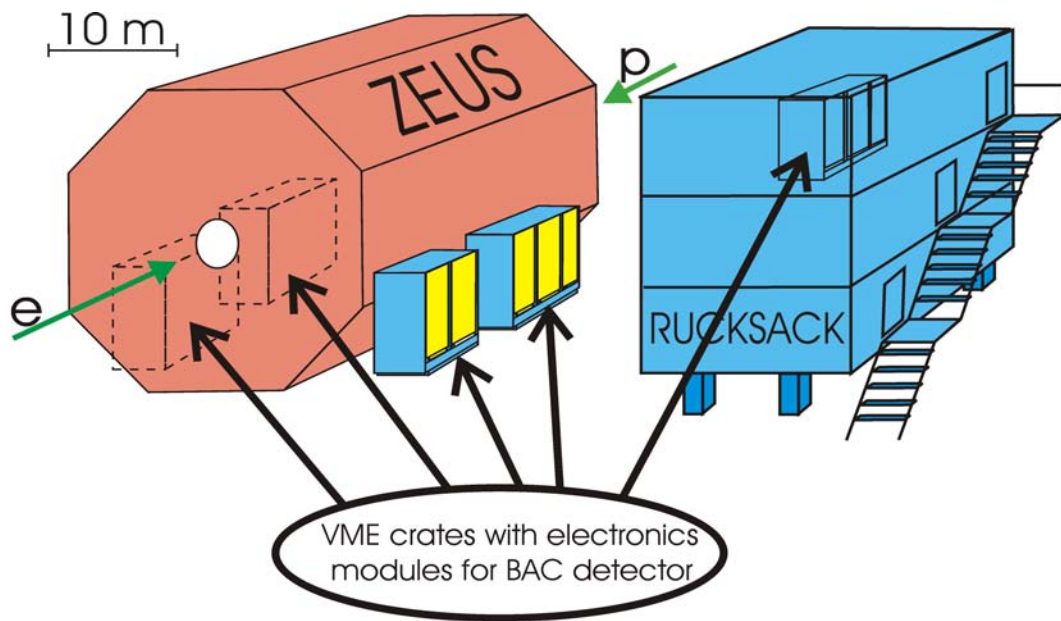


Figure 2.11. Placement of electronics modules

The detector is equipped with two kinds of readout:

- analog – allows to read the deposited energy (energy readout)
- digital – allows to reconstruct the particle trace (digital readout)

Block diagram for the analog readout is shown in Figure 2.12, for the digital readout in Figure 2.13. Charge from the chamber cathode pads is summed and amplified. The signal from this preamplifier is converted (Shaper) to a voltage than digitized. A digital representation of the charge is stored in a pipeline memory. Signals from chamber wires are connected to comparators with programmable thresholds. If the voltage from a wire is bigger than the comparator threshold, that information is written to a pipeline memory. Both analog and digital acquisition is done with the clock of the experiment.

2.2 Backing Calorimeter

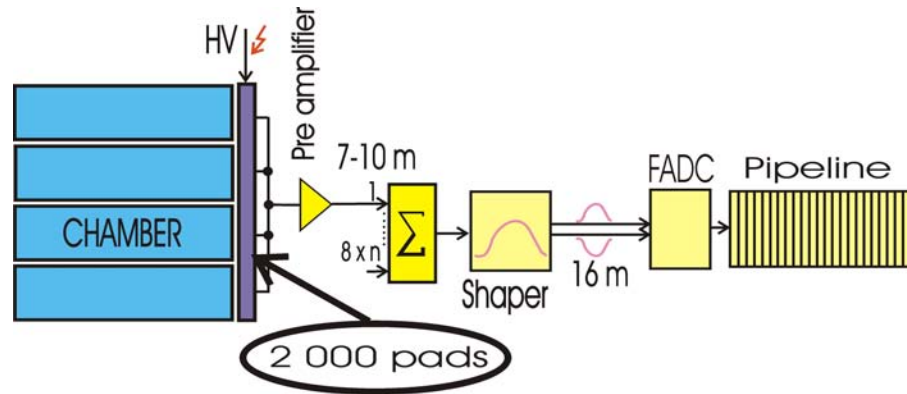


Figure 2.12. Energy readout

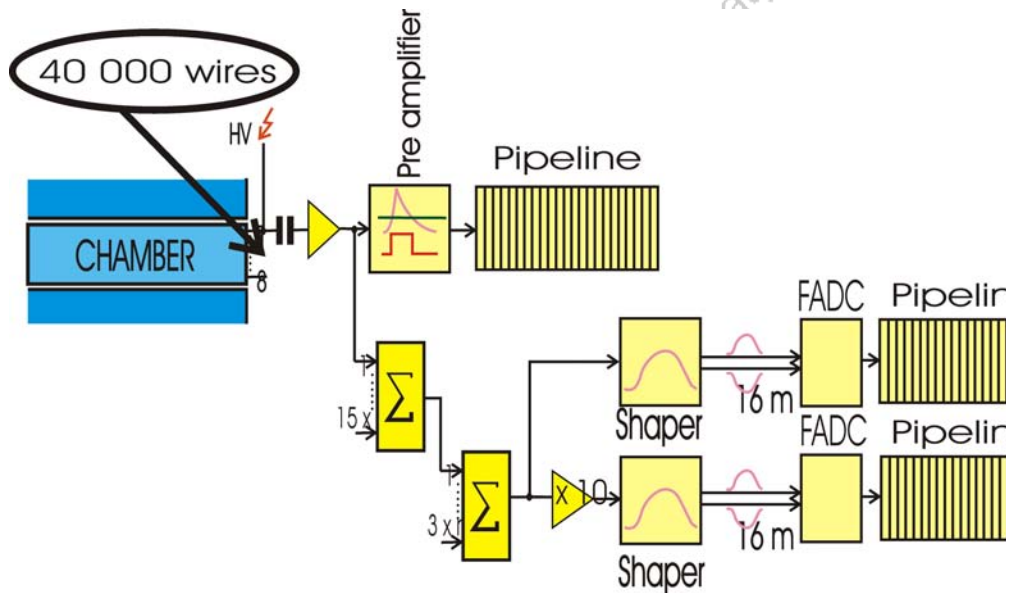


Figure 2.13. Position readout

2.2.3 Trigger system

The Backing Calorimeter is equipped with an energy and muon trigger. An area composed typically of up to 16 wire and strip towers (see Figure 2.12.) is the smallest unit of the detector for which the trigger [23] variables are calculated. The trigger decision [11] is produced using data coming from the wire and strip towers. Analog signals corresponding to the deposits measured in the wire and strip towers are digitized

2.2 Backing Calorimeter

by FADC's. A simply block diagram of the BAC trigger system is shown in Figure 2.14. Signals from wire towers are processed by WTT (Wire Tower Trigger) boards, while signals from strips are processed by STT (Strip Tower Trigger) boards. After conversion the data is stored in pipelines and simultaneously diverted to a Local Maximum Finder (LMF). The WTT board contains one LTM memory for each input channel.

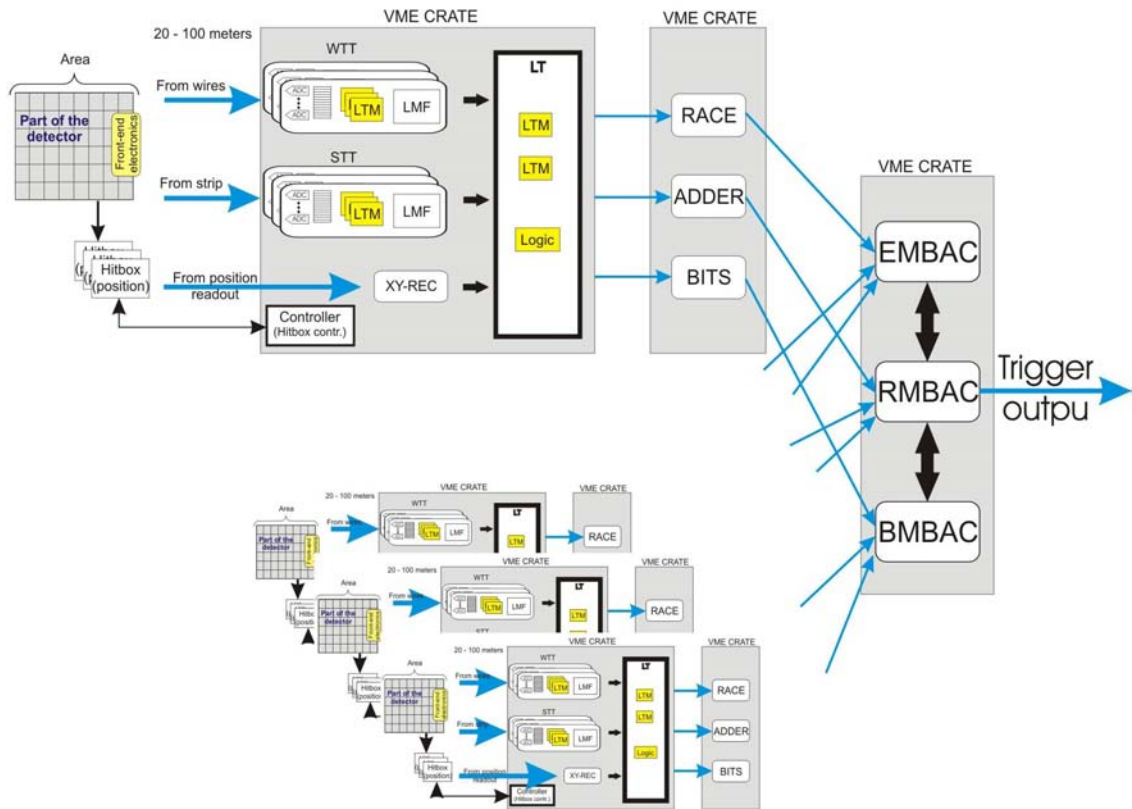


Figure 2.14. Block diagram of the BAC trigger system

After the analog to digital conversion, 8 bits corresponding to the measured deposit are used to address the LTM memory on the WTT board. The STT board contains two LTM memories for each input channel. One is used for energy, the other one for the transverse energy. Both LTM memories are addressed with 8 bits. On the STT and WTT boards, the sum of energy and transverse energy over the whole area is also calculated. Bits corresponding to Minimum Ionizing Particles (MIPs) are counted. The highest energy deposit together with its location is also being determined for the wire and strip towers. All these values are transferred to the main trigger board of the

2.2 Backing Calorimeter

area called LT (Logic of the Trigger) for further processing. The BAC muon trigger is using data from the position readout. The electronic system dedicated to the position readout contains a programmable Lookup Table Memory (LTM). This memory allows to separate muon from hadron cascades using fast pattern recognition.

The processing of the data from the area is performed on the LT board. The final energy from the area is calculated using a multiplexing circuit, which allows choosing between the deposit measured in the wire towers and in the strip towers. The mechanism includes the energy correction and allows selecting the value which is less biased. Processing of the trigger data by the LT board is also based on look-up table memories. The LT board contains two LTM memories, one of which is used for processing the energy data, and the other one is used to classify muons according to the topology of their trajectory. To classify muons, the LT board receives the arithmetic sum of the X bits (corresponding to the number of muon tracks registered in area) coming from the XYREC board and the number of MIPs (Minimum Ionizing Particles) from WTT and STT boards. As a result of this correlation between position readout and energy readout muons can be classified as those which were produced in the center of interaction, as cosmic muons and as the muons used for the calibration (perpendicular to the tower). The sum of transverse energy and energy from balconies is performed at two identical boards, called ADDER. Finding two highest deposits together with their location is conducted on the RACE board. Determination of the muon identification is performed by the BITS board. The output variables from this board contain information about the muon classification from 6 North and South areas. All above boards synchronize also the signals received from different areas.

Energy, transverse energy, the value and physical location within the detector of the two highest energy deposits and muon identifications are calculated as the final result. The final output of the Backing Calorimeter is produced on the MAIN boards (EMBAC, RMBAC, BMBAC). The EMBAC board calculates the sum of the total energy and transverse energy. The two highest energy deposits along with their physical location are determined on the RMBAC board. The BMBAC returns information about the muon identification as seen by the Backing Calorimeter: 13 bits contains the information about muons from interaction point for individual areas and 2 additional bits

coding the information about cosmics and calibration muons.

2.3 LLRF at the VUV-FEL

The LLRF system controls the electromagnetic field inside the cavity. A complete system consists of a probe which measures the field inside the cavity, a downconverter which converts the acceleration frequency of 1.3GHz down to an intermediate frequency IF (250 kHz, but also 81 MHz is evaluated), various controller boards (ADCs, DACs, DSPs and FPGAs), a timing and trigger distribution system and a vector modulator (VM). The downconverted probe signal is digitized by the ADCs and sent to the DSP/FPGA controller. The controller features implemented feed-forward and feedback algorithms [50]. It produces the driving signal for the VM, which consists of separated real (I) and imaginary (Q) parts. For the output signal calculation, the algorithm uses the vector sum of the electromagnetic field from 32 cavities derived from the probe signal. Also forward and reflected power is measured for each cavity. In the end, the system has hundreds of fast, high resolution, analog inputs (14 bits, 105MSPS ADC are used) and fewer outputs to systems like the VM, piezo controllers to compensate lorentz force detuning and microphonics of cavities, and monitor systems. A block diagram of the LLRF system is shown in Figure 2.15.

The VUV-FEL works in a pulse mode. This means that the electron beam is accelerated only during a given time. The required length of a RF pulse is 1 μ s with a repetition rate of 5 Hz.

There are two kinds of control algorithms:

- fast – algorithms work during RF pulse
- slow – algorithms work between pulses

2.3 LLRF at the VUV-FEL

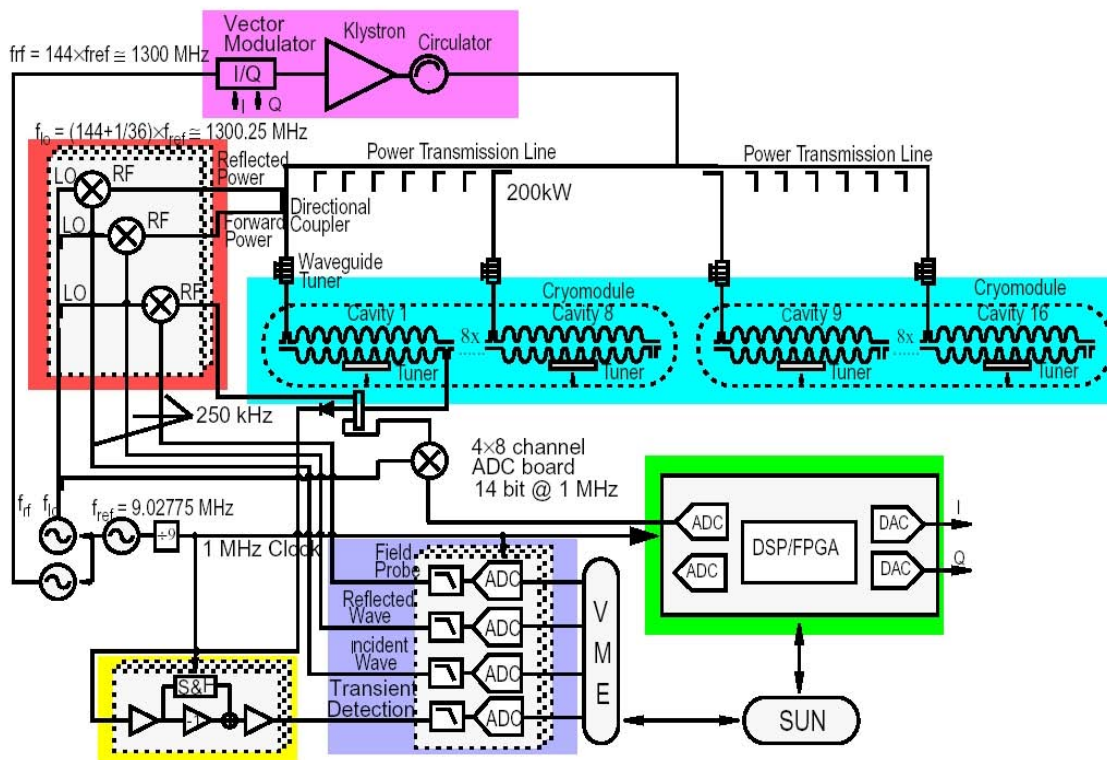


Figure 2.15. LLRF System for VUV-FEL

The RF phase and amplitude stability must be better than 0.01 and 0.1%, respectively. Accelerating cavities are supplied with a 1.3 GHz signal produced by 5 and 10 MW klystrons controlled by actuators (VM's) that act on its amplitude and phase. Digital data processing is performed in the control system and generating the driving signal for the klystrons.. The accelerator control system is distributed along the tunnel and installed in VME crates. The LLRF system has to operate with a reliability in excess of 99 per cent.. It is planned to have only one maintenance day per month.

2.3.1 Timing system and control system

The LLRF system works synchronously with the machine clock. A high stability clock with coded events [52], is distributed to all VME crates and to all control boards.. The clock parameters are crucial for stable operation of the linac.

VME boards work under the DOOCS control system [51]. This control system provides

2.3 LLRF at the VUV-FEL

control parameters, an interface to users and collects data from readout.. DOOCS is an object oriented, distributed control system and runs mainly on Solaris, SunOS and PC's with a LINUX operating system. DOOCS is equipped with interfaces to others programs such as LabView or Matlab. In DOOCS terms, a device server is an independent program that completely controls a number of devices and provides data to the network. A client is an independent program which receives that data and sends control messages to the servers. Parts of the control algorithms (slow) work on DOOCS servers.

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Chapter 3

Diagnostic systems for electronic components used in the HEP experiments

This chapter presents ideas of the complex tests needed to ensure the performance of electronic modules used in high energy physics experiments. Parameters describing system performance are defined. Requirements concerning the diagnostic system for electronic modules used in HEP systems are presented. Advantages of the novel methods proposed are explained and evaluated.

3.1 Introduction to the problem

Accelerators and detectors can have different sizes. They range from tens centimeters for a one cell cavity to a circumference of 27 km for the LHC at CERN. Depending on its purpose, a detector may range in size from a single semiconductor element with size of a few square millimeters to a cube with dimensions of 20-30 meters, e.g. the ATLAS detector at LHC with dimensions of 45 by 25 meters and a weight of 7000 tons. Also, the number of electronic channels may vary from single channel systems to millions of channels for big scale HEP detectors. It is obvious that the requirements are significantly different for various sizes of these devices. This thesis covers large scale, distributed

3.1 Introduction to the problem

electronic systems, with multiple hundreds of channels, with special consideration of parameters

There are many parameters crucial for a the desired performance of the whole system. Important parameters like sensitivity, resolution, stability, accuracy, etc, for the electronic modules used are described in detail in the system specifications. In addition to the parameters mentioned above which mainly describe the physical performance of the modules, the following parameters are crucial for the effective long term operation of the system:

- availability – information how long a machine is available for user operation, how many hours per year users can use the machine.
- reliability – how long the machine will work without interruption. If a failure of a subsystem occurs, how does it influence other subsystems and what kind of performance degradation has to be expected.
- operability – information on how easy it is(if it is possible at all) to control the machine by users. It includes calibration procedures, parameter changes, etc..
- maintainability – how easy (in terms of person power/money) it is to detect malfunctions in the system and repair these.

