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Abstract

ALICE (A Large Ion Collider Experiment) is one of the four main experiments at the CERN Large Hadron Collider. ALICE is dedicated to the study of strongly interacting matter. The ALICE collaboration plans a major detector upgrade during long shutdown 2, which is at present foreseen to start at the end of 2018 followed by Run 3 starting in 2021. The Central Trigger System (CTS) will manage different interaction rates i.e. 50 kHz in Pb-Pb collisions and up to few hundred kHz in pp collisions. This trigger system will also allow for different readout strategies. To cover these requirements the ALICE CTS will be completely redesigned. The upgraded trigger system will use new universal trigger boards, based on the Kintex Ultrascale FPGA, able to support up to 20 High-speed links and a novel Timing and Trigger Control system based on Passive Optical Networks. The new trigger downstream (CTS to Detectors) distribution will run with a 9.6 GHz signal.

Keywords: ALICE, Upgrade, Trigger System, FPGA, TTC-PON.

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Introduction

The primary objective of the thesis has been to design and testing the new Central Trigger System (CTS) of ALICE (A Large Ion Collider Experiment) at the CERN Large Hadron Collider (LHC). ALICE is the detector at the CERN LHC dedicated to the study of strongly interacting matter, in particular, the properties of the Quark-Gluon Plasma (QGP). The ALICE collaboration plans a major upgrade of the detector during long shutdown 2 (2018 – 2020). In Run 3 ALICE will be able to collect $> 10nb^{-1}$ of Pb-Pb collisions at luminosities up to $\mathcal{L} = 6 \times 10^{27} cm^{-2}s^{-1}$ corresponding to collision rates of 50 kHz, where each collision is shipped to the online systems, in the case of upgraded detectors, with continuous readout, or only after a minimum bias trigger has been issued for the other detectors. The ALICE upgrade also considers, in addition, the collection of $6 pb^{-1}$ of pp collisions at the equivalent Pb-Pb nucleon energy as well as $50 pb^{-1}$ of p-Pb collisions, both at a collision rate of up to 200 kHz. With these physics goals, the statistics of data in ALICE will be increased by a factor of 100 over the numbers achieved with the present ALICE detector up to LS2.

The ALICE Upgrade will require a very different triggering strategy in comparison to the current and hence a new Central Trigger System (CTS) is needed. The strategy for selecting event will also be different from that employed in previous runs. The CTS will keep the previous architecture, a Central Trigger Processor (CTP) and Local Trigger Units as detector interface, the heart of the CTS will be an universal trigger board called ALICE Trigger Board (ATB) based on Kintex UltraScale FPGA, and the implementation of a novel Timing Trigger Control system based on Passive Optical Networks (TTC-PON).

The first chapter of the thesis gives a general overview of the use of Trigger Systems in High Energy Physics Experiments, with special focus in the trigger systems in the Large Hadron Collider. The second chapter gives an state of the art of the ALICE-CTP during the LHC-Run 2, at the end of this chapter the performance of the ALICE-CTP during LHC-Run 2 is presented. The ALICE Upgrade plans (Physics and Detector) are briefly described in chapter 3, at the end of this chapter a detailed description of the trigger strategy for the LHC-Run 3 is presented. The chapter four shows the hardware implementation of the CTS,

with special focus in the description of the design and testing of the ATB which together with the TTC-PON system are the heart of the CTS, additionally shows the results of the extensive testing carried out to ATBs. Finally, in chapter 5 extensive qualification of CTS interfaces (TTC-PON and GBT) is presented, during the evolution of this chapter the very important parameters as latency and phase clock stability are presented. In the last section of the thesis a summary of the work done and achievements obtained is given.

1

TRIGGER SYSTEMS IN HIGH ENERGY PHYSICS

The first chapter gives an introduction of use of Trigger Systems in High Energy Physics experiments, a brief explanation about the main role and components of a Central Trigger System, and finally an overview of the trigger systems in the Large Hadron Collider (LHC) is then given.

1.1 Introduction

An intrinsic problem in High-Energy Physics (HEP) is that physicists are often confronted with high background rates, while the events with interesting physics information make up only a tiny fraction of the data. Figure 1.1 gives examples of processes selected and suppressed by the trigger system in a HEP experiment. The main task of a trigger system is to select physics events and suppress background events as efficiently as possible. Modern high-energy physics experiments collect data using dedicated complex multi-level trigger systems which perform an online selection of potentially interesting events.

