Tripple GEM Trigger and DAQ system using μTCA at CMS upgrade.

By

Waqar Ahmed

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Certificate

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Supervisor:

Prof.Dr.Shahid A. Khan
Dean-HOD
Department of Electrical Engineering.
COMSATS Institute of Information Technology
Islamabad,Pakistan

Co.Supervisor:

Prof.Dr Gilles De Lentdecker
Research Associate FRS - FNRS (Chercheur Qualifier)
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Author: **Waqar Ahmed**

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Abstract

The developments were rather generic, driven by the observation that modern technologies allow to design a DAQ architecture independent of the detector technology to which the DAQ system will be connected, providing freedom to the choice of the future experiment. It becomes clear now that the future particle and astro-particle experiments plan to use the most advanced technologies from the telecommunication and the digital programmable electronic industries: the Advanced Telecom Computing Architecture (ATCA or micro-TCA) standard and Field Programmable Gate Arrays (FPGA).Currently we are working on design of the DAQ system of the CMS Forward Muon Upgrade project which proposes to install Triple-GEM detectors instead of Resistive Plate Chambers in the first CMS muon station at 1.6 ¡η¡ 2.4 during the 2nd LHC long shutdown. The IIHE is also leading the design of the DAQ system of Askaryan Radiotelescope Array (ARA) project, for which radio-antennas are being spread over an area of several km2 in the South Pole ice, close to the IceCube experiment. In addition the IIHE contributes to the DAQ development of the Large TPC prototype for the ILC. In the framework of the CMS upgrades, the IIHE in collaboration with the University of Antwerpen is investigating the new micro-TCA standard, introduced by the telecommunication industry, to replace the VME electronics. With its high data throughput (several Gbps), high reliability and high availability, the micro-TCA standard combined with the most powerful FPGAs for the data processing should allow the future CMS DAQ system to cope with the LHC luminosity beyond the nominal value of 10^{33} cm^{-2}s^{-1}. Typically these systems require high data volume transmission, from 0.5 to 3.2 Gbps, from the detector to off-detector electronics where data are processed by FPGAs, as well as the distribution of precise signals like clock and trigger inputs towards the detectors. The high bandwidth transmission uses optical fibre transceivers and gigabit transceiver blocks (GTPs) routinely built into FPGA devices. We have also set-up a micro-TCA test bench equipped

with various Advance Mezzanine Cards (AMC), either commercial ones or designed by IIHE electronic engineers. In particular we are evaluating the CERNs Gigabit Link interface Board (GLIB) designed to test the GBT/Versatile optical link being developed by CERN for the next Tracker upgrade.

The micro-TCA technology is a relatively new telecommunication standard. It is planned to replace VME as the default technology for future particle physics experiments (LHC upgrades, ILC experiments, etc.). Consequently it still needs a lot of developments and specification validation for particle physics. Another aspect we are starting to develop is the implementation of complex algorithms on FPGAs. Indeed with the introduction of increasingly powerful FPGAs, it seems now feasible to run on such devices more advanced algorithms for trigger and track reconstruction. These developments are of interest for the LHC trigger upgrades and in particular for the future CMS track trigger.

Acknowledgements

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Waqar Ahmed

My Contribution

One of the characteristics of the experiments in the field of the High Energy Physics is that they are based on the teamwork. In the CMS experiment a few thousands of scientists, engineers and technicians were involved. Hence, it is obvious that not all issues discussed in this thesis are my exclusive contribution. The GEM detector trigger and DAQ sytem was proposed and designed by the Universit libre de Bruxelles CMS group, the group developed most of the custom electronic boards of the trigger system, prepared the firmware for the FPGA devices, carried out the production and installation of the trigger electronics. The GEM chambers were developed and produced by the scientists from Italy, USA, Pakistan, Beljium, India and CERN. The Brussel CMS group have consisted of a few dozens of people from the de de l'Universit libre de Bruxelles. I have been a member of the group for over three years. My tasks included: software development, testing the prototypes of the electronic boards, testing the GEM detectors and DAQ system during installation, proposing the firmware improvements and modifications, work on the optohybird modules. The on-line software for the PAC Trigger system, that is the subject of the Chapter 4, was developed mainly by two people: Micha Pietrusiski and me. Micha was themain architect of the software structure and implemented most of the low-level software. Based on that part, I have designed and implemented the test procedures for the trigger system as well as details of the hardware configuration process. Additionally, my task was to decide what diagnostic and monitoring tools should be implemented in the firmware of the trigger electronics and how to analyse and present the data acquired by those tools. The dedicated monitoring procedures were developed mostly by me and are a part of the PACT system online software. The hardware and firmware solutions for the synchronization of the chamber data and transmission channels were created by the main developer of the firmware for the PAC system Yifan young. My task was to find the ways of using those solutions in practice. I have worked out the methods for finding the optimal values of the synchronization parameters and implemented them in the dedicated software procedures, which allowed successful synchronization of the VFAT signal to optohybrid module. (at the moment for the cosmic muons). The analysis of the system synchronization from the data acquired during the cosmic muon runs, as well as the simulation of the muon hits timing, was performed by other members of the Brussel CMS group.