Many detectors and accelerators are not equipped with complex diagnostic systems. Simple test procedures exist, but only for some parts of the electronic modules. Usually they are called expert programs and used by hardware designers during the commissioning phase of a machine, but not for maintenance. Additionally these test procedures are usually not available to machine operators. Even if they exist, they operate on different computer platforms; there are no common, standardized interfaces to the electronics board. The lack of complex diagnostic systems causes reduced machine availability and increased human intervention is needed to locate failures. The distributed electronic modules implemented in most active accelerators require complex diagnostic systems, which allow locating any malfunction to the level of the module. Furthermore, a diagnostic system has to provide information on where to find a damaged

module

3.2 Diagnostic systems for electronic modules

The typical structure of a data acquisition system for a detector is shown in Figure 3.1. The system consists of front-end electronics installed directly on the detector; interconnected VME crates distributed around the detector, power supplies, communication to other subsystems (e.g. human protection or an accelerator), and to the control system. Data from the detector is initially processed by the front-end electronics, and then sent to boards installed in VME crates. Depending on the size of a detector, a data acquisition system has to process up to hundreds of thousands of input channels. In case of the BAC detector, 40 000 digital and 2200 analog channels have to be processed. Processed data is sent to a computer center, which requires a throughput in a range of 1-4 TB per day.

Usually, a detector is equipped with a slow control system [29] to monitor power supplies (low and high voltage), parameter of media used in the detector (e.g. composition of gas used in the detector, temperature) etc.

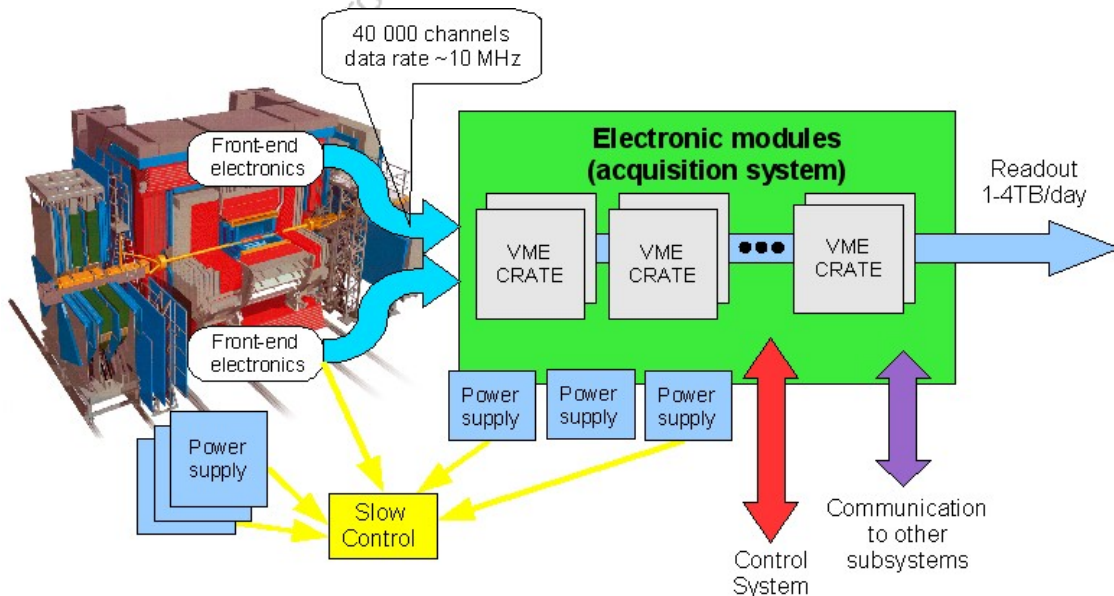


Figure 3.1. Detector

3.2 Diagnostic systems for electronic modules

The structure of a low-level RF control system for an accelerator is presented in Figure 3.2. The system consists of electronic modules - VME boards distributed along the accelerator, power supplies, communication modules to other subsystem (e.g. beam position monitoring or high power section) and software, being the control system for the hardware.

Probe signals from cavities are sent to electronic modules, and then processed. The output signal (error signal) of the digital controller drives the vector modulator and thus regulates the RF amplitude and phase. There is usually the possibility to make a readout from the controller, which can consist of input and outputs signals and other internal important data which is sent to a computer centre and stored there. Just like in the case of the data acquisition system in a detector, a slow control system monitors all power supplies used.

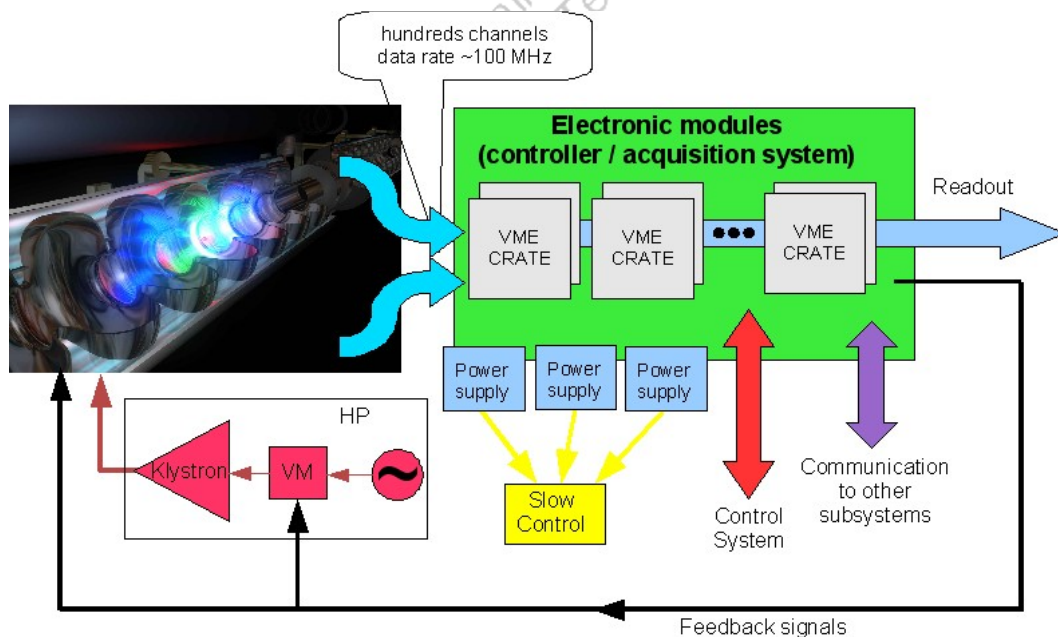


Figure 3.2. Accelerator.

A detailed analysis of the data acquisition system of the BAC detector and the low-level RF control system of the VUV-FEL showed that both systems have a similar structure of

3.2 Diagnostic systems for electronic modules

electronic modules. The data acquisition system or control system for HEP machines consists of hundreds of electronic boards put into crates. The most popular form factor for existing experiments is the VME/VXI standard allowing for a widely distributed system. Boards and crates are connected together by different types of links [18-A], which length reaches hundreds of meters. Both systems are example of distributed electronic system equipped with large number of inputs and outputs. Requirements concerning reliability, availability, maintainability and operability are similar. Places of electronic modules and data flow are shown in Figure 3.3. Output signals from detectors or probe signals from cavities are processed and transferred to acquisition and control system modules. In case of an accelerator, a feedback signal is produced by the electronics.

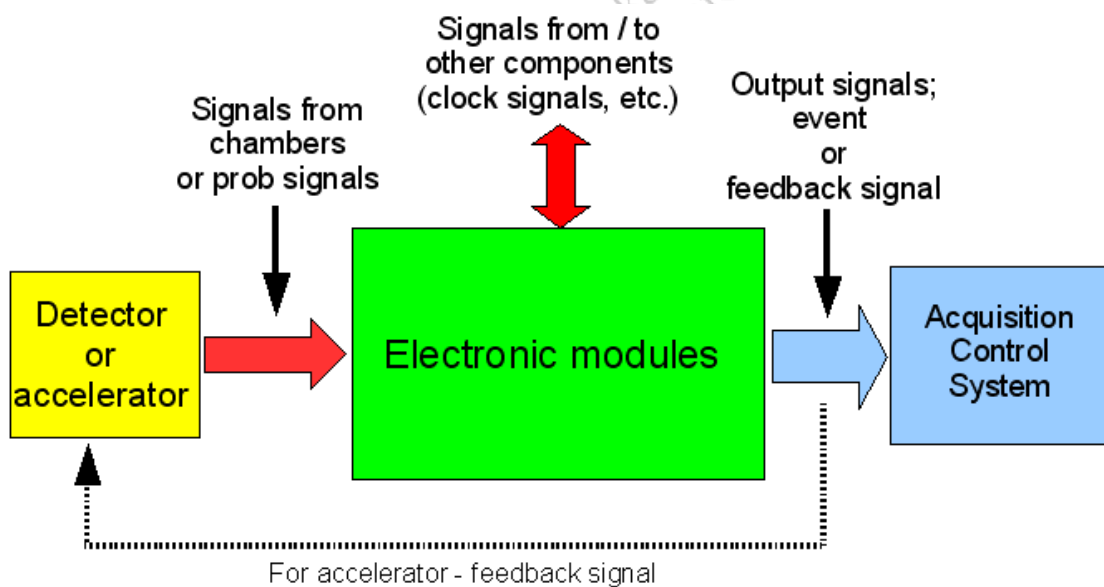


Figure 3.3. Electronic modules in detector and accelerator.

A possible test scenario of electronic modules is presented in Figure 3.4. A well defined test vector signal $I_s(t)$ is connected to the inputs of the electronic modules to be tested. The signal output vector $O_s(t)$ is measured. If the system transfer function $H(t)$ is known, the expected output signal $O(t) = H(I_s(t))$ can be calculated and compared with the measured signal. Also, rudimentary information about the operating condition of the electronics is known.: the system works or it does not.

3.2 Diagnostic systems for electronic modules

That information is however not sufficient. Some elements are installed directly in the accelerator or on the detector and thus not accessible during operation.. To access these elements it is necessary to erect a scaffold or remove heavy concrete shielding. During a maintenance day (which is usually once per month) a service crew has to be able to repair many failures. Some of them require the exchange of an electronic board, power supply or the repair of broken connections. Without precise information about the malfunction type and position within the system, maintenance requires excess manpower

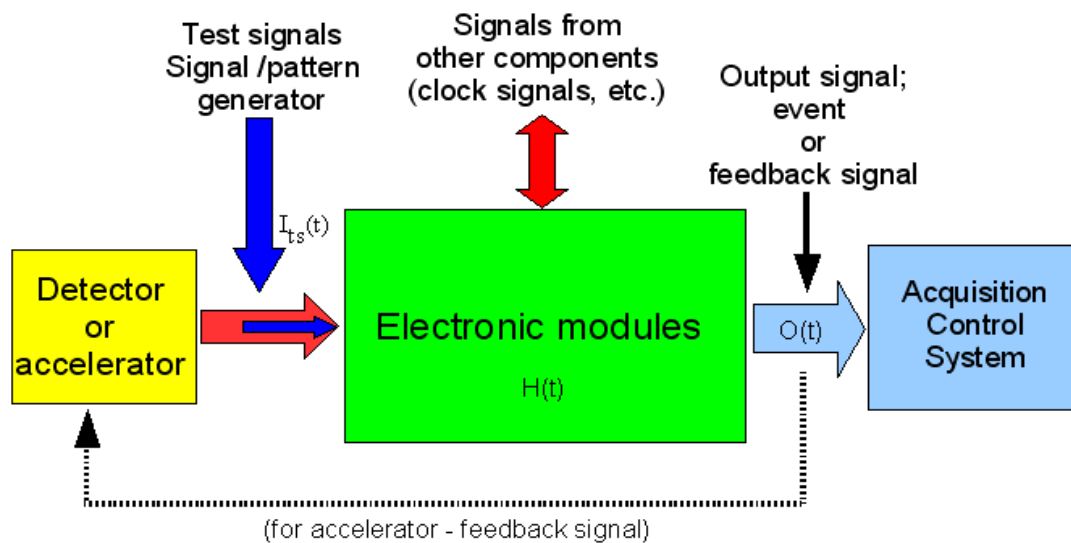


Figure 3.4. Tests of electronic modules with external test signals.

It is not readily possible to detect malfunction on the individual board level with the testing scenario presented in Figure 3.4. Data flow from the occurrence of an event to saving processed data on a hard drive requires multiple electronic boards chained together parallel to one another. In Figure 3.5 an example system, consisting of three chains with various numbers of boards having n inputs and m outputs each, is presented. Chain number one consists of the Board 11 up to Board 1X. At the end of all chains one board, Board M, collects data from all chains and produces the final outputs signal(s). Real systems consist of 100-1000 chains with up to 10 boards in one chain and up to a few hundred boards in the system. Both data acquisition system and control system used in HEP experiments have the structure presented in Figure 3.5.

3.2 Diagnostic systems for electronic modules

In the chain different types of electronic modules (electronic boards) are used, but they have some similarities. The block diagram of an electronic module is shown in Figure 3.6. In general, each electronic module is equipped with inputs, outputs, logic (DSP, FPGA), registers, memory and interface.

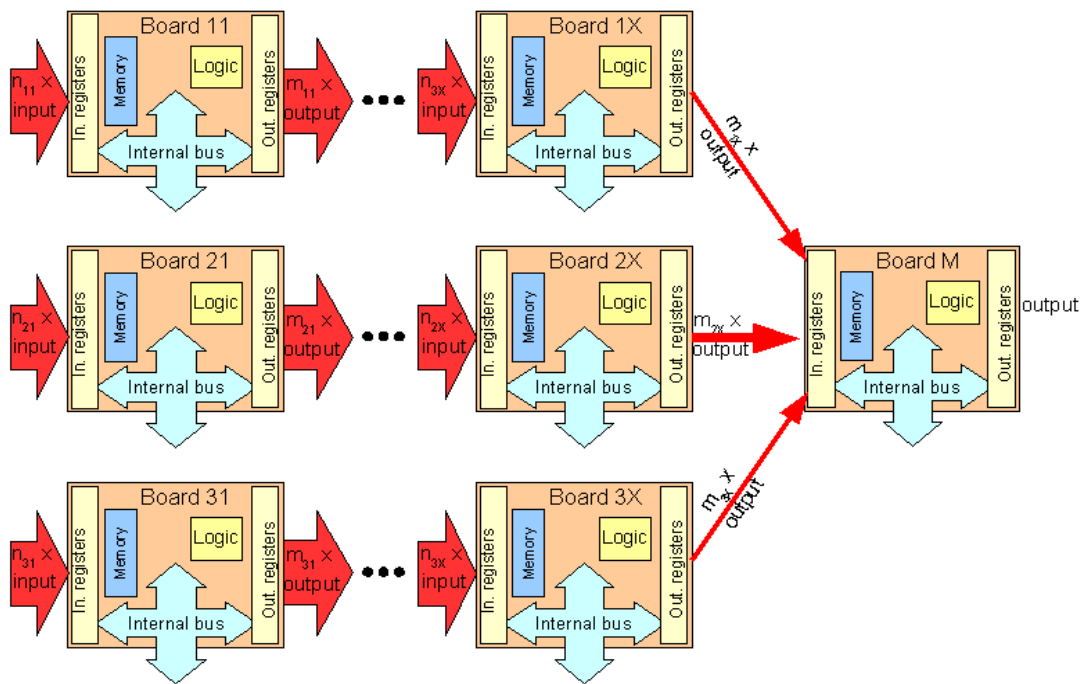


Figure 3.5. Structure of data acquisition and control system used in HEP experiments. Connection and data flow between electronic modules are presented.

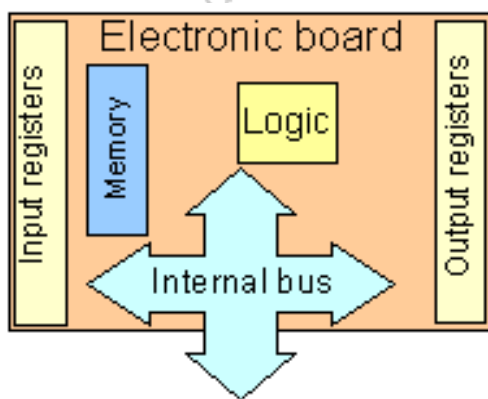


Figure 3.6. Single electronic module (electronic board).

Interface could mean VME interface, but also any communication channel such as PCI, GigaLink or Ethernet [18-A]. In most cases, access to each internal registers and memory is possible through a communication interface for which usually an internal bus is designed. The function of the electronic board depends on the logic implemented on the board.

3.2 Diagnostic systems for electronic modules

A standard method of testing an electronic board is presented in Figure 3.7. A test signal is connected to the inputs of the testing board, (in the example Board 2X) and A logic analyzer or oscilloscope is connected to the output. The behavior of the board can be tested.

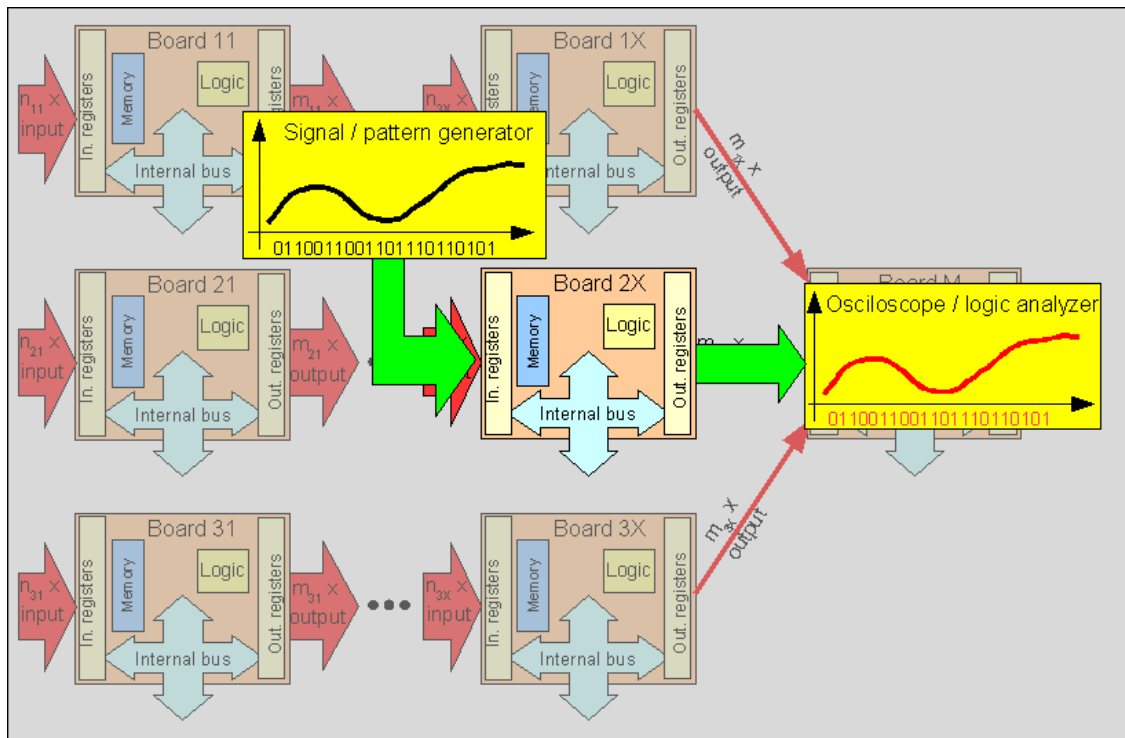


Figure 3.7. Standard procedure of testing electronic modules.