In spite of the advances in electronics, computing and data processing, HEP experiments

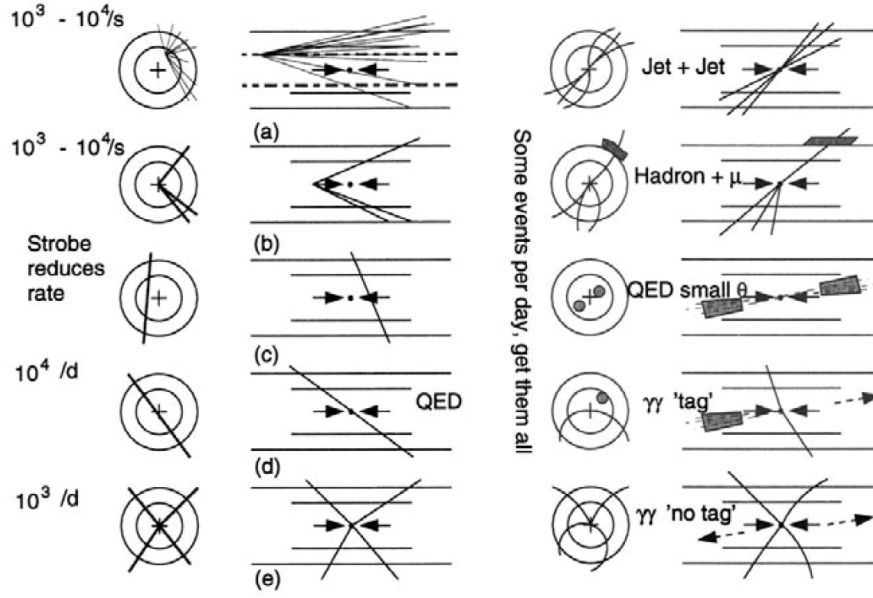


Figure 1.1: Topology of physics and background events in a e^+e^- collider experiment. Events selected are show at the right part. (a) Shower originating in the vacuum tube; (b) beam-gas interaction; (c) cosmic ray background; (d) coplanar and collinear beam-beam interaction; (e) multibody beam-beam event[1].

generally can not afford to cope with the large data volume generated in the detectors in real time. The quest to measure rare events necessitates an interaction rate and data volume that challenges the technical capabilities for data storage and analysis[1].

Different levels of trigger selection may prevent the recording of all events accepted by certain selections designed to cover phase space regions with high rates. The selection procedures reduce the initial interaction rates, often by several orders of magnitude to output rates acceptable within the bandwidth constraints and writes data to permanent storage. The low level in multi-level trigger systems are typically built in custom hardware using information from different detector components. The higher trigger levels often consist of computer farms performing partial or complete event reconstruction which allows the application of sophisticated decision algorithms [2].

Another special feature of trigger systems is the provision of experimental constraints (e.g

temporal spatial) and definition of the time of first interaction (T_0) with the main goal of selecting interactions of interest and reducing background. Ideally a particular combination of trigger selections is already foreseen at the design stage of the trigger configuration before data taking.

For the combination of trigger signals from different detectors a central system, often called the central trigger system (CTS) is needed. In addition to selection physics responsibilities; the central trigger also has the responsibility to initialize the detector front-end readout to the data acquisition system (DAQ), while at the same time synchronize all sub-detectors during that process.

The LHC brought new challenges to trigger systems. The hadronic interaction rate alone is so high that would easily saturate processing power and storage capabilities. In addition, a high degree of selection becomes mandatory. The trigger has to separate interesting physics process (signal) from well-understood process (background). Such a distinction is only possible if the trigger system takes into account the physics features in the event. For example the trigger may have to evaluate the lepton content, momentum balance, individual particle momentum and so on as soon as data are being recorded (in real time), which implies that data from calorimeters, muon chambers and tracking detectors have to be used in the trigger. Typically a number of different trigger conditions are required to satisfy all the physics goals of the experiment [1].

1.1.1 Elements of a trigger system

Multi-level trigger systems usually process data from several detector types. Table 1.1 gives an indication of how various detectors may provide the information for a specific trigger condition. The result of a trigger evaluation in a subsystem is made available to the central trigger, which in turn executes the global trigger decision and retains the event if one or more of the listed condition is fulfilled. The rate of events collected by a trigger decision can be scaled down by a *downscale factor* d (described in the next section). The final trigger decision for each trigger defined is recorded in the event itself for later analysis, using the

trigger information (e.g Orbit, Bunch crossing, etc).

In collider experiments, the data are collected usually in event samples of separate *runs*, in which stable detector performance and steady running conditions are maintained.

Table 1.1: The subsystems and trigger conditions employed in physics analysis

Trigger	Trigger Condition
Calorimeter	energy, total energy, jets from calorimeter
Electron	localized shower in the first layers of the calorimeter
TRD	charged particles with high momentum
Muon	penetrating tracks in the muon detector
Track	tracks and momentum (threshold)
Vertex	vertex position from tracking detector
Central	coincidences and thresholds from various subsystems

The trigger selection using a combination of different detectors should be necessary if individual trigger selections cover different regions of the analysis phase space, for example:

- Trigger selection sensitive to different objects in the final state, (*e.g a study of complex final states triggered via electron, muons and/or jet selection*).
- Trigger selection based on information from different detector components (*data analysis relying on trigger selections using signals from barrel and endcap muon chambers*).
- Trigger selection designed for different kinematics regions, (*e.g an analysis of events accepted by several trigger selections requiring the energy in a calorimeter to exceed different thresholds*).