Chapter 1

Compact Muon Solenoid Experiment and LHC

This chapter gives an introduction to the Large Hadron Collider (LHC) [1] and Compact Muon Solenoid (CMS) [2] built by European Organization for Nuclear Research (CERN) located at French-Swiss border near Geneva. There are four experiments which will take place at LHC: two general purpose detectors ATLAS [?] , CMS [2], and two dedicated detectors LHC-b [?] and ALICE [?] which will study b physics and heavy ion physics respectively. The figure shows the four experimental sights along the LHC ring. CMS is one of the major experiments being operated at LHC near the village of Cessey France which will take data of both p-p and Pb-Pb collisions.

1.1 Large Hadron Collider

LHC ring has just completed its installation at CERN and first proton beam was injected in the beam pipe in September 2008. LHC uses the former Large Electron Positron Collider (LEP) tunnel with 27 km circumference. The main physics goal is the search of Higgs boson and the testing of the standard Model of particle physics at the energy scale of 1 TeV. The LHC will be operated with proton-proton and heavy ion collisions with a center of mass energy of 14 TeV for proton-proton collision and 5.5 TeV for heavy ion collisions with a luminosity of 10^{34} cm^{-2}s^{-1} and 10^{28} cm^{-2}s^{-1} respectively. To achieve the design luminosity for p-p collision two beams with 2800 bunches are injected into the beam pipe with 25 ns gap. To keep the particles in

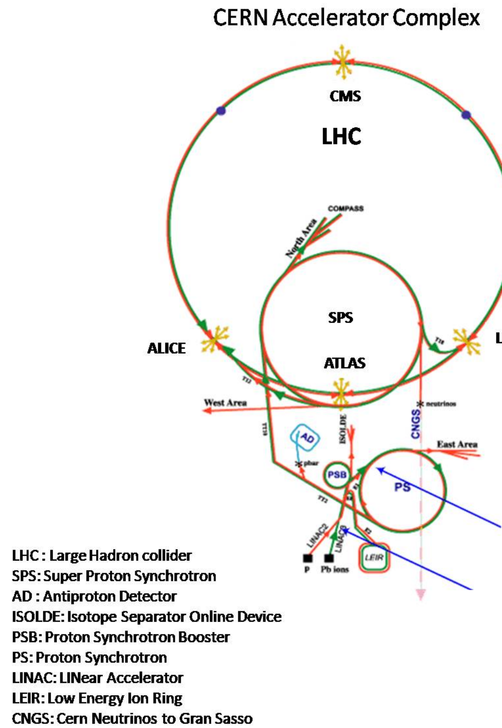

Figure 1.1: CERN accelerator complex

track 1232 superconducting dipole magnets producing a field of 8.3 Tesla are used. The figure 1.1 shows the schematic view of the CERN accelerator complex.

1.2 Compact Muon Solenoid

One of the general purpose detector CMS is located near the village of Cessey France. The high luminosity and short bunch spacing of LHC beam demanded a sophisticated detector. CMS detector is a very compact as compared to the other general purpose detector ATLAS which has more than twice the volume of CMS. CMS detector has an excellent muon system assisted by central tracking detector and solenoid produces a magnetic field twice large as used by ATLAS. This allows the accurate particle momentum measurement. The Figure 1.2 below shows perspective view of the CMS detector.