The method presented in Figure 3.7 has the following main disadvantages :

- it is necessary to disconnect inputs and outputs, which can cause additional damages,
- it requires the use of expensive tools on scaffolds,

Consequences of mentioned above disadvantages are:

- long time is required for maintenance,
- low availability, which could be increased,

3.2 Diagnostic systems for electronic modules

- diagnostic during short brakes of operation are practically impossible,
- there is no possibility to examine the logic configuration of a module.

Knowledge about the kind of failure in electronic modules and its precise location allows modification of the data acquisition or control procedures and thus provides continuous operation. It is usually more advantageous to take less data from a trustworthy part of the experiment than to take a chance of having fake or incorrent data in the sample taken. If e.g. some malfunctions exist in one part of data acquisition system of a detector, and it is still possible to take data from 95% of the chambers, there is no point to shut down the whole detector for maintenance. It is sufficient to modify the data acquisition software and exclude the corrupted channels.

In Figure 3.8 another idea for a test procedure for electronic modules is presented. Part of the chain of electronic modules is shown. It consists of four boards: “Board 11”, “Board 12”, “Board 13”, “Board 14”.

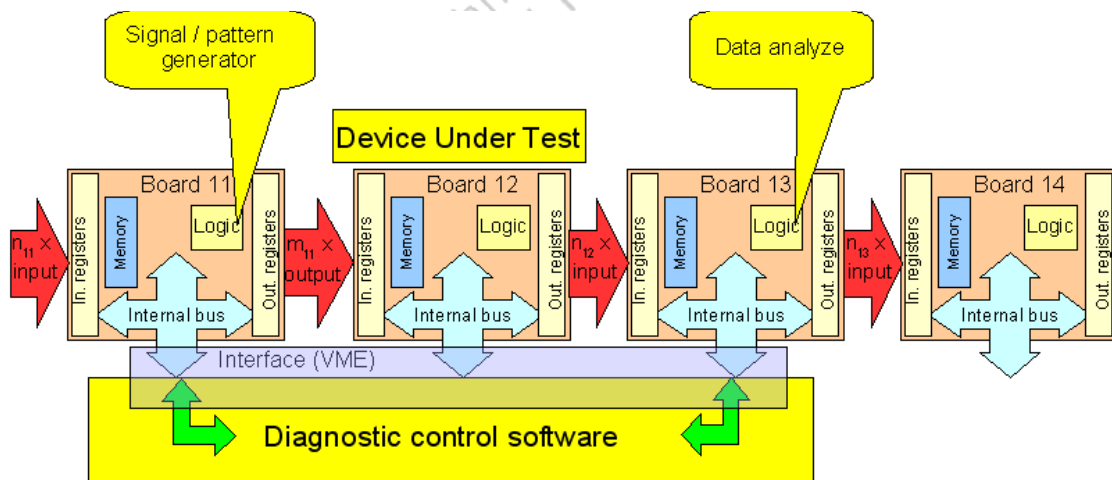


Figure 3.8. Idea of tests electronic modules in the system.

To test the board designated as “Board 12” (DUT – Device Under Test) the two neighboring boards (the previous (“Board 11”) and next (“Board 13”) in the chain) can be used. If it is possible to write and read data from and to boards: “Board 11” and “Board 13”, then the first can be used as a source of test signals and the second one as a data analyzer. All these boards are normally connected together, there is no need to

3.2 Diagnostic systems for electronic modules

change or add any connections. All boards are controlled by diagnostic control software. These boards in conjunction with the control software can be called a diagnostic system for any given electronic module or system. The software is an integral part of the diagnostic system based on the method presented. The diagnostic control software drives and controls the board used as signal source and receives data from board used as logic analyzer. If the logic on the boards is programmable (by the implemented FPGA's) and it is possible to change that logic through an interface, then the logic can be modified also for diagnostic purpose. The intelligence of the diagnostic system depends exclusively on the control software. That method allows to check all boards in a chain, one by one or whole chain starting from beginning to end.. Any damage can be localized up to the:

- board,
- channel in the board,
- block of or component on the board.

During tests with an external signal source both board and acquisition software can be used for data analysis (result of test), depending on which part of the system has to be checked.

A diagnostic system can be connected to a database [10],[26, [27]]. This database can contain configuration parameters, result of tests, information about the location of all electronic modules and the mutual connection between them. After a test, a map of failures can be displayed. For physicist there is the immediate information on where not to expect proper data from. A diagnostic system equipped with such a database is a powerful tool for maintenance. In addition, it can be equipped with external sources of test signals to allow the following tests:

- coarse, fast test with the external source. The possibility to check the complete chain of electronic boards, calibration parameters, timings signals and the configuration during short brakes of detector operation,
- precision tests. This allows to examine each memory, register, logic unit and locate damage,
- monitoring – which works in parallel to the control/data acquisition system. It

allows to monitor crucial parameters of the system.

The result of such tests can be used to modify the data acquisition or control system to improve its performance and minimize disturbances of normal operation. There is no real possibility to repair the system at any time. A diagnostic system connected to the database can significantly decrease the time needed for maintenance. Information about the structure of the diagnostic system can be found in [1-A],[2-A], and [3-A].

3.3 Summary

An analysis of the data acquisition system of the Backing Calorimeter and the field controller for the low-level RF system of the VUV-FEL showed that the architecture of the electronic modules used is very similar, although they are used for a completely different purpose. Both systems have common requirements for the system performance. Tests with an external source of test signals cannot give unambiguous information which board in a chain is damaged.

The ideas of test procedures presented utilize neighboring boards and offer the possibility to locate a damage board in the chain of electronic modules. A diagnostic system with both testing methods gives an excellent opportunity for different rough and detailed tests of electronic modules and allows the precise localization of a damaged board. The presented system does not require significant hardware modifications. Even if the external source is not added, it is possible to test a significant part of the electronic modules without any hardware modification.

The failure of the diagnostic system for electronic modules used in HEP must not stop the experiment. In addition, a diagnostic system should:

- decrease maintenance cost. (if the system will be able to locate the source of malfunction the downtime is significantly decreased),
- increase availability – shorter interruption of operation means higher availability,
- be flexible – it should be possible to add or change testing procedure if necessary.

3.3 Summary

Even the best diagnostic system cannot increase reliability! Reliability depends on design of electronic modules and software which control whole system.

With the experience gained by working on a diagnostic system for electronic modules used in HEP experiments, the following conclusion can be drawn. During the initial design stage of the electronic systems, the necessity of a diagnostic system is commonly neglected or postponed to a non specific time in the future. The main reason is to save money, but also the assumption that electronics will never fail, which is obviously not true. Maintenance problems are not considered. Usually after the first few years of operation, complex diagnostics are required, electronic modules start failing and time required for maintenance grows.

Taking advantage of the structure of electronic modules used in HEP experiments and some smart for electronic modules itself it is possible to design a diagnostic system using the ideas presented in this chapter. The designer of the electronic modules must provide access to internal registers, logic elements on electronic modules, and there must be the possibility to connect test signals to front-end electronics. This would guarantee the possibility to equip an electronic system with sophisticated diagnostics without any need for hardware modification.

Chapter 4

Diagnostic System for BAC detector

This section describes the diagnostic system designed for the Backing Calorimeter [8A]. Requirements and sources of perturbation are presented. The idea, concept, and realization of diagnostic system will be explained.

4.1 Requirements for the diagnostic system

The main tasks of the diagnostic system are:

- failure detection
- the test of all electronic
- the examination of the connections between boards
- the check of logic and algorithms
- the check of the timings
- the analysis of the correlation between failures
- the presentation of the test results.

Requirements for the diagnostic system are partially determined by the detector and its requirements, which have been presented in Chapter 3. Some special, additional

4.1 Requirements for the diagnostic system

requirements are imposed by the HERA accelerator and BAC detector must fulfill them. During normal operation, HERA runs seven days a week, 24 hours each day. Every few weeks there is 'access day' scheduled, this means that the accelerator is switched off and staff can enter the tunnel to perform maintenance work. From the point of view of the detector, HERA has three, sometime four, 20-30 minutes long brakes in operation during a day. Every 6-8 hours the accelerator must be filled again with electrons and protons. This time is not scheduled and during that period, with some exception*, detectors do not need to be operational.

There are also additional requirements from customer which causes other restrictions imposed on the diagnostic system. One of the most important limitations was to build the diagnostic with limited manpower and resources.. Practically, new hardware design and complete replacement of the old hardware was impossible.

Initially, based on HERA and customer requirements primary demands for the diagnostic system for the BAC detector were defined:

- 1) the diagnostic system must increase availability of the detector
- 2) decrease maintenance cost
- 3) failure of the diagnostic system must not disturb operation
- 4) it is necessary to find a way to diagnose the detector base on existing data acquisition system of the detector (lack of money for new design and hardware).

The main task of the diagnostic system it is provide higher availability for the detector. This requirement can be met, if the downtime due to maintenance and repairs can be decreased. In addition, if the diagnostic system is able to validate the configuration data for the acquisition system, data credibility and detector availability will be improved. Furthermore, a reliable diagnostic system increases machine maintainability.

4.2 Sources of perturbations

First of all it was necessary to identify the sources of potential problems in the Backing Calorimeter. There are three main reasons why the detector may not be able to gather

4.2 Sources of perturbations

data:

- failures in its electronic components
- wrong configuration data for the acquisition system
- problems with the control software

Failures in electronic modules can occur at any time in any module. The problems most often observed concern:

- power supplies
- front-end electronics (hit-boxes)
- the connection between boards
- the trigger system.

Wrong configuration data can make data gathering impossible. Each digital input (of over 40 000 in total) is equipped with comparators [4] with a programmable threshold. A too high threshold value of the comparator may make it impossible to register any particle, whereas a too low threshold will cause fake data to appear with the real data and due to an increased rate of the trigger system will lead to an increase in dead time.

The BAC detector can also be used to detect cosmic muons, but this requires the HERA accelerator to be switched off as the particle collision signal is then unwanted background.

4.3 Test signals

Analysis of the data acquisition and trigger system showed that some elements may be used as a source of test signals. The idea of the diagnostic system is based on the ideas presented in chapter 3.

The system has two kind of test signals:

4.3 Test signals

1. external - multi channel signal generator, called pulser – directly connected to the outputs of gas chambers.
2. internal – some elements of the system can be used to test other electronic modules used in the data acquisition and trigger system

A natural source of test signals are cosmic muons. Unfortunately it is impossible to predict where that signal appears and when. There are places, where that probability is higher, others where it is lower.

4.4 The concept of the diagnostic system

Communication with all electronic boards of the Backing Calorimeter is only possible through the VME bus of the specific crate where the given board is connected. Also front-end electronics installed on the detector is seen in VME space addresses. Each VME [5] crate is equipped with its own bus controller, called transputer [6],[7]. All transputers are connected together by special communication links. One transputer at the top is connected to a DEC Alpha-Station computer which controls the transputer network of the BAC detector. The diagnostic system was designed on the client-server architecture [1-A], [2-A] and its underlying idea with the most significant elements is shown in Figure 4.1.

The diagnostic system [3-A] consists of a hardware, database[9] and server and client applications. The slow control monitors all power supplies and temperature sensors. In addition, the application stores data from the slow control system to a database. This database contains information about the placement of all boards, power supplies, connection between boards, etc.

4.4 The concept of the diagnostic system

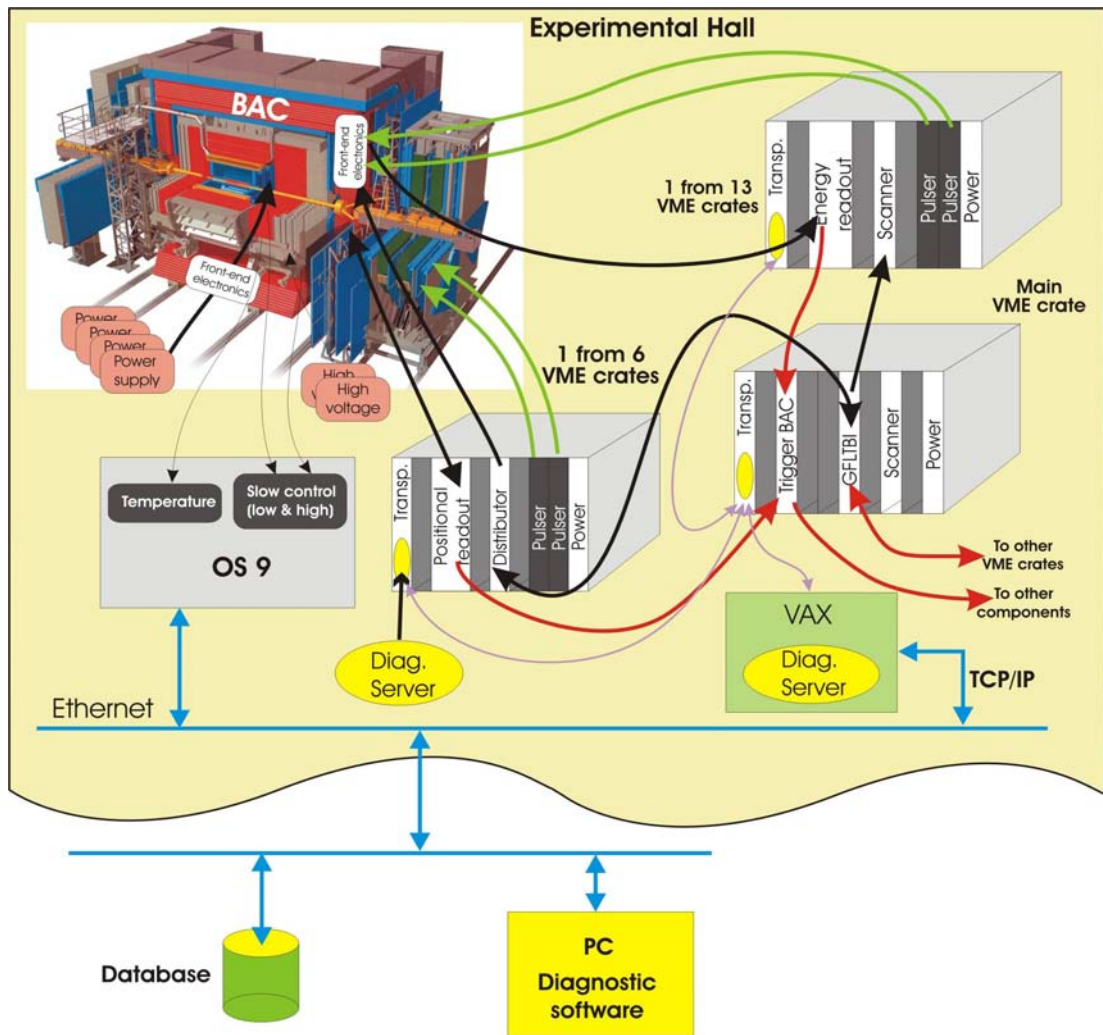


Fig. 4.1. Client-server architecture

4.4.1 Hardware layer

Analysis of the data acquisition system of the Backing Calorimeter showed that many its electronic boards may be used as a source of test signals for other subsystems of the detector. Many boards in the data acquisition system are connected sequentially and this architecture arises the possibility to simulate input data on one board by driving the output previous one. The data acquisition system is shown in Figure 4.2.

4.4 The concept of the diagnostic system

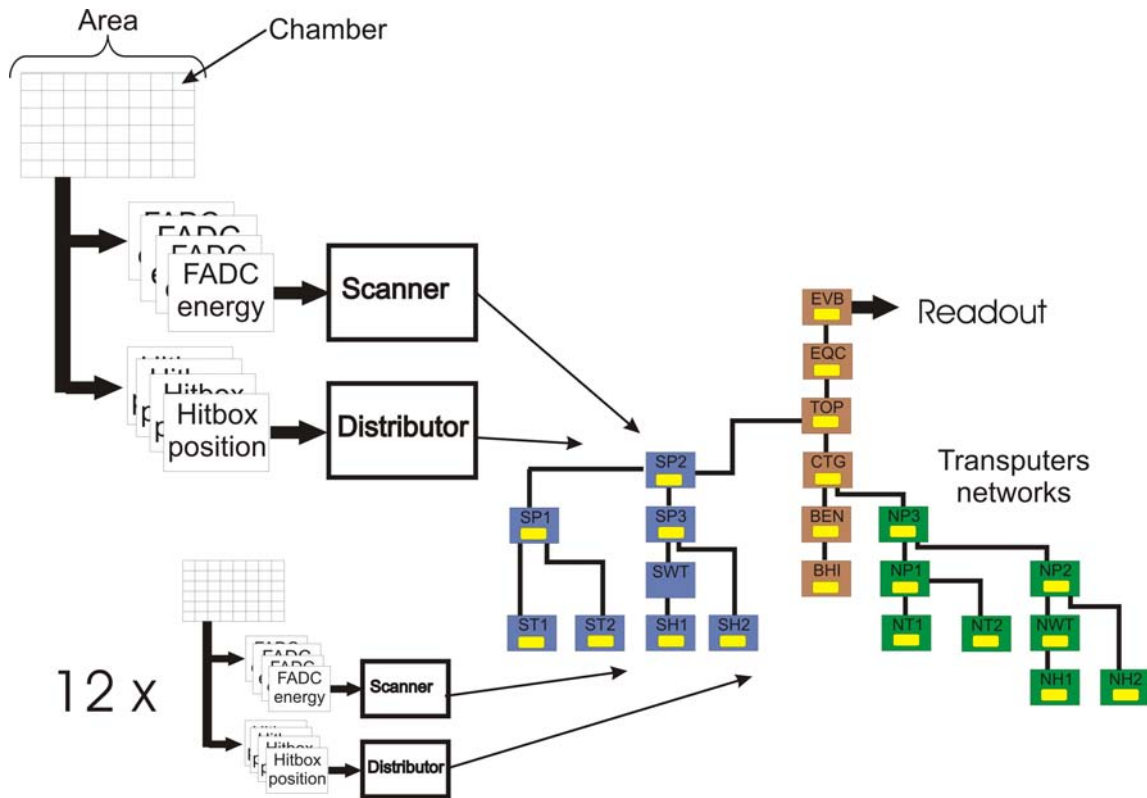


Fig. 4.2 Data acquisition system

The FADC boards are equipped with internal memory to save the samples from the ADCs. It is possible to write data to that memory and this feature may be used to simulate the energy of a particle. It allows examining even individual analog channels of the data acquisition system. Similar to the FADC boards, Hitbox [25], used for position readout, is also equipped with memory to store the results of particle detection. In this case data can be written to an internal memory and the trace and kind of any particle (muon or hadron) may be simulated.