1.1.2 Synchronization and Readout

Modern colliders use a clock to provide a synchronization signal; typically this signal is derived from the Radio Frequency (RF) driving the beams in the accelerator (e.g ~ 400 MHz for LHC). The bunch Crossing Time (BC) is an integer multiple of clock periods typically from 25 to

100 ns (e.g 25 ns for LHC). The same BC time reference drives the transfer of signals from the detectors, their digitization and the placement in the electronic front-end pipelines. The trigger timing function (*i.e the T_0 mentioned in previous sections*) is hence reduced to the bunch identification, that is the identification of the bunch in which the interaction occurred. Commonly not all bunch locations are filled in a collider. Gaps in the fill pattern are used to safely extract beam. The fill pattern is a priori known or can be derived from beam identification signals. In terms of trigger decisions, the simplest trigger called *minimum bias trigger*, is hence the one that reads out the detector for every interaction.

It should be noted that the temporal alignment of the signals from different detectors, as needed to evaluate the coincidence of signals from the same bunch crossing, can be an challenging task. With thousands of channels each with its own signal propagation distance, delay of all electronic channels must be adjusted for optimal timing within a bunch crossing to ensure full detector efficiency.

The Trigger delays hence have to be adjusted so that a late detector is channeled through a short delay and the signals of early detectors travel through a correspondingly longer delay before the coincidence is formed (Figure 1.2). This adjustment of delays is an important step of the trigger commissioning. Initially all signals of one detector component are brought into coincidence. Following that internal timing, overall delays are adjusted so that all detectors are synchronized, this task is typically realized in the central trigger.

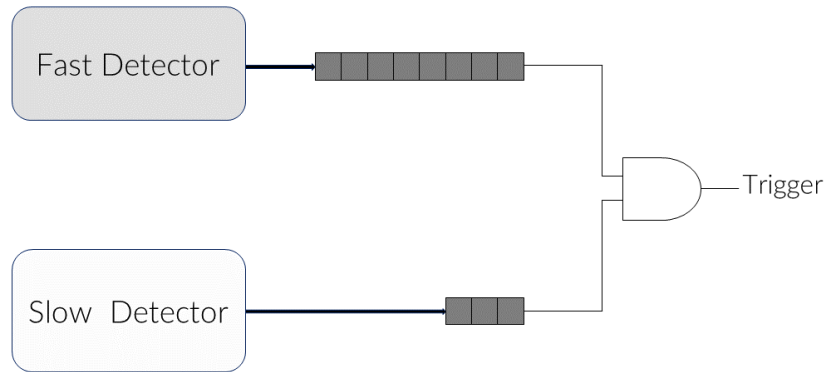


Figure 1.2: Different detectors require adjustable delays from a proper coincidence of the signals in the trigger.

A trigger system should select all good event candidates and reject most of background events. Commonly in HEP experiments the event rate is so high that the on-line data acquisition system must therefore reduce the incoming raw data by several orders of magnitude. The border line between on-line and off-line data handling is defined here as follows: on-line data acquisition operates with the data from their first appearance in digital form up to writing them onto a permanent storage medium; off-line analysis is any analysis which reads the information from that medium [3].

1.1.3 Central Trigger System

In HEP experiments it is very rare that the signal from just one detector is used to initiate the readout of entire experiment. In most cases a better selection can be realized when employing coincidences of at least two different signals, and the logical AND of signals is probably the most frequently realized trigger logic. However, there are many more logic conditions that can be used in the Central Trigger System (CTS) for the selection of events, for example:

- Logical AND and OR of two or more signals.
- Majority logic: (n out of m detectors have responded, with $n \leq m$).
- Threshold: n lines encode a digital value, for example energy E , and the condition $E > E_{th}$ is used to trigger.
- Topological patterns with a well-known signal profile.

Another important feature of the Central Trigger System (CTS) is the *trigger latency* which can be defined as the time to form trigger decision and distribute it to detectors. In some cases the CTS must provide a synchronous decision within the duration of the bunch crossing interval with extreme precision (e.g. 50 ps). Since standard computers would not guarantee the response in real time and for every bunch, custom electronics using high technology are employed as solution.

When the specifications of the trigger system are very complex to achieve, *Field Programmable Gate Arrays* (FPGAs) provide an excellent solution. These high density architecture chips combine logic cells with storage cells. Their logic function is programmed at startup so that they maintain much of the flexibility. Nowadays FPGAs can be operated at GHz rates, so that serial computations can be envisaged even in between bunch crossing.