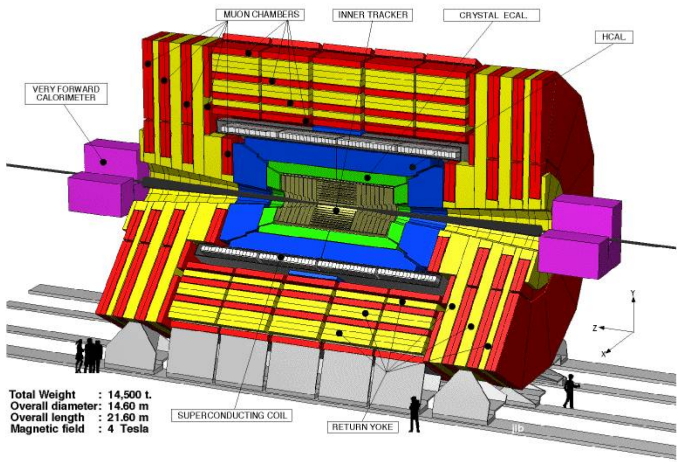

Figure 1.2: Longitudinal view of CMS Detector.

The overall dimension of the CMS detector are 22 m in length 15 m in diameter with a total mass of 12500 tons. The coordinate conventions are as follows: The interaction point which lies in the middle of barrel part of the CMS where the two beams collides is referred as the origin of the coordinate system. The x-axis points radially inward to the center of the LHC ring. The z-axis points along the direction of the beam pipe and the y-axis points vertically to the surface. The azimuthal angle ϕ is measured in the x-y- plane from x-axis. In the y-z-plane the angle θ is measured form z-axis. The pseudo rapidity is defined as $\eta = -\ln(\tan(\theta/2))$. A more details of CMS experiment can be found in [**?**, **?**].

1.2.1 Inner Tracking System

Tracking system of CMS is designed to take the huge particle flux coming for LHC collisions. The CMS tracker consists of about 20000 silicon sensors with a total area of 210 m^2 having a diameter and length of about 2.4 m and 5.4 m respectively thus its acceptance is up to $\eta < 2.5$. Tracker is located directly around the interaction point therefore it receives a very high particle flux. Per bunch crossing around 1000 charged particles will hit the tracker at the radius of about 4 cm therefore at such a distance the tracker has to be radiation hard. The inner tracker mainly consist of silicon pixel detector and silicon strip sensors. The whole system is surrounded my 4 Tesla homogenous magnetic field [?].

1.2.2 Silicon Pixel Tracker

The pixel tracker is subdivided into two parts: First, three cylindrical barrels located at radii of 4.4, 7.3 and 10.2 cm around the interaction point with a length of 53 cm. Second, on each side of the barrel two discs complement the tracker at $z = \pm 32.5$ and $\pm$ 46.5 cm. Therefore, for every charged particle with $\eta < 2.5$ hitting the tracker, three high precision space points will be measured. The pixels have a cell size of 100×150 μm^2.

1.2.3 Silicon Strip Tracker

The silicon strip tracker surrounds the pixel tracker. Here the inner and outer part is different. The inner barrel (TIB) consists of four layers ranging from 20 to 55 cm and covering $|z| < 65$ cm. Three tracker inner discs (TID) are located at each end in the region of $65 < |z| < 110$cm. The inner strip tracker measures four spatial points for each trajectory. The resolution for a single point is 23 to 34 μm. The inner part is surrounded by the tracker outer barrel (TOB) comprising 6 layers, which extend from 55 to 116 cm in radius and ± 118 cm in z. The barrel part takes out 6 measurements with a single point resolution in between 35 and 53 μm. Finally the outer tracker is completed by 9 end cap discs (TEC) on each side ranging from $124 < |z| < 282$ cm and $22.5 < r < 113.5$ cm.