The first level trigger (FLT) [19],[23] works together with the data acquisition system. Electronic components in the FLT are also connected sequentially and presented in Figure 4.3. The boards RACE, ADDER, EMBAC, BMBAC, RMBAC are equipped with FPGA chips. It presents an excellent opportunity to implement some diagnostic modules on the board. FLT is a much more complex system than the DAQ. Some diagnostic elements have been implemented in the FPGAs of the trigger system. These boards have

4.4 The concept of the diagnostic system

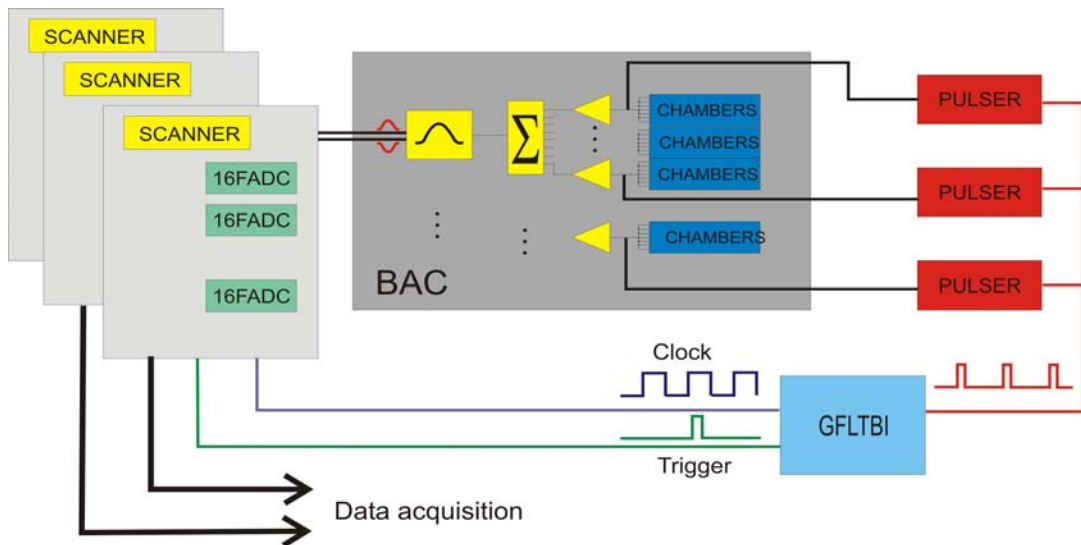


Fig. 4.4. Test with pulser

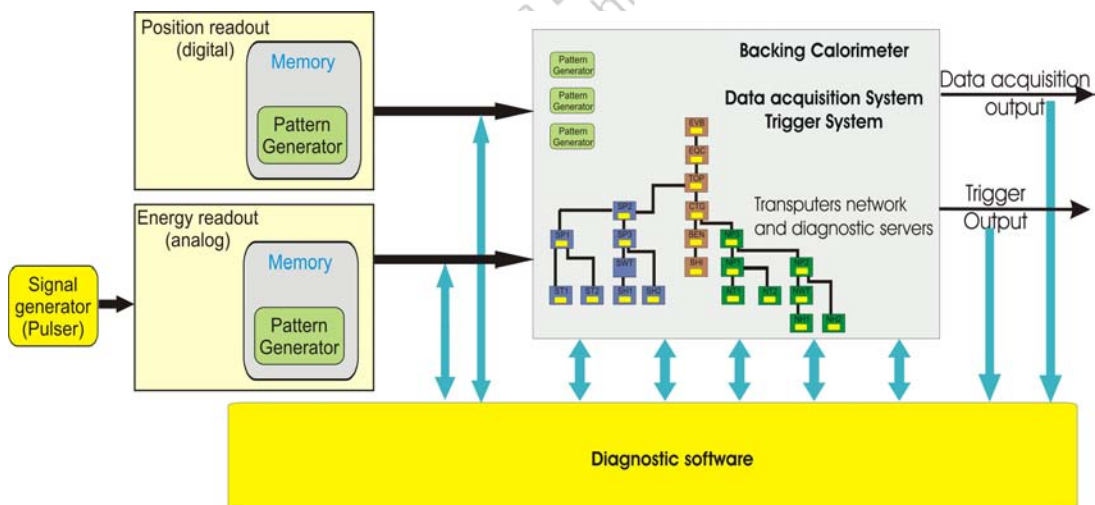


Fig. 4.5. The diagnostic system

The diagnostic system consists of sources of tests signals, both pulse generator and the Backing Calorimeter hardware used to examine another parts of electronic modules.

4.4.2 Software layer

The software [4-A] is an integrated part of the diagnostic system of the Backing Calorimeter. The connection between hard- and software is shown in Figure 4.6.

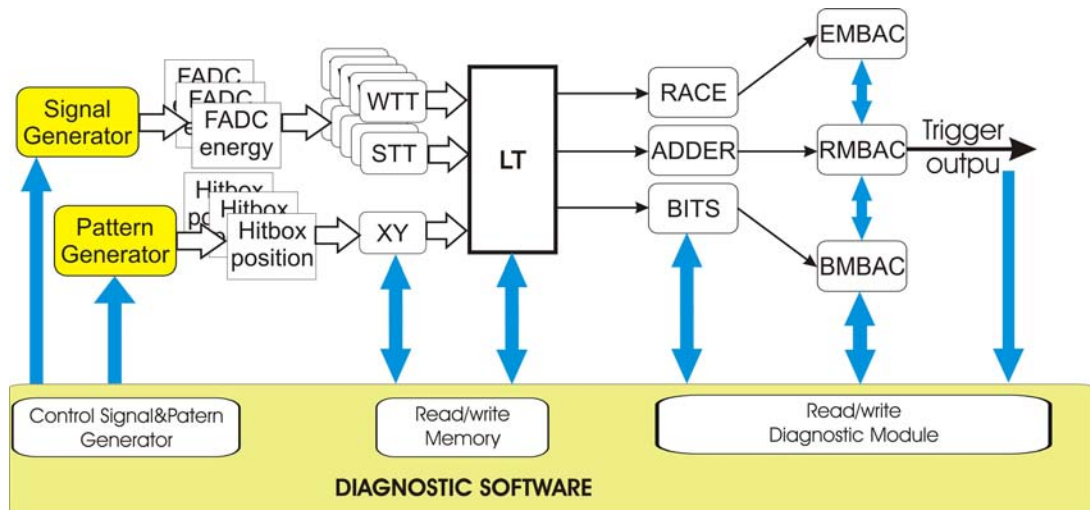


Fig. 4.6. Software layer of the diagnostic system

The software controls all electronic modules of the detector. As mentioned above, the software consists of two parts: server and client. Communication between a client and a server is done via Ethernet; the TCP/IP protocol has been implemented. It was assumed, that both communication and executive layer must be as simple as possible. All sophisticated work will be done by the client application. For a client application, any server is transparent. Connections and dependencies between programs in the server are shown in Figure 4.7.

The server consists of two layers:

communication layers – program which works on a VAX computer and is responsible for transferring data from the Ethernet to the transputer and vice versa. The programming has been done in C, working under the VMS operating system.

executive layer – a group of programs which work on the transputers in VME crates. These programs enable data reading from the VME bus, data writing to the VME bus, and handling interrupts. Some atomic instructions, specific to the Backing Calorimeter

4.4 The concept of the diagnostic system

(e.g. data readout) are also implemented. The programming is done here in the OCCAM-2 language.

The client application is the most important part of the diagnostic system for the Backing Calorimeter. All logic of the diagnostic system for BAC is concentrated in the client application. The diagnostic system software controls the whole hardware during tests. The application presented are written in C++ and works under MS Windows.

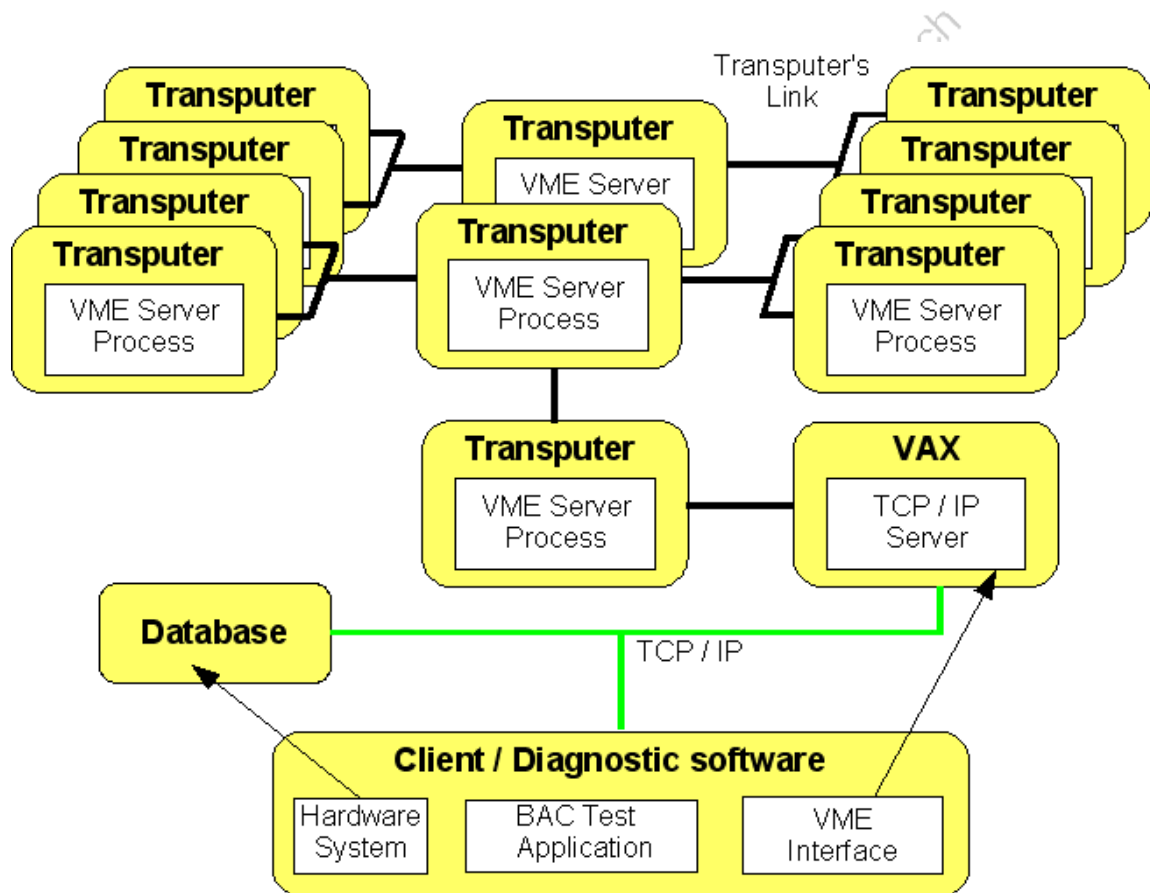


Figure 4.7. Deployment diagram of the BAC test system.

All calls are done through the collection of a few abstract C++ classes (interfaces). Each VME crate has a corresponding object in the system, which realizes the interface (VMEInterface). Operating such an interface works as if the operations are done locally, instead of calling TCP. Instead of calling to a TCP packet, receiving the packet by the

4.4 The concept of the diagnostic system

TCP/IP server, sending message to the transputer network, performing VME operations and returning the result is done „behind the scenes”. Grouping of VME operations was introduced to increase system efficiency. It is possible to register observers of particular crates by working with VME interrupts. The observers are notified about each interrupt and receive data relevant to this event.

The BAC access library consists of the following, co-working components:

- Class groups mirroring the BAC system in a hierarchical way. The class object THardwareSystem (singleton) includes information about all VME crates (TCrate) in the system. Each TCrate objects includes objects mirroring the devices present in a particular crate. These objects, in turn, have the relevant access and monitoring methods for particular devices. They fulfill the roles of containers and enable system control as a whole. They enable the setup of the whole detector or specific types of devices like event building, run control, etc. The object hierarchy is constructed dynamically based on the information included in the database.
- Class groups implementing specialized tests (THardwareTest). These classes use the objects described above. They perform tests, simulations and system calibration. The test results may be automatically written to a database. Test factory (THardwareTestFactory) has methods to build, accessible for particular device or sub-system, objects THardwareTest
- Classes realizing graphical user interface.

The libraries described above are kernels of applications used for testing, running simulations and calibration of the BAC detector. This kernel may be used to work with specific devices in a nondependent testing stand.

The main panel of the diagnostic software is shown in Figure 4.8. All VME crates are listed, access to each device is possible. Different procedures and test are available using

4.4 The concept of the diagnostic system

the bookmarks shown.

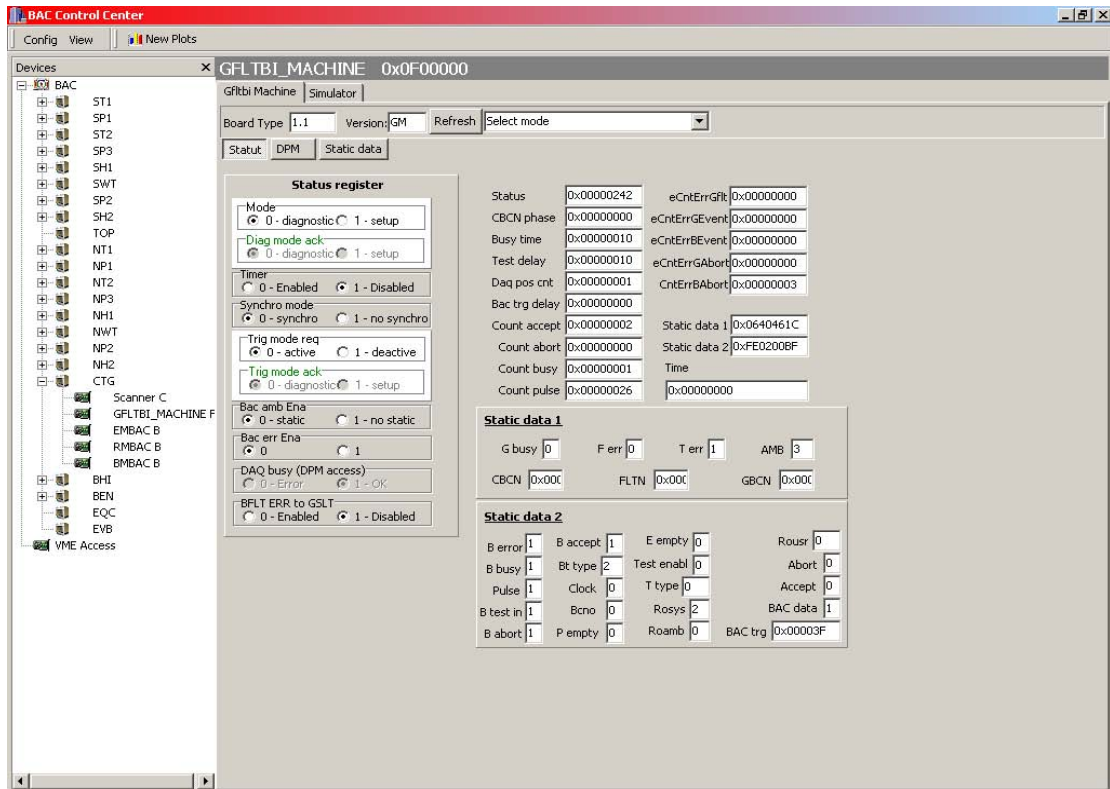


Figure 4.8. The main panel of the diagnostic system

4.5 Summary

The diagnostic system can work in three states:

- 1 – monitoring
- 2 – diagnostic
- 3 – data acquisition in diagnostic mode

The diagnostic system presented worked in a real HEP experiment. It was implemented without changes into an existing data acquisition system. It has been tested and used during maintenance. The diagnostic system solved many problems and was an essential

4.5 Summary

tool during work on the BAC trigger system. The basic requirement has been met – the system has been built without significant changes in hardware and improved the overall stability of the system.

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Chapter 5

Algorithms and testing method of the detector

The aim of the diagnostic system for the ZEUS Backing Calorimeter is to maintain high efficiency [38] and maintainability of the detector. Presented in chapter 4 system it is only tool which allows to communicate with electronic system. The main diagnostic is done by algorithms implemented into client application.

5.1 Hardware tests

Hardware tests are performed according to algorithm presented in Figure 5.1. The diagnostic software downloads list of electronic modules from database and its addresses. Information about space addresses, memories, register and logic elements are fixed in virtual class for given type of the board. The system produces a pattern, writes and reads data to memory and registers. Operation is repeated N time, each time wrote and read data are compared. In case of failure information is stored in database. Only successfully tested hardware can be used in another test and included to data acquisition and trigger system of the BAC detector.

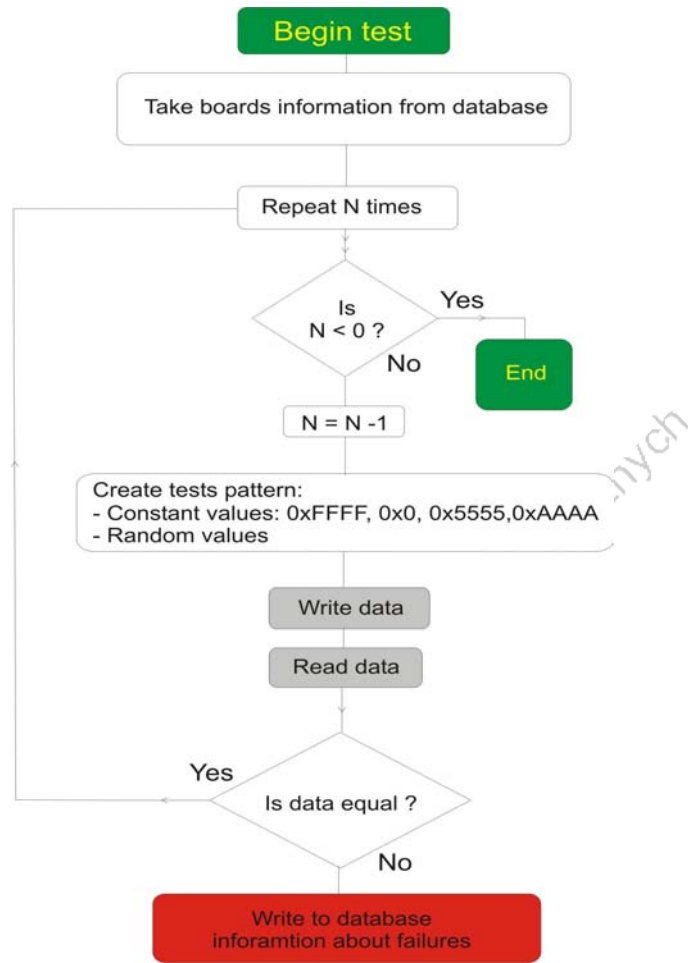


Figure 5.1. Algorithm for static tests of electronic modules.

Example result of test of Hitboxes conn to the SH2 controller is presented in Figure 5.2. Fault elements are marked. Base on this test physicists know which area of the detector does not work properly – see Figure 5.3 right. The same test gives information to a maintenance crew where failure elements are located. - see Figure 5.3 left. Placement of Hitboxes on the detector is shown on Figure 5.4 .