1.1.3.0 Buffering

The cross section σ , of a physics process defines a rate, ν , for an interaction per time interval: $\nu = \sigma \mathcal{L}$, where $\mathcal{L}$ is the instantaneous luminosity. The trigger have to cope with different interaction rate, and, consequently different amounts of events. In order to de-randomise the arrival time, events are stored in a temporary buffer once they have been triggered by the level-1 trigger system. The advantage of using the buffer strategy is that the further processing capability no longer has to be adjusted to fit in the smallest possible time period between triggers (i.e. the next bunch crossing). It is mandatory that the processing time, T_p has to satisfy the constraints on average, $\langle \nu \rangle \leq 1/\langle T_p \rangle$. Otherwise the buffers would eventually be exhausted. As a protection feature, once the buffers get the maximum capability, the trigger system must be inhibited in order to avoid overwriting of events [1].

1.1.3.0 Dead Time

An important concept in the design of the trigger system is the dead time. Dead Time is generally defined as the fraction of total time where valid interactions could not be recorded for different reasons. The most common reason coming from electronics components they have a finite reaction time, for example due to the discharge of capacitors or the reestablishment of the initial conditions after processing an event. While the trigger electronics are designed for processing with the maximum possible rate, the readout electronics of the detector channels may have been laid out for a considerably lower rate, since only the events accepted at the first level of trigger must be read out. High trigger rates may hence saturate the readout

capacity of the detector, so, commonly the electronics associated to detectors have a feedback signal (i.e. a busy signal) to indicate to the trigger system that it must stop the transmission of the trigger signals.

The dead time fraction f_D , is defined as the fraction of the time of active bunch crossing for which the trigger system is inhibited over the total run time. It is a very important component in the measurement of the cross section:

$$\sigma = \frac{\nu}{(1 - f_D)/\mathcal{L}}. \quad (1.1)$$

In comparison with non buffered system, dead time arises whenever the next event $n + 1$ follows the event n at a time $t_{n+1} < t_n + T_p$, where a constant processing time, T_p , has to be assumed for simplicity; while in multi-buffer systems the variations are drastically levelled out and the dead time is reduced considerably. With n buffers available in the system, the dead time fraction from this step can be computed from the sum of the individual Poisson distribution,

$$f_D = 1 - \sum_{k=0}^n \frac{\mu^k}{k!} e^{-\mu}, \quad (1.2)$$

with $\mu = \nu T_p$. An example of expected behaviour of f_D as a function of μ is shown in figure 1.3 for $n = 1, 3$ and 5 buffers. It is clear that with more buffers available higher input rates can be supported: for example a dead time of 50% is reached at 1.7 kHz for one buffer and 3.7 kHz, and 5.7 kHz, for 3 and 5 buffers, respectively for an assumed processing time T_p , of 1 ms.

Since dead time is very important to all measurements of cross sections, it is worthwhile to mention a subtlety arising in collider experiments; the dead time may become a function of the bunch number in the fill pattern of the collider. In principle the above concept of dead-time can be extended easily, it is advisable from the point of view of physics analyses to retain the simplicity of an overall dead time. It is necessary to keep in mind that the capability of measuring a *bunch specific dead time* has to be designed into the trigger hardware components. For example, a good trigger scheme must be designed in such a way that dead time is minimized and the number of good events processed per time unit is increased.

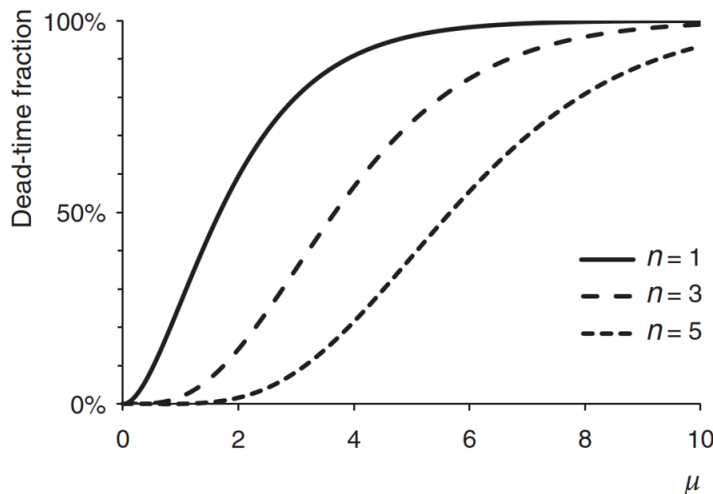


Figure 1.3: Dead time fraction, f_D as a function of the input rate, $\mu = \nu T_P$, for 1, 3 and 5 buffers in the input chain. T_P is the processing time and ν the input rate for a given cross section.

1.1.3.0 Trigger Interaction Rates

Trigger conditions designed for different physics goals must be optimized such that the total recording rate of the experiment does not exceed its electronic capabilities (e.g maximum bandwidth). For a multi-purpose detector the overall rate must be shared amongst the trigger types, which are related to the different physics goals of the experiment. Since the latter and the conditions of data-taking (e.g instantaneous luminosity, background rates) change over time, multi-purpose trigger systems require flexible modifications of the trigger setup to control the rate of accepted events. Values of threshold parameters may be changed (e.g the E_T threshold for electromagnetic objects could be increased in order to reduce the rate of the corresponding trigger condition) or even the logic combinations in the central trigger may be modified. Evidently the trigger logic must make provision for such flexibility, which can be realized by the programmable logic mentioned previously.