1.2.4 The Electromagnetic Calorimeter-ECAL

The Electromagnetic Calorimeter used in the CMS is designed to have precise measurement of the electron, photon's energy and direction. ECAL is positioned outside the tracking system at the distance of 120 cm from the point of interaction. For a good energy resolution and fine granularity for spatial resolution lead tungstate ($PbWO_4$) crystals are used. These crystals are used because of high density around

8.28 g/cm^3, short radiation length 0.89 cm and small Moliere radius of 2.2 cm. The light produced in the crystals is gathered with silicon avalanche photo-diodes. Around 80 of the light is emitted in the first 25 ns. ECAL is divided into end cap (EE) and barrel ECAL (EB). Geometrically Barrel covers $\eta < 1.48$ and the end cap covers η from 1.48 to 3. Each crystal has a 26×26 mm or 0.0174×0.0174 mm^2 in η, ϕ plane. The length of crystals is 230 mm which correspond to the radiation length $25.8X_0$. In the end cap region the area of cross section is 28.62×28.62 mm^2 and the length of each crystal in the end cap region is 220 m which corresponds to the radiation length of $24.7X_0$. More details can be found in [**?**].

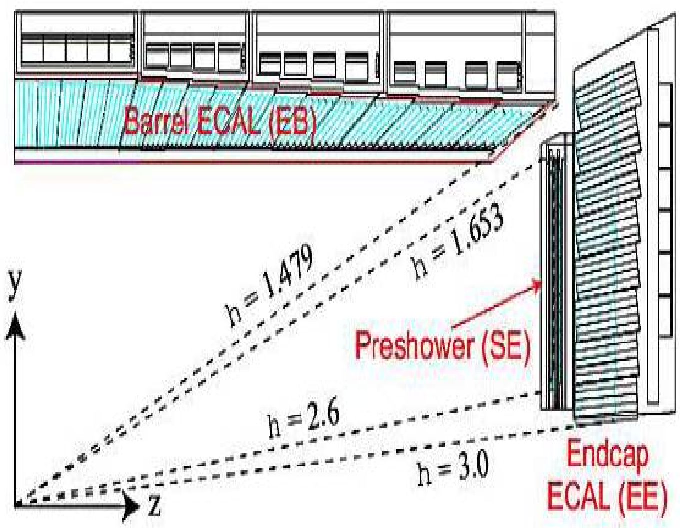

Figure 1.3: Longitudinal view of electromagnetic calorimeter.

1.2.5 Hadron Calorimeter-HCAL

The Electromagnetic calorimeter is surrounded by Hadron Calorimeter HCAL. The HCAL measure the energy of hadrons and their products. HCAL is located at a distance of 1.77 m for the interaction point. HCAL can be divided into four parts: barrel (HB), end cap (EB), outer barred (HO) and Hadron forward (HF).The barrel part covers the $\eta < 1.3$, Hadron End cap covers the range from $1.3 < \eta < 3.0$.

The Hadron End cap receives high counting rates as compared to the barrel part. For eta less than 1.3 Hadron Outer barrel (HO) is used to cover this η ranges. The forward calorimeter (HF) covers the η region up to 5.0. Here, the environment is very hostile due to high radiation and energy deposition. Hence, quartz fibers were chosen as calorimeter material. Particle showers exceeding the Cerenkov threshold of $E > 190KeV$ will be detected. The segmentation in $\eta \times \phi$ is 0.175×0.175 mm^2.

1.2.6 Muon System

The Muon system of the CMS carries an immense importance. In this outer most region of the detector only muon and neutrinos can manage to pass through it without depositing their large fraction of energy. The Muon system is developed to provide a fast identification and efficient reconstruction. Three different types of the gaseous detector are used in the muon system which are RPC's, CSC and DT. In the barrel region four layers of muon chambers are located along with Drift tubs. In the end cap region $0.9 < \eta < 2.4$ Cathode strips are used along with the RPC. The complete track of muon is obtained after combining the information from the silicon tracker. The DT and CSC detectors are used to obtain a precise position measurement, while the RPC's are, due to their very fast response and time resolution of the order of 1 ns, dedicated for timing information and the trigger purpose[**?**, **?**].

1.2.7 The Trigger

At the LHC, with a center-of-energy of 14 TeV and the luminosity of 10^{34} cm^{-2}s^{-1}, the event rate is about 10^9 Hz and each event needs a typical space (event size) of 1 MB. Therefore, the data stream coming from the detector is around 1.2 TeraByte/s. It is therefore impossible for the detector electronic system to record all events with such a high frequency. The trigger system is used to select the useful and interesting events and reduce the event rate to a range manageable by the data acquisition system. The CMS trigger system will reduce the event rate down to 100 Hz. This reduction level is done through three levels of triggering. The Level-1 (L1) reduces the rate to 100 kHz in the high luminosity regime and 50 kHz for the low luminosity phase [**?**, **?**]. The L1 decision to pass the event to the next level of trigger must be taken in 3.2