5.1 Hardware tests

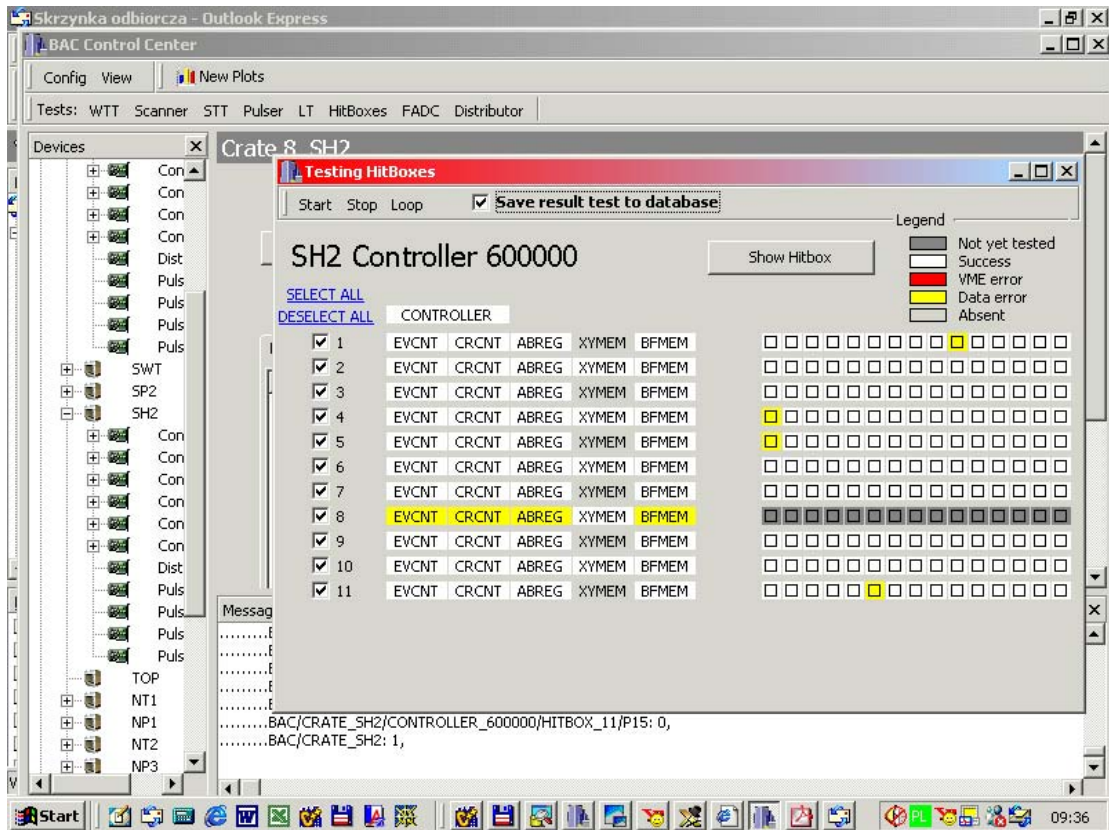


Figure 5.2. Example result of static tests of electronic modules.

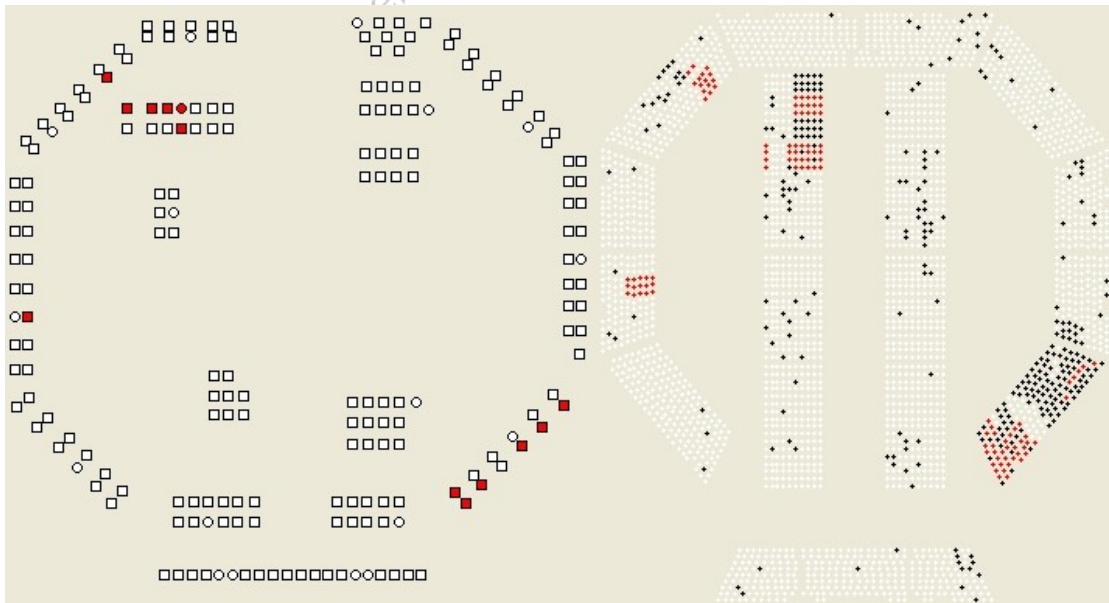


Figure 5.3. Placement of front-end electronics on the detector.

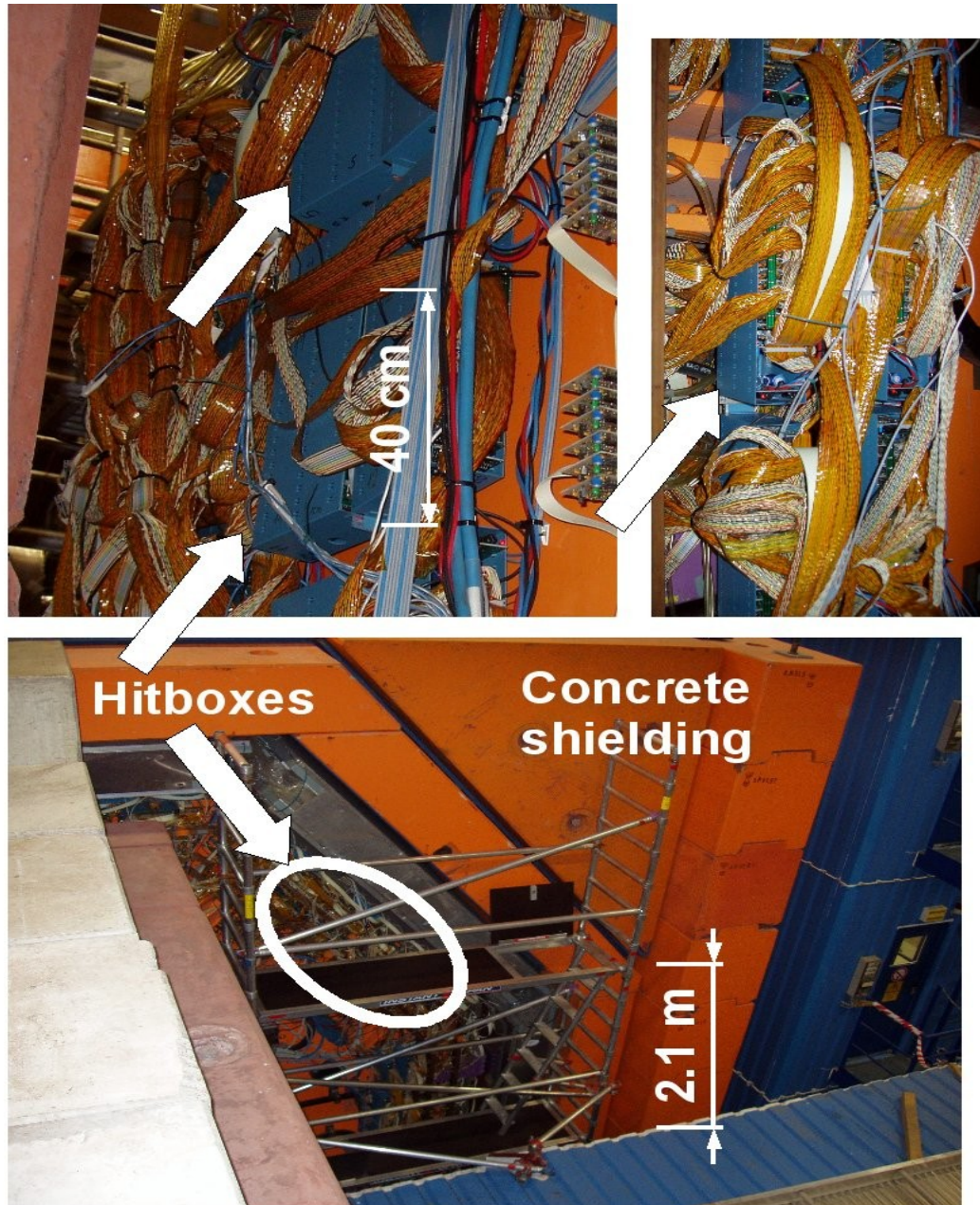


Figure 5.4. Hitboxes on the detector.

5.2 Readout

The goal of this test it to check electronic component between chamber and pipeline

5.2 Readout

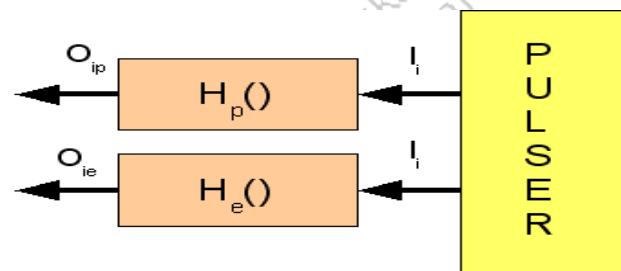
memory. The test includes front-end electronics, FADC, WTT, SST boards, Scanner board for energy readout [21] and Hitboxes [25] and its controller, for position readout. Tests of readout are done with a pulse generator. For given input signal $I_{i_test}(t)$ output signal $O_{i_test}(t)$ should be registered. Output signal is described by formula, see Figure 5.5:

$$O_i(t) = H(I_i); \text{ where } H(t) \text{ is a transfer function}$$

The transfer function $H(t)$ is different for energy and position readout, but the same for each channel. For position readout the transfer function is described:

$$O_i(t) = I \text{ when } I_i > T, \quad O_i(t) = 0 \text{ when } I_i \leq T,$$

and where T is the threshold comparator.



$H_p()$ - the transfer function for position readout
 $H_e()$ - the transfer function for energy readout

Figure 5.5. Tests with pulser.

For energy readout parameters of output signal for given inputs signal has been matched experimentally. After test data are analyzed and displayed. Results of test are presented in Figure 5.6, and 5.7. All outputs signal from with area are classified as good signals. Software automatically detect wrong channels and write that information to data base. This information is included in a configuration data for data acquisition system.

5.2 Readout

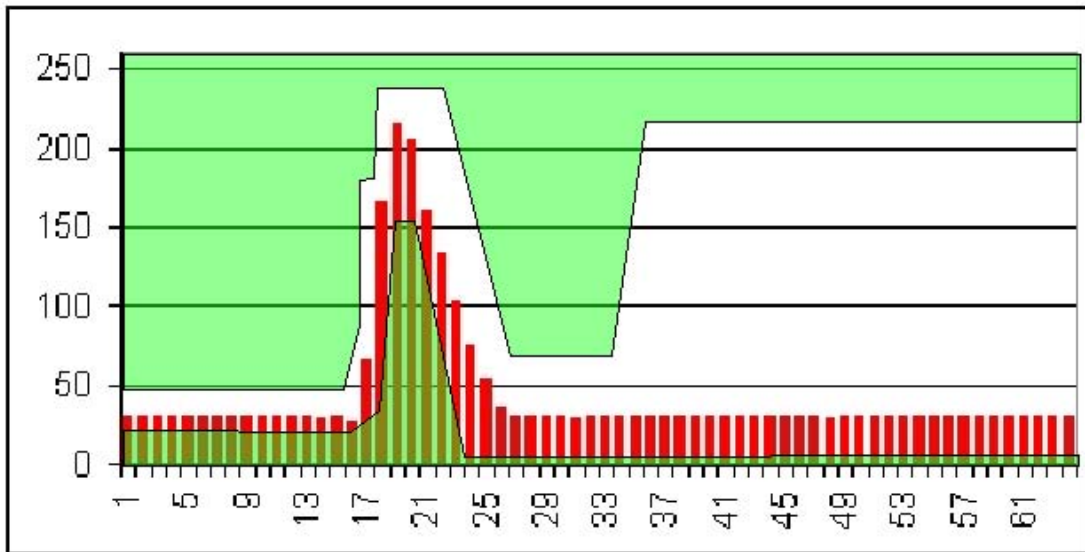


Figure 5.6. Proper analog signal registered during test.
X – axis time in counts from trigger signal
Y-axis – amplitude in FADC's counts

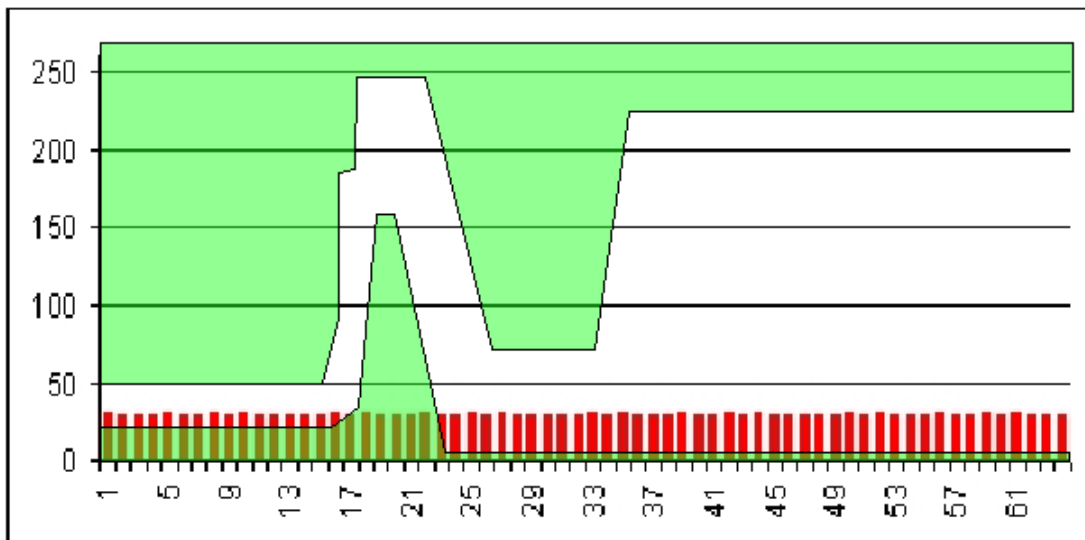


Figure 5.7. A signal registered by diagnostic software. Channel with problem.

5.3 Trigger

During data acquisition signals from chambers are connected through amplifiers to

5.3 Trigger

FADCs and Hitboxes. These components are equipped with the LTM memory and it is possible to write data to these memory through the VME bus. That operation allows to simulate the output signal. During tests a signal and pattern generator are connected to an energy and position readout as input signals [13-A]. The boards: XY, RACE, ADDER, BITS, EMBAC, RMBAC, BMBAC form a chain, each of which is equipped with dedicated diagnostic module on board.

Diagnostic processes are controlled by the diagnostic software. The trigger boards are connected in a chain. The diagnostic software allows to create dummy data and to write that data to boards which are in the chain. The diagnostic system allows to test the trigger decision coming from each area (1 - 13) or to test the final trigger data. The diagnostic module is equipped with an input simulator, output simulator, histogram blocks, registers and counters. The input simulator allows to write data to the inputs of the board and disconnect from the previous board. In this case it is possible to read data on the output of the board or to read data on the input to another board. The main goal of the output simulator is to simulate input data for the next board. The histogram block increments a set of counters for all different signal types. It can counts positive decision of trigger from chosen area, for example.

It is possible write and read data directly to memories of electronic modules used in position readout. That property allows to simulate data directly in the input circuits of the Hitboxes. It enables the usage of the Hitbox as a digital signal generator. The test signals generated by the diagnostic system allow carrying out a precise analysis of the logical circuits of the trigger. The configuration data can also be tested.

The signal generator enables analysis of the analog channel and the trigger. It is controlled by the diagnostic system. The signal generator allows to simulate the appearance of a charged particle in an arbitrary position of the detector. The procedure test may be carried out for all channels or in parallel for all of them. The precise results are provided by the tests of single channels, in which much more test time is required.

A natural source of the test signals are cosmic muons. They are ever-present and identical to those generated in collisions in the accelerator. The frequency of the cosmic muons is lower. It is impossible to predict their time and place of appearance. Thus, they

5.3 Trigger

could not be directly used to test the detector electronics. They may be used to investigate the time dependencies between the generated signals in different parts of the detector during the muon time-of-flight. The cosmic muons are used to test the timing settings and tests of trigger circuits, i.e. searching for individual muons. The test of the trigger is the last procedure performed by the diagnostic system. Before that, it is necessary to examine all the trigger boards and the connections between them. The information about problematic channels is stored in the database.

The test algorithm for FLT is shown in Figure 5.8. For the starts the diagnostic software generates input data, for example, data which correspond to one particle with high energy or data corresponding to a muon or a hadron. The diagnostic system takes information about the electronic condition from the database and. send this data to the memories of the FADCs boards and Hitboxes.. Parallel to that. data created by the diagnostic software and written to boards' memory are analyzed by the diagnostic system. The same data can be used to examine one or all wires or even a whole area. When the diagnostic system sends simulated data to the detector, the system starts the readout from tested boards and collect data. Readout data are sent to the diagnostic software and compared with expected values calculated by the diagnostic system. In case of disagreement in data the system can identify failure and locate hardware responsible for this effect.

An energy trigger decision is produced from data coming from the wire and strip towers. Analog signals correspond with the energy deposit measured in wire and strip towers are digitized by WTT (Wire Tower Trigger) and STT (Strip Tower Trigger) boards. Data from FADCs (WTT and STT) are stored in a pipeline and simultaneously diverted to a Local Maximum Finder (LMF). Principle of LMF circuit is described by following formula:

$$A_{in}(i-1) < A_{in}(i) \geq A_{in}(i+1),$$

where: A_{in} is the amplitude of incoming signal,

and $i-1$, i and $i+1$ correspond to the consecutive FADC samplings.

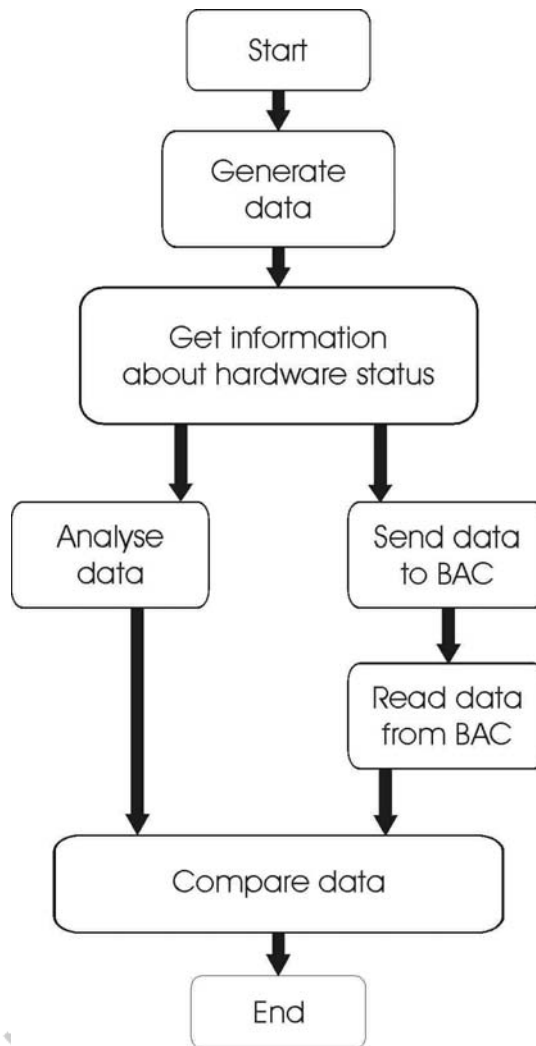


Figure 5.8. The test algorithm for BAC FLT logic.