An important parameter in a trigger system in HEP is the bandwidth. The bandwidth

limits at the different trigger levels may prevent the recording of all events fulfilling high rate trigger conditions. Such conditions are nevertheless useful since they may, for example, serve as a trigger monitor for the evaluation of the trigger efficiency or allow physics studies in special regions of the phase space (e.g measurements at low p_T). An artificial, but well defined, prescaling of such high rates triggers helps to constrain the rate. The corresponding downscale factor d , is included in the trigger conditions, such that on average only every d th selected event is recorded. The corresponding downscale procedures can be implemented via simple counters leading to deterministic downscaling, or via a more sophisticated random selection mechanism. The use of the downscale mechanism is hence an important step in setting up the trigger mix for a multi-purpose experiment. The experimental simplicity of a trigger condition with lowest possible physics bias has to be contrasted with the statistical losses introduced by a high downscale factor. The optimal mixture is often not a priori known.

1.1.4 Trigger System and HEP Data Analysis

The action of the trigger selection has implications for the physics analysis, The shortcuts and approximations introduced during hardware selection in the first trigger levels affect the boundaries of the phase space. Offline, these inefficiencies must be corrected for to obtain a fair representation of the original event distributions. In addition, the correction for the well-quantified event losses in the trigger selection has to be evaluated and applied.

The correction for the trigger implications in an analysis comprises three steps:

- The choice of trigger conditions from the complete trigger mix that promises high efficiency for the physics process under study.
- The evaluation of a trigger efficiency preferentially from the data itself to safeguard from possible inadequate descriptions in the Monte Carlo simulation.
- The application of a correction for inefficiencies together with the effects of the trigger selection (e.g downscale procedure).

The efficiency of a trigger condition is defined as the ratio of the events accepted by the trigger condition to the number of events that would be included in the offline analysis without applying the condition to an unbiased event sample (cf.1.3). Inevitably this definition depends on the phase space defined in the analysis offline.

The trigger efficiency correction using data itself necessitates the availability of an independent data sample collected with a reference trigger condition (e.g. minimum bias condition) to the studied trigger[2]. Since the efficiency typically varies as a function of some kinematic variable, q , the efficiency has to be determined differentially:

$$\epsilon(q) = \frac{\text{number of events selected by trigger conditions}}{\text{number of events selected by reference trigger condition}}, \quad (1.3)$$

where only events fulfilling the offline selection are used. The effect a trigger threshold can have on a quantity measured can be seen in the “turn-on curve” of the corresponding trigger efficiency of Figure 1.4. The event variable, q , may correspond to, for example, the E_T of the electron. The quality of the trigger selection, that is, the resolution, σ_q , is reflected in the steepness of the turn-on curve. The curve also displays the events lost above $q = 1$ and the additional events that enter the sample due to resolution effects for $q < 1$.

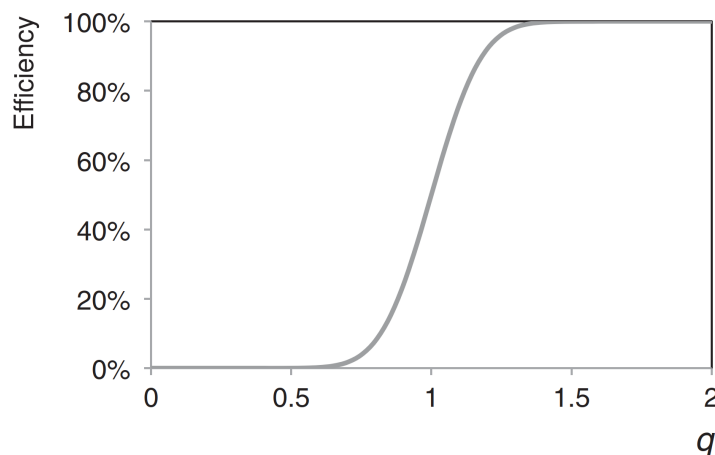


Figure 1.4: Trigger Efficiency turn-on curve applying a threshold criterion on a single event quantity as a function of the corresponding value, q , determined offline (assumed threshold $q = 1$, trigger selection $\sigma_q = 0.2$).