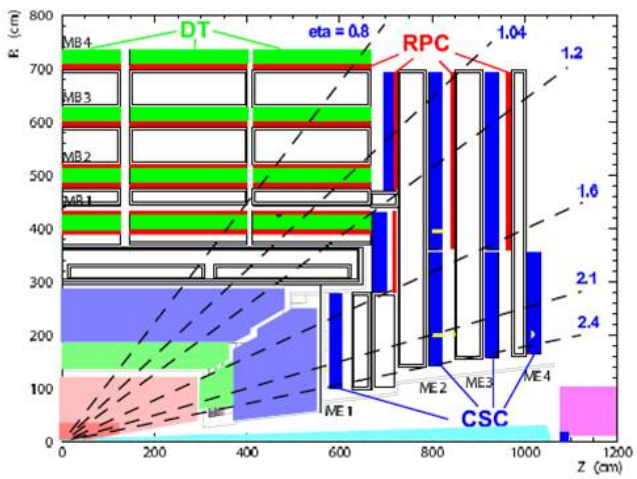

Figure 1.4: A section of detector where RPC are installed.

μs. The L1 trigger uses only a coarse granularity information from calorimeters and muon system because the decision must be taken in a time which is very short to read all the data from the whole detector. The High Level Trigger (HLT), which consists of Level 2 and Level 3, is the second step of the trigger chain. It has been designed to reduce the L1 output rate of 100 kHz to the output rate of 100 Hz. The HLT code performs the reconstruction and selection of physics objects using the full event data with the granularity and matching information from different sub-detectors. These objects are electrons, photons, muons, missing energy, hadronic jets. The selection or rejection of such objects allows to achieve the output rate of 100 Hz for events in the permanent storage medium.

1.2.8 General Structure of the CMS trigger and DAQ

The CMS trigger and data acquisition system (TriDAS) is designed to inspect the detector information at the full crossing frequency and to select events at a a maximum rate of O(10^2Hz) for achieving and later off-line analysis. The CMSDAQ has to read out all front end electronic, to assemble the data from each bunch crossing into a single stand alone data structure, to provide these data to the processing element that execute the High Level Trigger (HLT).

The DAQ system provides the first place where the entire information from the physics collision can be inspected. It is also the place where the complete picture of the detector response to the collision can be monitored, thus providing early feedback to physicists running the experiment. The DAQ is therefore the system that implement

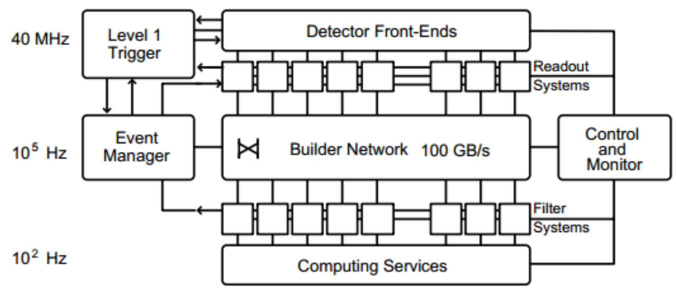

Figure 1.5: Architecture of the CMS DAQ system

the two crucial function that exentually determine the reach of the physics program:

1: Event selection.

2: Control and monitoring of the detector elements.

The architecture of the CMS DAQ is shown in Fig 1.5 it consists of the following elements.

1. **Detectors front-ends:** The modules that store the data from the detectors front-end electronics upon the reception of a Level-1 trigger accept signal. the front end electronics are the responsible of the corresponding subdetectors.

2. **Readout System:** The modules that read the data from the detectors front end electronics system. The data stored, untill they are sent to the processor, which will analyse the enent.

3.**Builder network:** The collection of network that provides the interconnections b/w the readout and the filter system.

4.**Filter system:** The processors, which are provided by the readout. They execute the HLT algorithum to select the events to be kept for off-line processing.

5.**Event Manager:** The entity responsible for controlling the flow of data (events) in the DAQ system.

6. **Computing services:** All the processor and networks that receive filtered events as well as a small fraction of rejected events from the filter farm.
7.**Controls:** All the entities responsible for thr user interface and the configuration and monitoring of the DAQ.

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