The goal of an energy trigger is to find the highest energy deposit together with their location. The trigger system measure also the total energy registered in the BAC. Using simulated data with well know values one can check the energy summation and “RACE” board mechanism for each individual area as well as for whole detector.

The muon trigger must distinguish a muon from another particle, particularly a hadron [33]. The example tracks of moun and hadron registered in the one wire of the BAC are shown in Figure 5.9. The difference between the muon and hadron track pattern is obvious. The algorithm to separate muons from hadrons tracks is: if the number of

5.3 Trigger

“active” layers is approximately equal to the number of “active” chambers than this event corresponds to muon. Otherwise when the number of “active” chambers distinctly exceeds the number of “active” layers such an event corresponds to a hadron.

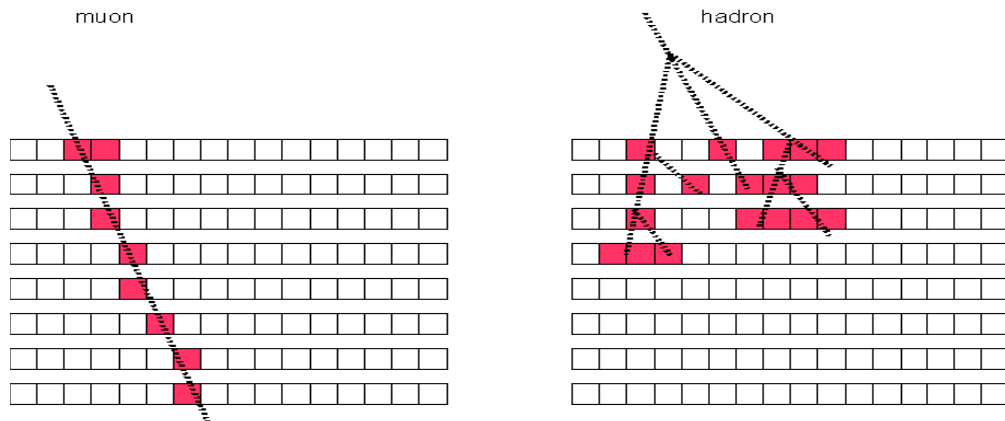


Figure 5.9. The example tracks of muon and hadron registered in the one wire of the BAC.

5.4 Timing signals

Timing is very important for data registered by BAC. All signals generated by the same particle must be seen by data acquisition system at the same time. It is necessary to synchronize data from different parts of the detector. Data from position readout must appear in system in the same time together with correspondent data from energy readout. Without synchronization it is impossible to gather data. Electronic boards of the BAC detector are equipped with hundreds registers which must be properly adjusted. Algorithm for timing adjustment is shown in Figure 5.10. Tests can be performed with:

- external test signal
- built in function into hitbox.

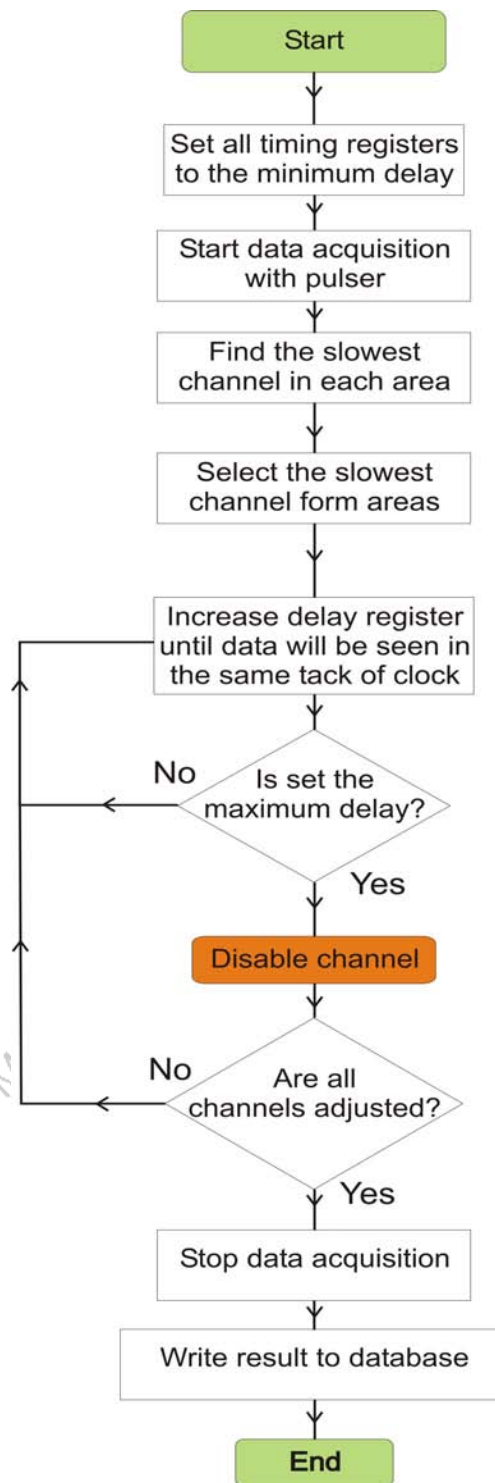


Figure 5.10. Algorithm for timing adjustment with external and built in hitbox function.

Timing adjustment procedure can be applied only to properly working electronic modules. Idea of algorithm is that information about energy (analog readout) and

5.4 Timing signals

position (digital readout) must appear in data acquisition and trigger system with the same clock (at the same time), because both signals has been produced by the same input signal.

In Figure 5.11 position (digital) signals from wires in the same chamber are presented. Signals from one chamber should be seen in the same time. Properly adjusted signals are presented in Figure 5.12 and Figure 5.13. First of them shows property adjusted timing for data from position readout, second one signals seen by trigger. Information about energy and position is in the same time.

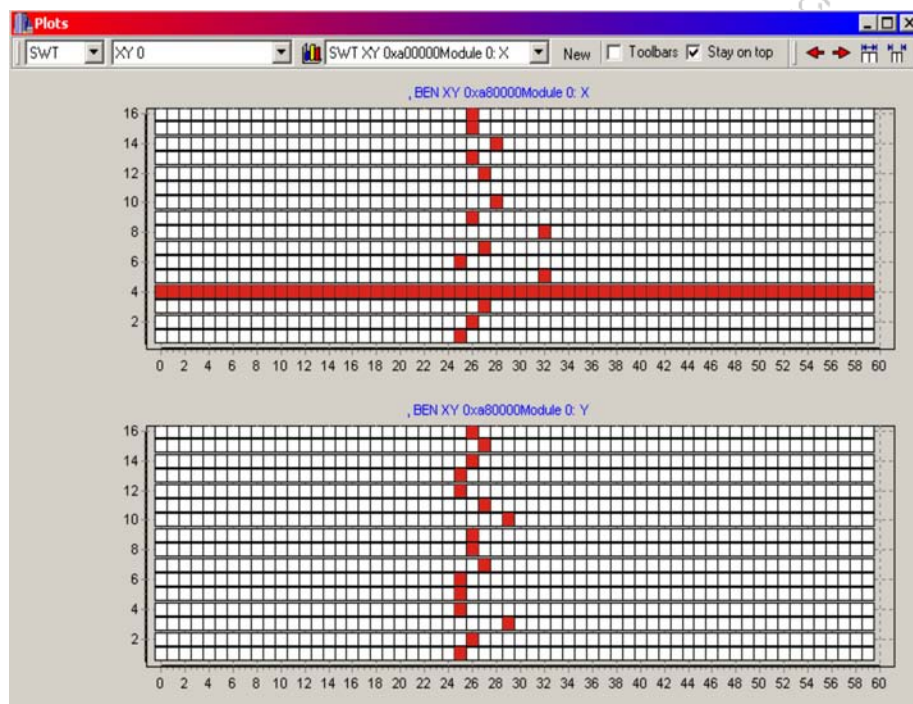


Figure 5.11. No adjusted signals (position readout).

5.4 Timing signals

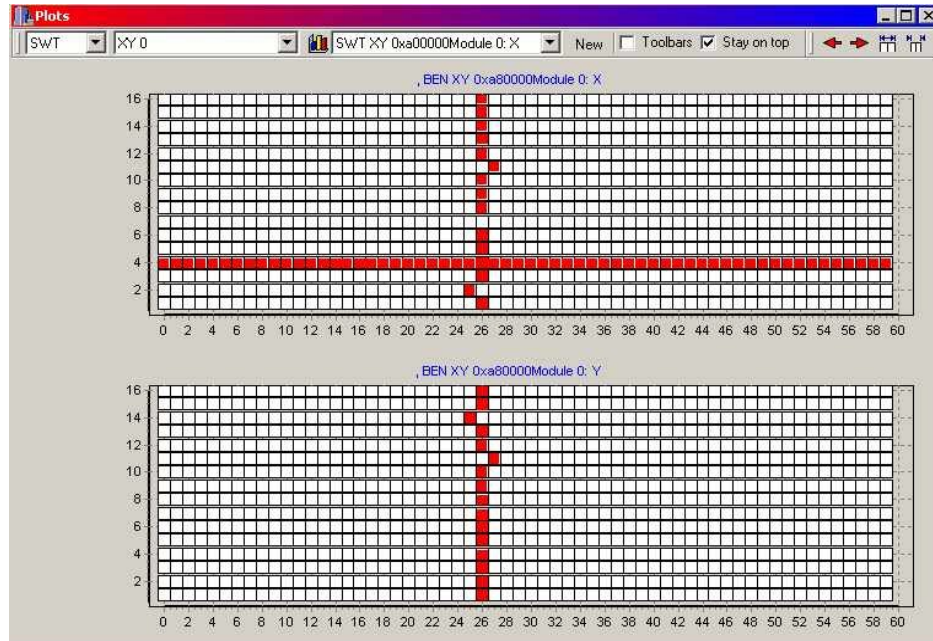


Figure 5.12. Adjusted timing signals (position readout).

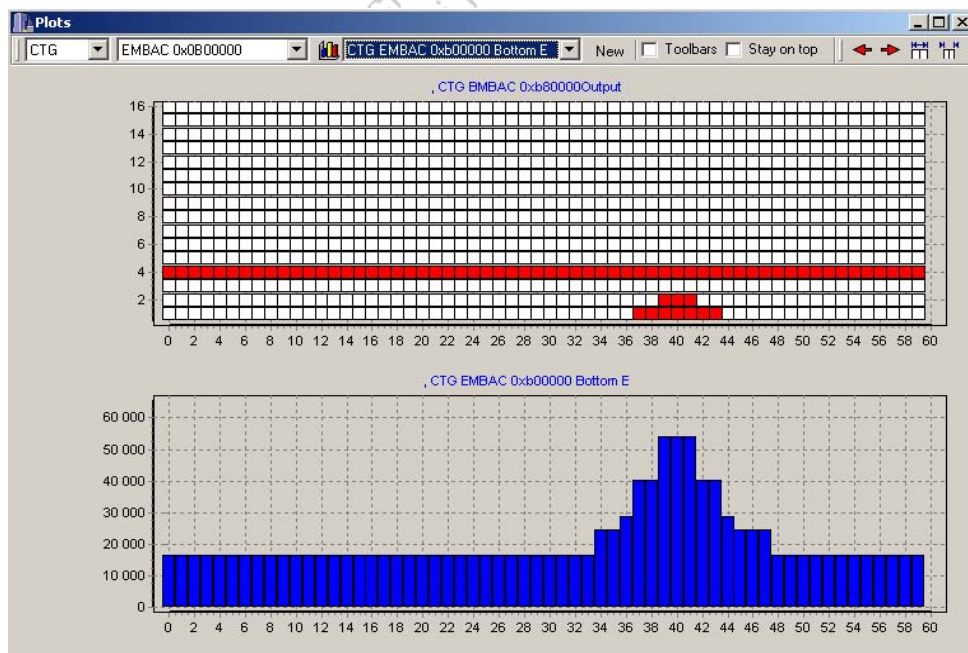


Figure 5.13. Synchronization position and energy readout.

One of the final test is the functional tests. The goal of that test is to evaluate the work of

5.4 Timing signals

particular electronic modules during the realization of the assigned functions in the experiment. Timing and synchronization is checked, in particular energy and position channels and time correlation. Fig.5.13. presents an example of the test readout from two trigger channels of BAC detector. The upper window shows the position readout, while the lower – energy from muon transfer registered by the EMBAC board. Both channels are from the same region of the detector. A visible time correlation between the registered energy deposit and particle path registered by the position readout. This diagram enables check of the synchronization in particular channels. Automatic investigation of the energetic pulses and corresponding, respective data from the position readout enable full functional tests of the trigger circuit. The presented data were registered gathered in the following conditions: no beam in HERA accelerator, non dependent work of BAC detector with internal triggering unit. The test used cosmic muons, which are equivalent to the products of particle collisions, but its rate is a few hundred times lower. The tests with cosmic muons are used to test the trigger decision and synchronization from particular parts of the detector.

5.5. Threshold tuning of the BAC position readout

One of the most important task of the diagnostic system is to tune thresholds [9-A] of comparators in the position readout. The Backing Calorimeter is designed to identify muons produced at the interaction point and to measure their directions. Muons are charged particles which interact with matter mainly due to ionisation, thus they are very penetrating. The detection of muons in BAC is performed by the “position readout” which makes use of the anode wires of the BAC proportional gas chambers. Each such a wire is connected via preamplifier and comparator to the digital readout which registers one bit of information every 96 ns. For each chamber consisting of 7 or 8 wires the resulting pattern of fired wires is stored in a pipeline. In case of a positive trigger decision such information is transfered into further levels of data acquisition system and finally recorded in the off-line data base. A typical signature of a muon observed in BAC is a single track passing through a set of consecutive layers leaving an energy deposit in

5.5. Threshold tuning of the BAC position readout

one or two neighbor anode wires in each layer.

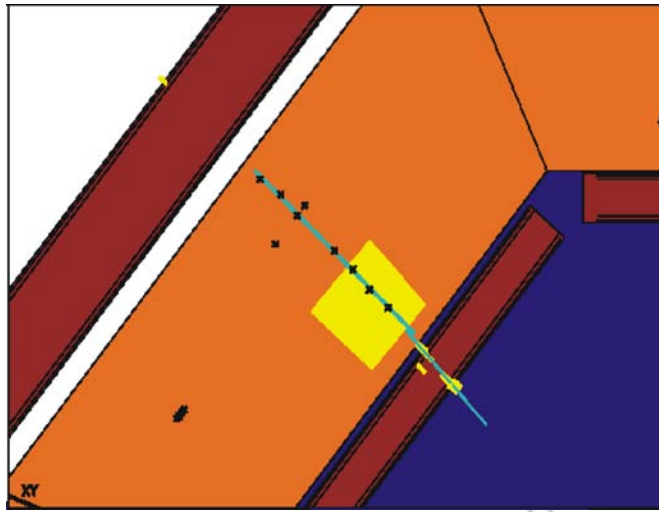


Figure 5.14. Typical, properly reconstructed, muon event observed in the Backing Calorimeter. Black crosses correspond to the position of the anode wires (hit readout) while the light yellow rectangle denotes the muon energy deposit measured by the cathode planes (pads).

Detector BAC has the limited efficiency for particle with low energy (below 3GeV) and for some particles not all detector layers produce a signal exceeding the comparator level. However such a “gaps” on the muon trajectory are not danger and the off line algorithms (physics analysis) are usually capable to fit a proper track. Much more harmful are detector noises [Figure 5.15] which can produce a “fake” muon signal. They are mainly caused by a too low value of the comparator threshold for the corresponding readout channels. Many internal and external factors may influence the amount of noisy signals produced in the detector, Main reasons are following:

- 1) internal instability of the gas-chamber (e.g. sparks in the high voltage);
- 2) internal noises in the analog part of the readout system (too sensitive preamplifiers),
- 3) external electromagnetic noises inducing fake signals on the transmission cables.

The presented above conditions usually are not stable in the time and an adequate setup must be performed on the regular basis.

5.5. Threshold tuning of the BAC position readout

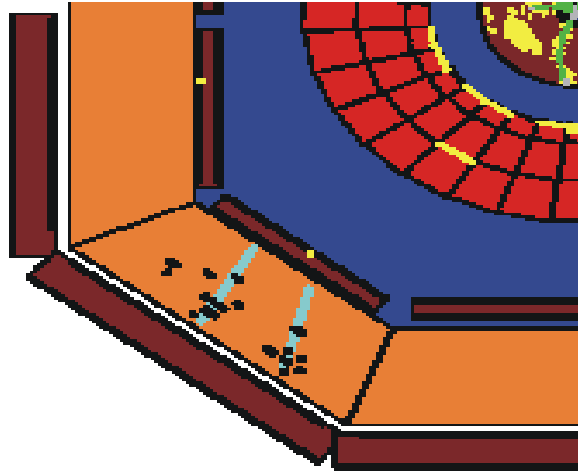


Fig. 5.15. Noises in the hit readout registered in the Backing Calorimeter. The straight lines represent the “fake” muons which are not related to any physical trajectory observed in the detector.

The position readout consist of about 40'000 wires and the off-line algorithms cannot suppress all kind of noises observed in the detector. Therefore it is very important to control them already on-line by properly adjusted comparator levels. Moreover, a high level of detector noises causes a larger size unwonted of readout banks and can be responsible for a longer dead time. Too high level of the comparator thresholds will reduce the detector efficiency and can significantly degrade the detector performance. Thresholds tuning is the last procedure from series of tests and is prepared only for the boards which successfully passed the previous tests. After this operation data acquisition system has got new configuration data.

The threshold tuning is related to position readout - digital channels. Analog signals from gas chamber are connected to comparators, which discriminate the real signal form noise. The threshold can be set independently for each gas chamber. The level of threshold determines the number of mistaken data being analyzed. Proper setting of comparator thresholds is very important for the readout and trigger system. In case of the readout unwanted data may increase the dead time and decrease quality of muon reconstruction. In case of trigger system too low thresholds cause to high trigger rate and the detector will register false events. On the other hand the threshold level cannot be to

5.5. Threshold tuning of the BAC position readout

high, because the detector will lose its ability to record real particles. The problem of noise suppression in such a large detector is very complex. For instance two consecutive executions of the same procedure can produce different sets of thresholds. The goal of this procedure is to find parts of electronic, which generate noises with the highest probability. The main sources of noises in the detector are:

- electromagnetic noises (transmission and power supply cables),
- power supplies,
- instability of the front-end analog preamplifiers.

5.5.1. Threshold tuning method

The choice of comparators thresholds should be done in the same conditions as when the data acquisition is performed. During this test all other ZEUS components should be turned on and high voltages on the gas chambers should be switched on. From the observations it is known that “optimal” value of comparator threshold depends also on the rate of the data acquisition. The frequent the decision about event selection the bigger value of comparator threshold must be in order to reduce the rate of false events. Presence of false signals appears to be related to the frequency of control signals.