Frequently the event sample used in the analysis is composed of events with a variety of trigger conditions. Hence the efficiency correction cannot be applied as a simple factor in the cross section calculation. Instead, each event has to be considered individually with its corresponding weight. The weight for event j depends on the trigger condition i in run k and can be computed as

$$w_j = \frac{d_{ik}}{\epsilon_{ik}(q_j)}, \quad (1.4)$$

d_{ik} is the downscale factor for trigger i in run k and $\epsilon_{ik}(q_j)$ is the efficiency of this trigger in this run as a function of a set of event parameters, q_j . If the downscale factor, d , and the efficiency, ϵ , do not vary over the phase space of the physics analysis, the weights of the events $j = 1 \dots, N$ passing the offline selection criteria, including the trigger requirement, are computed as $w_j = \frac{d}{\epsilon}$, and the original number of events can be calculated as $N_{orig} = \sum w_j = N \times (\frac{d}{\epsilon})$. Large variations in the downscale factors from run to run may lead to results that are statistically not very significant, since large factors dominate the results in 1.4. Under these circumstances it is advantageous to resort to a luminosity normalized weight calculated over all runs. This average weight is calculated from the number of selected events, N , and the original events, N_{orig} :

$$w_j = \frac{N_{orig}}{N} = \frac{N_{orig}/\sigma}{N/\sigma} = \frac{\sum_{k=1}^{N_{runs}} L_k}{\sum_{k=1}^{N_{runs}} L_k \frac{\epsilon_{ik}(q_j)}{d_{ik}}}, \quad (1.5)$$

with N_{runs} and L_k representing the total number of runs and the dead-time corrected integrated luminosity of runs k , respectively. As expected for a given number of original events, that is, for given a integrated luminosity, the averaged weight for a trigger depends only on the total number of events collected via this trigger, N . An optimization of the downscale factors during data-taking increases the statistics of the sample, reduces the weights and increases the statistical significance as desired [1].

1.2 Trigger Systems at LHC Experiments

As explained in previous sections, an intrinsic problem with hadron colliders experiments is that physicists are confronted with high background rates while the important events

1. Trigger Systems in High Energy Physics

1.2 Trigger Systems at LHC Experiments

with interesting information, for example for exploring possible New Physics or for precision measurements of Standard Model physics, make up only a tiny fraction of the data rate. For example, the rates for the production of vector bosons or the Higgs boson are about ten orders of magnitude lower than the total proton-proton interaction rate, as shown in Fig 1.5 [4].

In order to reduce rates to manageable levels several techniques could be applied, because simply cutting on the transverse momentum of secondary particles one would have to use very high thresholds, resulting in significant loss of physics data. Therefore, a complex online event selection is absolutely necessary at high-energy hadron colliders.

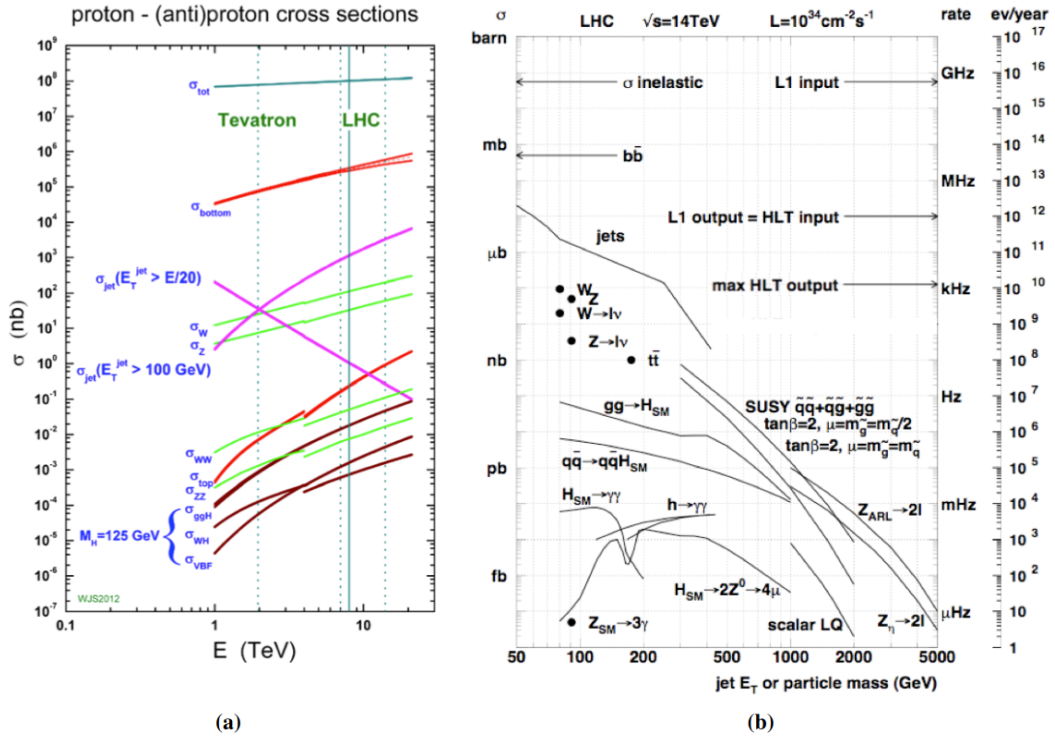


Figure 1.5: (a) Total interaction cross sections and cross sections of some of the physics processes that are being studied at the LHC plotted versus collision energy. Up to 4 TeV collision energy, cross sections are given for proton-antiproton collisions while for higher energies they are given for proton-proton collisions. (b) Cross sections of various interactions plotted against the transverse momentum of jets produced in these interactions or against the mass of particles created in them.

The four major experiments at the LHC have different challenges to solve in the context of the trigger systems (see figure 1.6), all of them are equipped with a complex hardware trigger system. ATLAS¹ and CMS², which are investigating particle physics at the energy frontier, both require high trigger rates and use large event sizes. LHCb³, which uses a single-armed forward detector, does not have to handle such a big event size but needs to accept even higher data rates in order to reach the statistics to achieve their physics goals. ALICE⁴, has as its main goal the study of the quark-gluon plasma in lead-lead and has interactions, has a low trigger rate because the luminosity is much lower when the LHC is operating in heavy-ion mode than when it is producing proton collisions. However, due to the high particle multiplicities in heavy-ion collisions the event size in ALICE is much bigger than in the other LHC experiments.

In the ALICE experiment the idea of using trigger systems is to read out only a part of the detector possible, at reduced granularity, at the full bunch-crossing rate of the LHC. These data provide a preselection of physics events. Only for these “triggered” events are the full detector data read out and forwarded to DAQ system.

1.2.1 Trigger Systems of the ATLAS and CMS experiments

The physics triggers in ATLAS and CMS will have to retain as many as possible of the events of interest for the diverse physics program of these experiments, including:

- Higgs searches (Standard Model and beyond), e.g $H \rightarrow ZZ \rightarrow \text{leptons } (e\mu), \rightarrow \gamma\gamma$, and $H \rightarrow t\bar{t}$, $H \rightarrow b\bar{b}$.
- SUSY searches, e.g producing jets and missing transverse energy (missing E_T).
- Searches for other new physics using inclusive triggers that it is hoped will be sensitive to unpredicted new physics.

¹A Toroidal LHC Apparatus

²Compact Muon Solenoid

³LHC beauty

⁴A Large Ion Collider Experiment

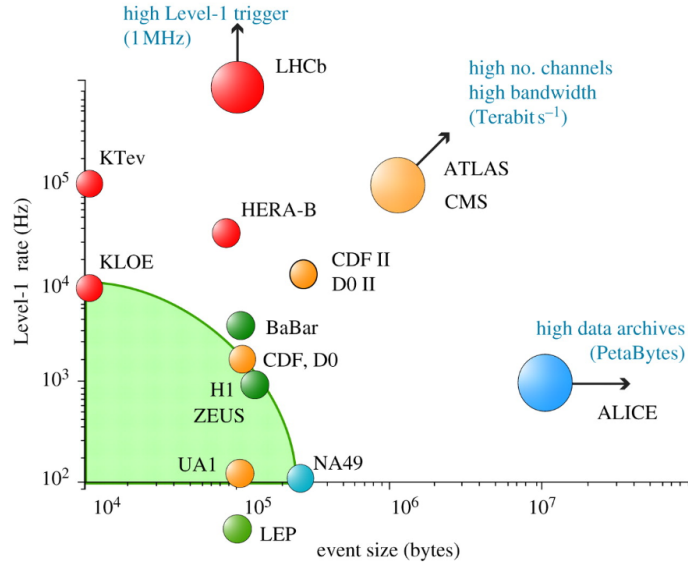


Figure 1.6: Trigger rates and event sizes of various High Energy Physics experiments.

- Studies of Standard Model process that are of interest in their own right, and must be understood as backgrounds to new physics, e.g. W and Z boson, top and beauty quark production.

ATLAS and CMS have a similar structure of the trigger system, but ATLAS has 3 trigger levels and CMS just 2. The Level-1 trigger systems of both experiments (see figure 1.7), have been based on their calorimeters and muon systems while the inner trackers are read out only in case of a positive Level-1 trigger decision. In both experiments, the Level-1 trigger latency is a few microseconds ($2.5 \mu s$ for ATLAS and $4 \mu s$ for CMS). The Level-1 trigger rates were required to stay below 70 – 100 kHz so as not to overload the detector readout, ATLAS and CMS have been using High-Level trigger systems implemented in computer farms to carry out a subsequent selection of data and reduce the data rate to permanent storage to below 1 kHz.