To achieve good set of thresholds, one has to know the previous threshold's values for each comparator, and the information of signal produced with such a setting. If the chamber number N , with the threshold $T=4$ produced false signals throughout last couple of days during regular data taking, and it appears from the tests, that with the actual setting $T=4$, it does not give false signals, the threshold should be increased, and the fact noted. If throughout the next few days the chamber N does not give any false signals with $T=5$ threshold, and $T=4$ comes out of the next tests, the $T=4$ value can be sustained. The thresholds setting is based on the algorithm shown in Figure 5.16. Threshold values are changed between T_{\min} and T_{\max} . All comparators are set in the same time. Readout is performed in parallel from all detector. For well optimized thresholds it is important take many data, i.e. 50, 100 or 1000 events per chamber. But this also costs time. Each event has got information about 40'000 wires. Test must be organized to maximize efficiency

5.5. Threshold tuning of the BAC position readout

and minimize time needed for test. Next the data taking is repeated with changing steering signals: with ACCEPT [19] signal frequency varying, activating the signal of canceling of events (FAST CLEAR). The diagnostic system counts how many signals from the chamber has appeared. Tuning the thresholds is a stochastic process. The system assumes that if less then 1% signals from the chamber has appeared, the threshold is correct. Later on, every chamber threshold history is checked, and the decision about sustaining or changing each threshold is taken.

The same method, based on algorithms presented above, can be applied for tuning threshold for comparators connected to gas chambers located in common palace, called "tower". The tower is the smallest unit for data acquisition system. One "tower" is shown in Figure 2.12. Usually "tower" consist of 30 gas chambers. In case of this method, readout has got very short stream of data and data transfer form detector to diagnostic system is very fast. This method allows to collect data with very high rate and make good statistic.. This option helps to examine instable towers, precisely tuning threshold with high statistic. Unfortunately, even though comparators thresholds for various conditions are set well, in a some system configuration false signals happen to appear. For correcting this, an option for observing the signals coming out of the detector has been added. In Figure 5.15 the cross-section of the Barrel is presented. It shows 2 "fake" moun tracks passing through the detector and the noises. The operator has always possibility to set manually each comparators' threshold to tune some threshold according to own requirements.

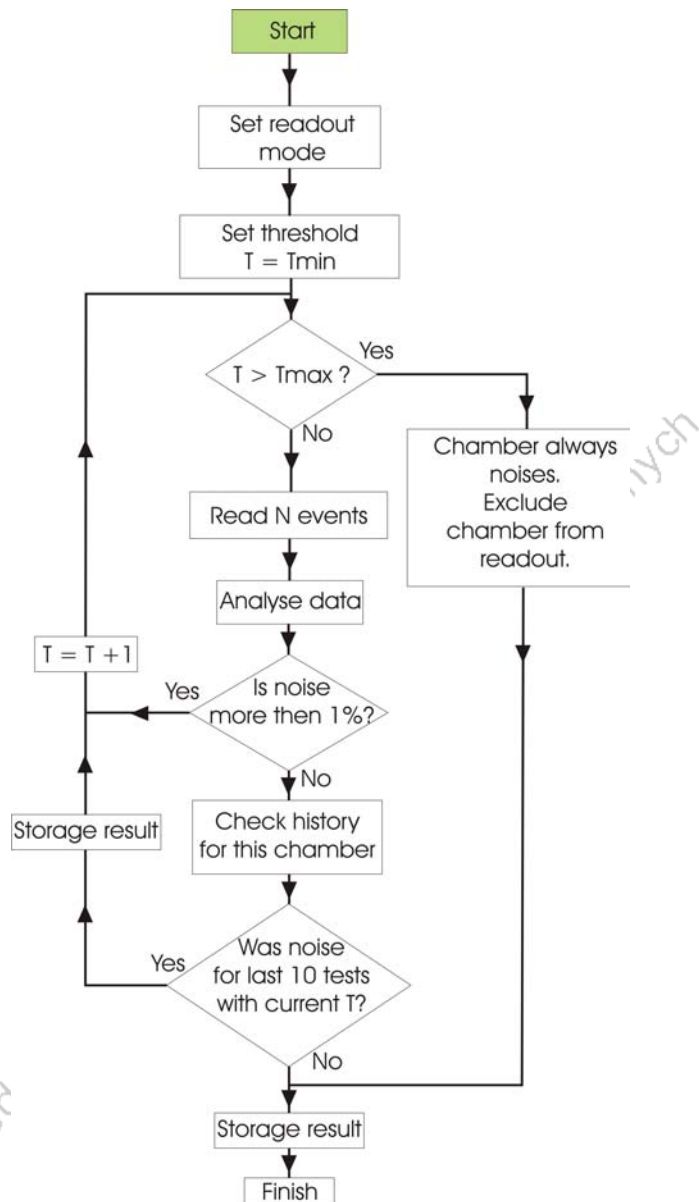


Fig. 5.16. Algorithm of searching for optimal comparator threshold

5.6 Summary

The diagnostic system has been implemented in the experiment and preliminary test have provide considerable results. The functionality of the system allows to verify the evaluation of the trigger variables. Its application as a very useful tool to identify the

5.6 Summary

hardware failures in the trigger channels been also demonstrated. The diagnostic system enables making precise tests of FLT. The test results are saved in database. These results are used off-line for analysis and comparisons. The results give the history record of BAC status. Data are used for seeking correlations between all hardware breakdowns.

Presented idea and assumed solution of the diagnostic system in a form of a collection of object oriented software modules enabled to build reliable and functionally expandable practical system for BAC.

In addition to the testing and verifying of the trigger logic the diagnostic system allows for:

- measure trigger rates from different areas
- on-line monitor the status and control registers
- inspect on-line histograms
- compare readout from different boards
- compare readout data and calculated data
- monitor a trigger decision from different areas
- change on-line setup
- change on-line simulation parameters
- tests configuration for data acquisition

The use of the diagnostics significant decreased the time needed to localize the failure and repair it. In the past, in case of failures which did not stop operation, information about dead areas of the detector was available after 2-3 weeks, when physics analysis has been done. The presented diagnostic system allows location of failure within 30 minutes. The maintenance work has been also improved. Now, before 'access day' a maintenance crew can precisely locate damage boards, a broken connections, prepare replacement. Scaffold can be put in the place where is need. The possibility to test the configuration data ensures that the trigger will work more efficient.

5.6 Summary

Result of data presentation is shown in Figure 5.14 and measured efficiency of the trigger is shown in Figure 5.15.

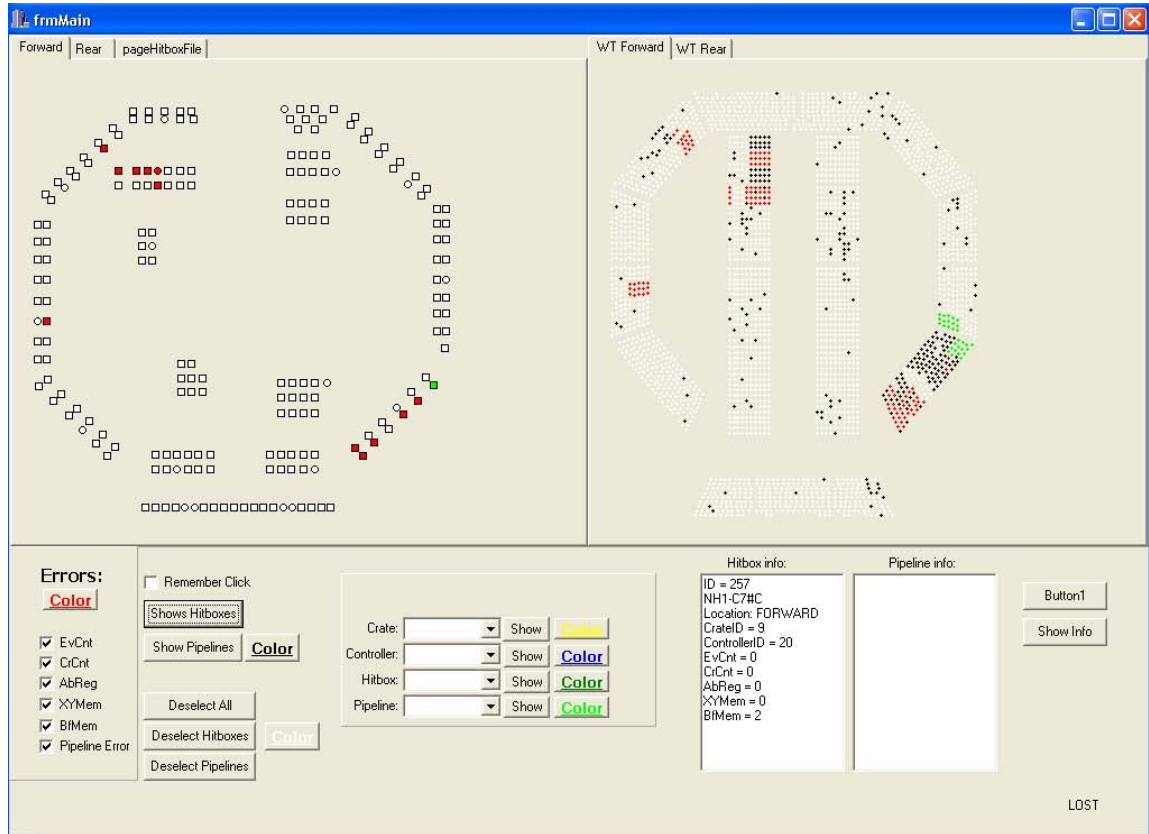
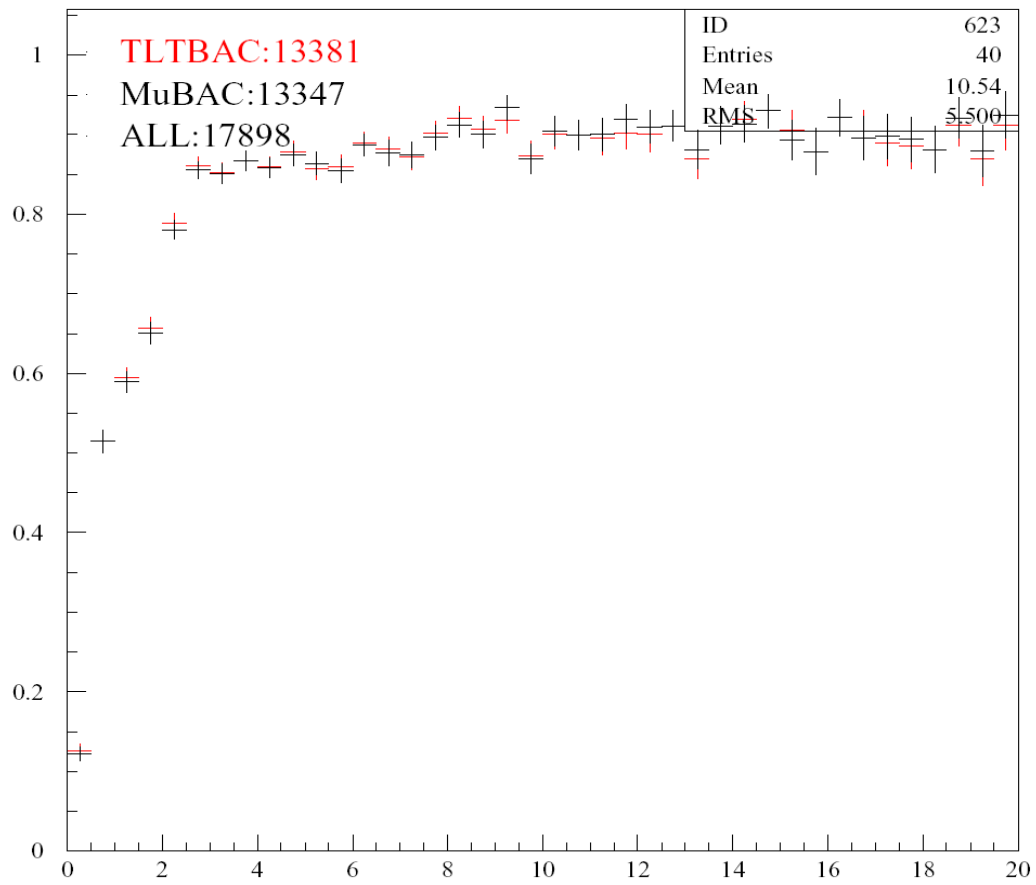


Figure 5.15 Data viewer

The efficiency [36] of the BAC is measured based on two neighbor detectors. The trajectory and trigger decision are compared. Before year 2000 archived efficiency did not exceeded 75%. Since the diagnostic system support operation, the BAC detector increases efficiency up to 85-90%. A plot with measured efficiency is shown in Figure 5.15.

5.6 Summary



Chapter 6

Fault detection in the LLRF system

One of the most important goals of the diagnostic system is to provide the high availability of the low-level RF system required for continuous operation of the accelerator. This chapter describes the concept for a diagnostics for the low-level RF system for VUV-FEL. A new controller, with a novel design which includes postulates for the diagnostic system is presented.

6.1 Requirements for the LLRF diagnostic system

It is impossible to predict all ways a system or component can fail. Therefore a diagnostic system is needed in order to monitor the hardware and in case of failure switch the system off or to a redundant one. It should also be able to perform offline tests of devices and diagnose the failure reason. Due to the scale of the accelerator, it is also important to have information about the location of a broken part. Owing to the complexity of the LLRF system and dependencies between its parts, the diagnostic system should monitor as many devices as possible. This requires all devices to provide

6.1 Requirements for the LLRF diagnostic system

some hardware and software interface through which tests can be performed. The diagnostic system itself should provide a user interface for experts and operators.

The main tasks of the diagnostic software are:

- fault detection
- performing the complex tests of the all electronic boards
- the examination of the connection between boards
- checking logic and algorithms
- checking the timing
- monitoring power, temperature, etc.
- storing test results in a database
- presentation of the test results.

6.2 Concept of the diagnostic system

The VUV-FEL accelerator consists of sequence of kryomodules with each module incorporating 32 superconducting cavities, the RF power distribution system, and an external klystron for each module. Every cavity is equipped with an antenna, which probes the RF field inside the cavity. To provide a stable RF field inside the cavities, a control system is needed. One kryomodule and its RF controller are schematically depicted in Figure 6.1. The system consists of down converters, ADC boards, DAC boards, DSP board (based on the Texas Instruments DSP processor C67), a vector modulator, a timing system, power supplies, and the control system. All boards are VME boards. The signal from a cavity probe is connected to a downconverter board and then to digitized by ADCs and fed to the DSP/FPGA board. The main controller consists of the DSP/FPGA board, ADC boards, and DAC boards. Analysis of the system showed that there is the possibility to access internal registers, memory and logic via the VME interface. Furthermore it is possible to simulate input and output data in the ADC, DAC and DSP modules. This makes it possible to construct a diagnostic system based on the ideas presented in chapter 3.

6.2 Concept of the diagnostic system

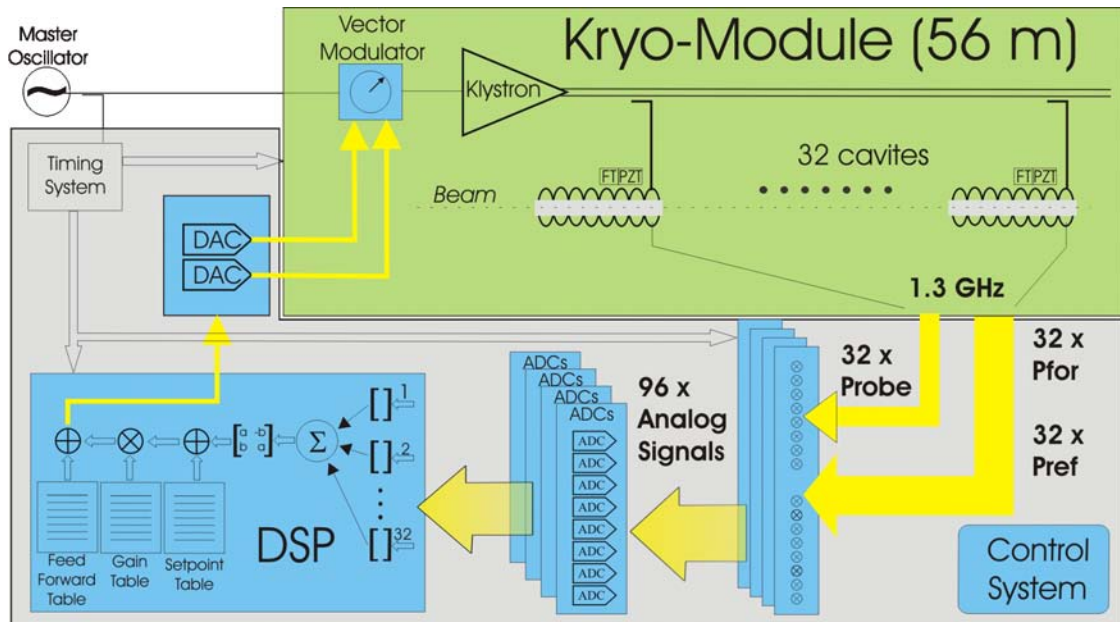


Figure 6.1. Structure and signals in low-level RF system.

The general concept of the diagnostic system [12-A] for the low-level RF is given in Figure 6.2. It consists of a hardware and software layer and is distributed among different hardware devices. In more detail, that means a controller, two monitoring ADC boards, and sources of the test RF pulse. One monitoring ADC board is connected to the output of the vector modulator, the second one measures the klystron output power. The source of the test signal is connected to the inputs of the downconverters. RF switch allow the selection of either the probe signal of the test signal. Timing parameters and the power level of the test pulse should be similar to the real cavity signal and well known. Access to electronic modules is possible via DOOCS servers and VME controllers, as SUN SPARC CPU's are installed in the crates. The complete analysis of the data from the electronic modules is done by the diagnostic software. It controls the diagnostic hardware through the VME bus.

6.3 New hardware for LLRF

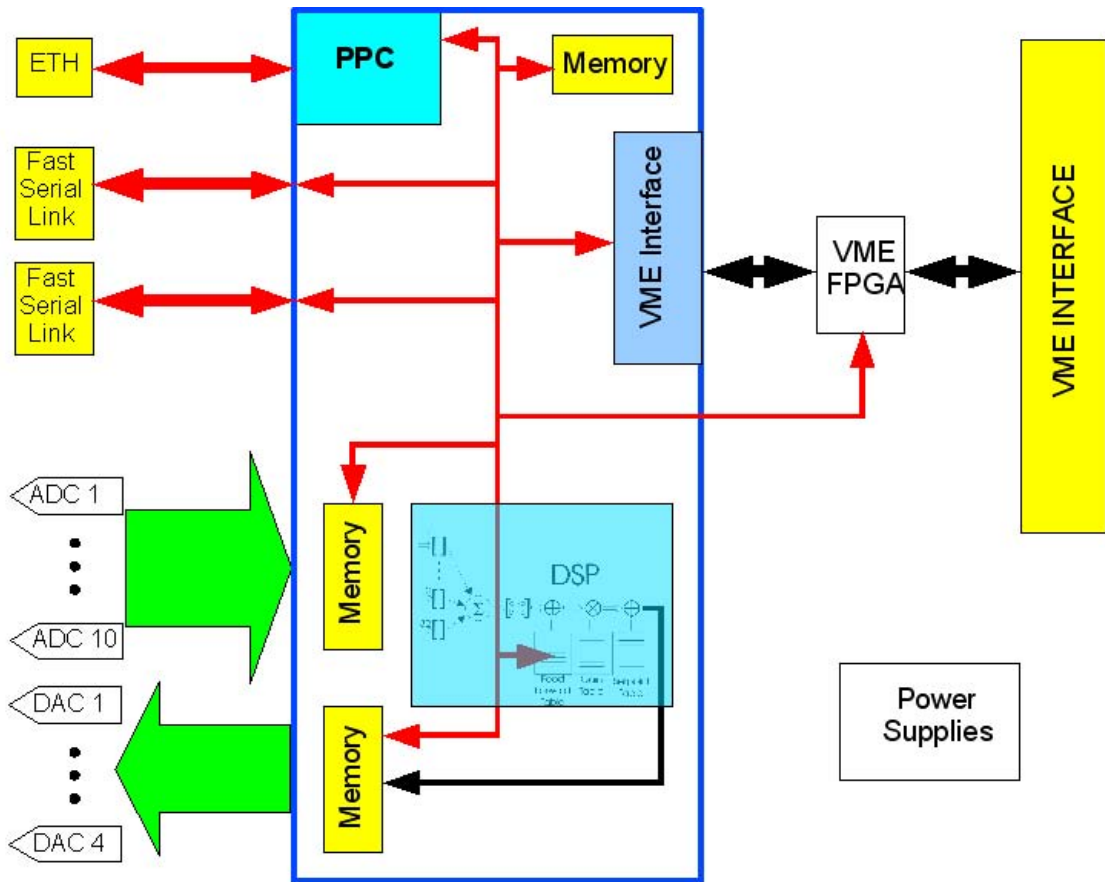


Figure 6.3. Block diagram of new controller for LLRF.

The new controller board, called SIMCON 3.1L [15-A] consists of 10 ADCs, 4 DACs, FPGAs, Power PC (PPC), VME interface, memory, Ethernet connection and two fast serial links. The design is made such that it is possible to access all logic elements, memory, and register using different media. The board is connected to the rest of the system by VME interfaces, but all parameters can be read via Ethernet or by fast serial link as well. In addition to the communication bus between VME FPGA and main FPGA, there is a special link between the FPGAs, which allows for redundant communication. This board is equipped with the diagnostic module, which can detect critical signals in the controller, such as timing signal, errors in calculation (overflow). Diagnostic modules can also calculate histograms of given values or count different events and make it available for diagnostic purposes during normal operation. Based on this board new diagnostic functionality can be easily added and changed in the future.

6.3 New hardware for LLRF

The board is not equipped with an analog test signal; it was assumed that a test signal from the RF system will be connected to the downconverter. That allows examining the downconverter as well as ADCs. Linearity of the dawnconverters can be analyzed. The picture of the SIMCON 3.1L control board for the LLRF is shown in the Figure 6.4. On the board, there are temperature sensors and a power monitors accessible by different interfaces.



Figure 6.4. New control board.

The new control board has been installed and tested at DESY in the VUV-FEL accelerator. The LLRF control system based on that board controls the RF GUN [50] and Kryomodule ACC1. During a few months of operation, the system proved to be very flexible and versatile.

6.4 Test procedures

Test procedures have been designed for the old (DSP-based) version of controller as well as new one. The underlying idea of the tests procedure is similar in both cases, but their implementation to new controller was simpler. The VUV-FEL is under constant

6.4 Test procedures

development and presented below tests were used to support of that development. The experience gained while working with this system will benefit the development for the European XFEL [49] accelerator.

6.4.1 Hardware tests

Hardware tests must detect any malfunction in the electronic modules. Interfaces, access to registers and memory are tested. The test is performed by algorithm presented in chapter 5.1, only implementation is different. An exemplary result of a test is shown in Figure 6.5. The diagnostic system found a dysfunctional board, “ADC prob” in module ACC1.

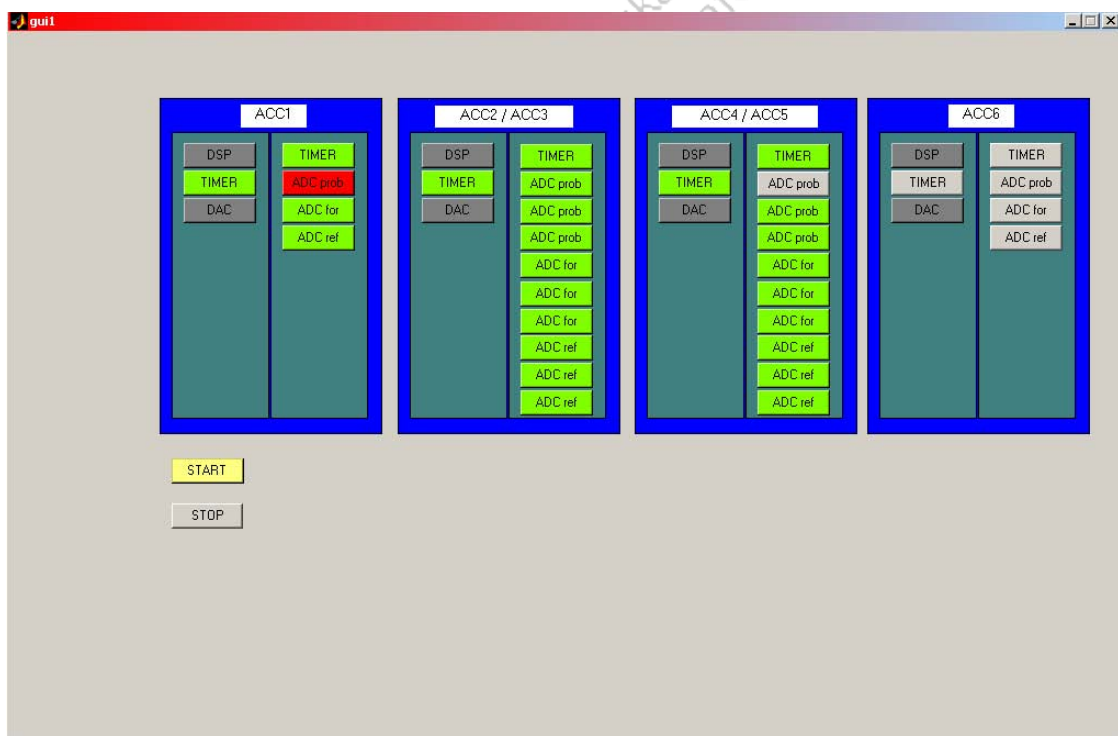


Figure 6.5. Main panel of the diagnostic system for LLRF.

6.4.2 Monitoring

An important goal of the on-line diagnostic system is to monitor different events, power and temperature on different boards. The off-line analysis can correlate events and help to investigate when and where a problem appears. The diagnostic system [17-A] takes data from the input and output of the DSP/FPGA controllers, calculates outputs and compares the predicted output with the output from the controller. Internal data is accessible through DOOCS servers [52]. Monitoring points are presented in Figure 6.7. Data is gathered in crucial points of the controller and analysis information about system performance. Figure 6.8 presents measured phase of the vector sum. The calculated mean value of the phase is fluctuating. This observation allowed find problem with phase drift with a master oscillator.

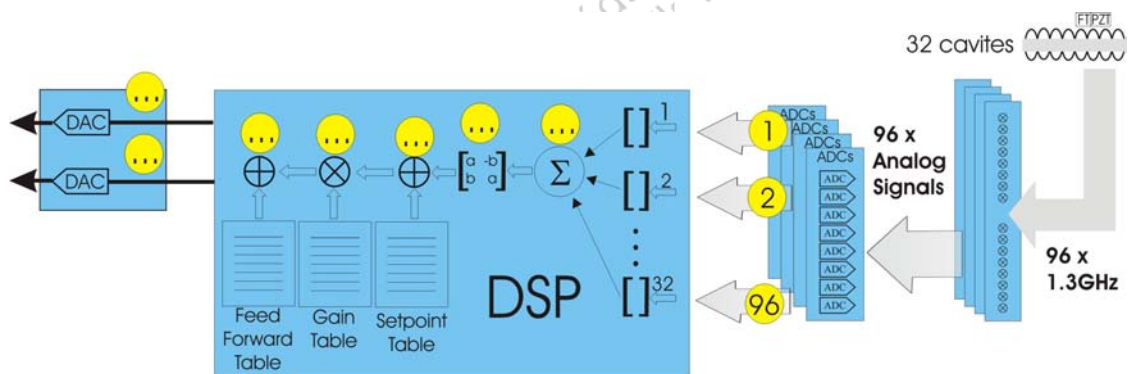


Figure 6.6. Monitoring points in the LLRF.

A typical RF pulse measured by the control system is shown in Figure 6.8. The pulse has a length of 1300 μs , but from point of view controller only 500 μs is important. During these 500 μs the LLRF system must provide a stable RF field inside the cavities. In Figure 6.9, the vector sum and signal from one cavity registered by the diagnostic software is presented. During one pulse, the gradient in cavity 1 suddenly drops. The diagnostic system discovered a quench of a cavity, which can be extremely for a cavity leading to the destruction of a cavity. This kind of monitoring (quench detection) will be implemented as one of many diagnostic modules into the hardware in the future.

6.4 Test procedures

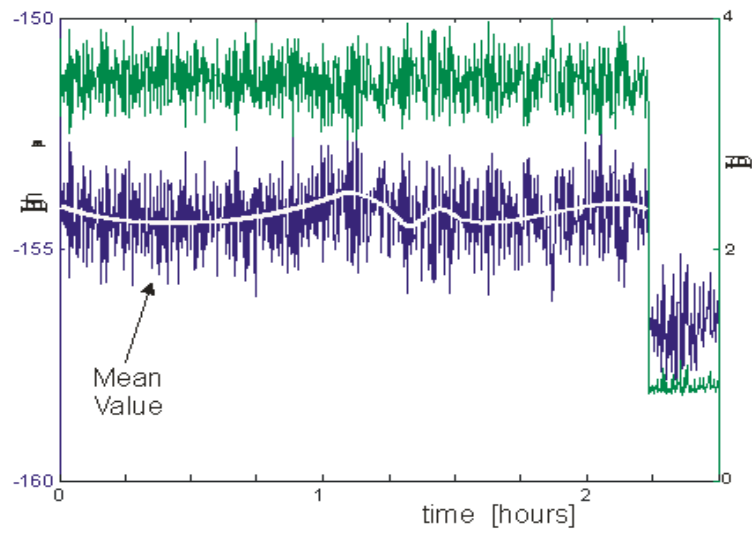


Figure 6.7. Measured phase seen by controller.

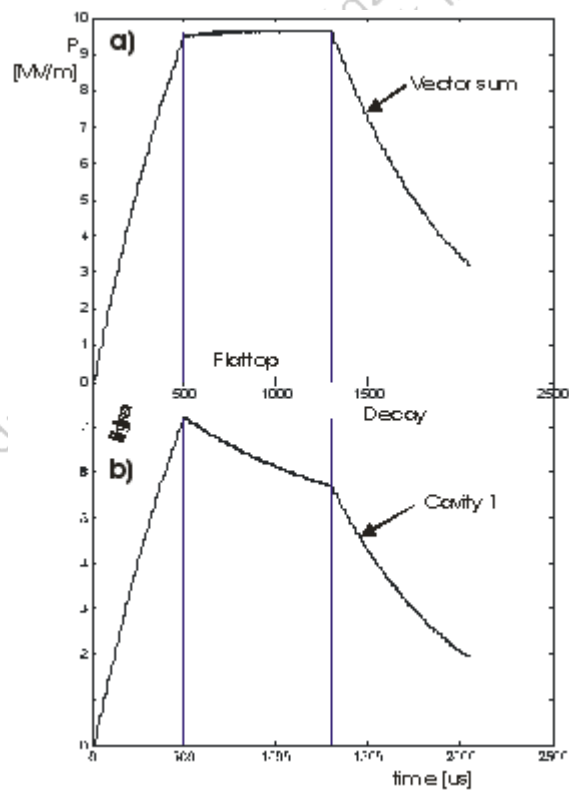


Figure 6.8 The vectorsum and cavity 1 field registered by controller.

6.4.3 Controller tests

This class of test is called “dynamic tests”. These are performed under normal operation conditions, but with simulated input signals. All electronic modules can be examined, except for the cavity probes. As the electronics are installed in a radiation environment, single events upsets can be caused in the controller, therefore it is necessary to check the logic of the boards.

There are following kinds of test signals:

- *external RF source test signal* - it allows to examine the functionality, logic and connection for the whole LLRF system. All electronic boards are included into the test. The test signal is applied to the input of the system. For the given test signal, the diagnostic system knows the proper output signal. This known output signal is compared with the actual measured output from the tested system, see Figure 6.2. If these signals are not equal, this means something in the system is wrong. There is also the possibility to find the location in the electronic modules chain, where the failure occurs.
- *signal and pattern generators based on the system electronic modules* – it allows to examine each electronic module very precisely. Different test configurations are possible. That method is used to test the logic element.
- *cavity simulator* – [6-A],[7-A], connected to electronic modules instead of cavities allows to work with full speed or step mode operation. Very useful device during development of new version of the control system hardware and software.

A test algorithm with test signals from internal and external sources is presented in Figure 6.10. The diagnostic system calculates the expected signal value in different point in the chain of electronic modules and compares with measured values. In case of incompatibility, an error is reported. All algorithms implemented into the controller are deterministic, it is possible at each stage to calculate the expected value in the controller. This kind of test is useful during debugging a new version of hardware described in

6.4 Test procedures

VHDL or in DSP.

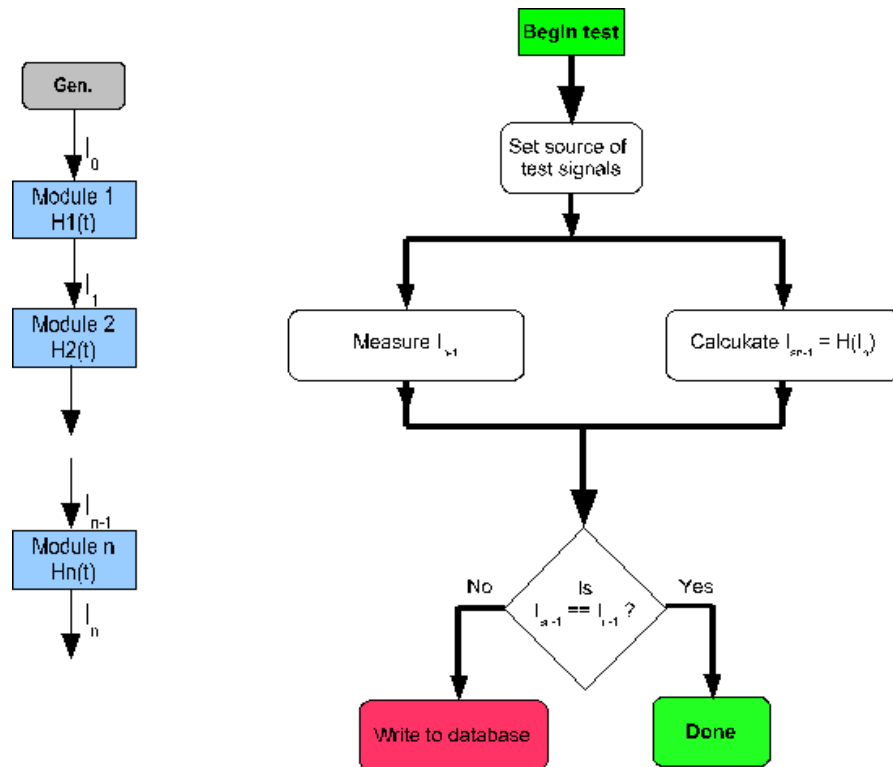


Figure 6.9. Algorithm for test with external source test signal.

6.5 Summary

The presented idea and the realization of the diagnostic system for the old and new control board for the LLRF proved that it is possible to equip the existing control modules with a diagnostic system. It supports the maintenance and development process in the VUV-FEL accelerator. The time needed to locate faults has been decreased, as well as effort needed for maintenance. Data registered by the diagnostic system can be used by the designers and experts to improve the construction and algorithms. The presented solution does not severely increase the cost of the design and manufacturing of the electronic devices, but ensures a longer uptime of the whole system.

Chapter 7

Conclusions

The aim to build this system was to assure the proper working of the BAC detector, and in the case of detecting abnormalities to find them out as soon as possible, detect the place of the error and the causes of the failure. The diagnostic system for the Backing Calorimeter has been designed and realized. Its operation in real environment proved that such system can significantly support operation. The diagnostic system significantly decreases time needed for failure localization and enabled tests of configuration data for data acquisition system.

An initial test of the overall feedback for the LLRF of the VUV-FEL system with a new controller demonstrated successful. The diagnostic system allows to identify defect LLRF components or malfunctioning software. Collected diagnostic data can be used by designers, experts to improve the construction and algorithms. The presented solution does not severely increase the cost of the design and manufacturing of the electronic devices, but ensures the longer operation time of the whole system and can save money and effort used for the maintenance.

In this work it has been shown that electronic components for HEP experiments are

Conclusions

similar and diagnostic system for both can be designed the same way. All these Chapter 1.2 have been duly proven. In particular, the fact that the systems work reliably, detects the malfunction and support operation of the BAC detector. The construction of the diagnostic systems without crucial modification of existing hardware proves Thesis 1. The presented systems were tested using data from a real-world, from high physicists experiments. Successful operation of the experiments and diagnostic system proves Thesis 2. In addition, the diagnostic system for the Backing Calorimeter increased availability of the detector to the user operation. It has been achieved by significant reduction of time needed for failure detection and maintenance. Two kind of failures of the BAC detector exist:

- failures which stop user operation – the problem is seen immediately after occur and it is impossible to continue experiment. In that case the BAC detector is excluded from the run till problem is solved.. The diagnostic system allows to decrease time needed for failure detection from few hours till about 80 minutes, which is needed for full diagnostic of the detector,
- “fake” data – as a result of failure in electronic modules or wrong configuration data the data acquisition system gathers data which never appeared in the detector or will not able register any particle passing the detector. The user got information about that kind failure after 3 days or even after 3 weeks, when physics analysis has been done. Although the detector has been working the detector has been not available for user operation, collected data was worthless. The diagnostic system works during short brakes in operation of the HERA accelerator and can detect this kind of failure maximum after 6-7 hours.

The diagnostic system for the Backing Calorimeter with is build-in thresholds tuning function is able to proper configuration data for a data acquisition system. Achieved results proved Thesis 3. The level of threshold determines the number of mistaken data being analyzed. Proper setting of comparator thresholds is very important for the readout and trigger system. In case of trigger too low thresholds lead to high rate of false events

Conclusions

registered by the detector. On the other hand the threshold level cannot be too high, because the detector will lose its ability to record real particles. In the beginning of 2000 the measured efficiency of the BAC detector did not exceed 75%. Currently the detector achieves up to 90%. 100% will never be achieved, because there is no access to some electronic modules installed directly on the detector.

In this work it has been shown how to design electronic modules for HEP experiments, which in the future allow to equip these electronic modules with sophisticated diagnostic elements. Future work will not require modification in design and installed electronic modules.

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