Specifically, the Level-1 trigger thresholds for ATLAS and CMS at LHC design luminosity are:

- Single muon $p_T > 20$ GeV (rate ~ 10 kHz) or a pair of muons each with $p_T > 6$ GeV

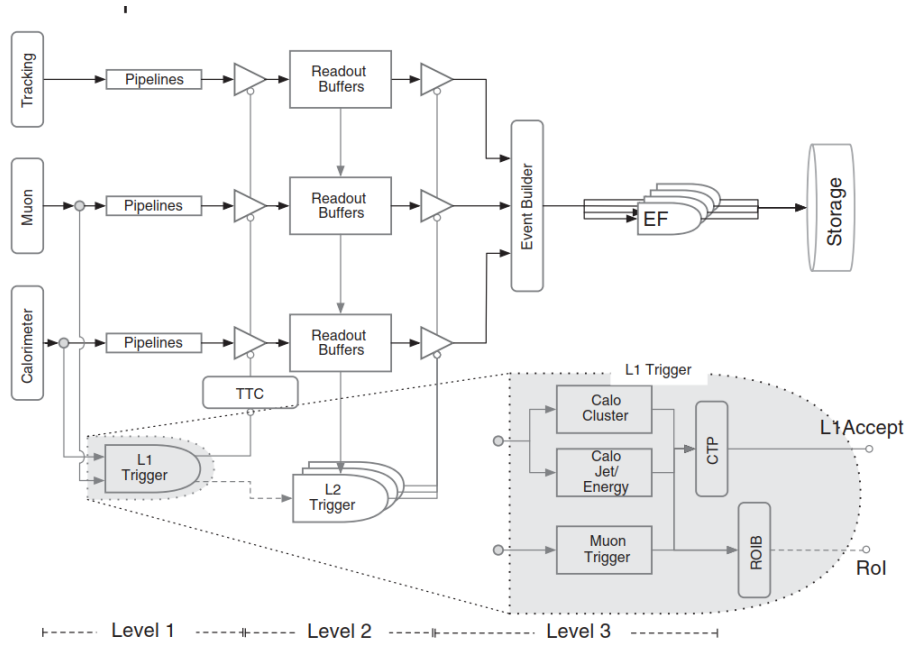


Figure 1.7: Schematic view of the three-level ATLAS trigger system.

(rate ~ 1 kHz).

- Single $e/\gamma p_T > 30$ GeV (rate ~ 20 kHz) or a pair of e/γ each with $p_T > 20$ GeV (rate ~ 5 kHz).
- Single jet $p_T > 300$ GeV (rate ~ 200 Hz), or compound triggers such as “jet $p_T > 100$ GeV and missing $p_T > 100$ GeV” (rate ~ 500 Hz), or “four or more jets $p_T > 100$ GeV” (rate ~ 200 Hz).

One important difference between ATLAS and CMS is present in their High-Level trigger system. In CMS, the whole detector is read out when a Level-1 trigger is received so that the High-Level Trigger can access the full detector information and use it for calculating in decision. In ATLAS only “Regions of Interest” (ROI) determined by the location of the Level-1 trigger signals in the detector are read out from the detector and put at the disposal of the High-Level trigger, which can then decide to read out the full detector.

1.2.2 Trigger system of LHCb

The LHCb experiment is specialized for studying b-physics. It does not operate with very high luminosity ($\sim 2 \times 10^{32} \text{ cm}^{-2}\text{s}^{-1}$). The aim of LHCb is rather to measure the rate and branching ratios of b-decays to a very high accuracy. In order to minimize statistical errors, large data samples are required. LHCb must work with comparatively very low p_T thresholds. The level-1 trigger will search for muons, electrons/photons and hadrons with $p_T > 1 \text{ GeV}$, 2.5 GeV and 3.4 GeV respectively. The level-0 trigger operates with an output of up to $\sim 1 \text{ MHz}$. To measure and trigger on the short tracks of b-mesons between the primary vertex, where they are created, and the secondary vertex, where they decay, the information of the tracker in the high-level trigger is needed. The aim is to record an event rate of only $\sim 200 \text{ Hz}$ [5].

1.2.3 Trigger system of ALICE

The ALICE experiment⁵ focuses on the observation and analysis of heavy-ion collisions. During certain times the LHC operation is devoted to colliding lead (or Xe) ions in order to allow experiments to study the quark-gluon plasma state created in such collisions. ALICE also takes data in proton-proton periods for reference[4]. The heavy ion collisions are very demanding from the DAQ point of view (See figure 1.6), the total interaction rate is smaller than in the proton-proton collisions, the luminosity is $\mathcal{L} \sim 10^{27} \text{ cm}^{-2}\text{s}^{-1}$, and the trigger rate is $\sim 800 \text{ Hz}$. On the other hand, lead-lead collisions create very complex events, with tens of thousands of tracks per collision. (see figure 1.8).

In ALICE the trigger selects “minimum bias” and “central” events (rates are scaled down to achieve appropriate fraction central to minimum events in readout rate, $\sim 40 \text{ Hz}$), and events with dileptons (rate $\sim 1 \text{ kHz}$ with only part of the detector read out). However, the event size is huge (up to $\sim 40 \text{ MByte}$), due to the multiplicity in lead-lead collisions at LHC energy. The ALICE trigger system has four hardware levels (Level-M, Level-0, Level-1 and Level-2)

⁵The ALICE trigger system, will be described in detail in the next chapter.

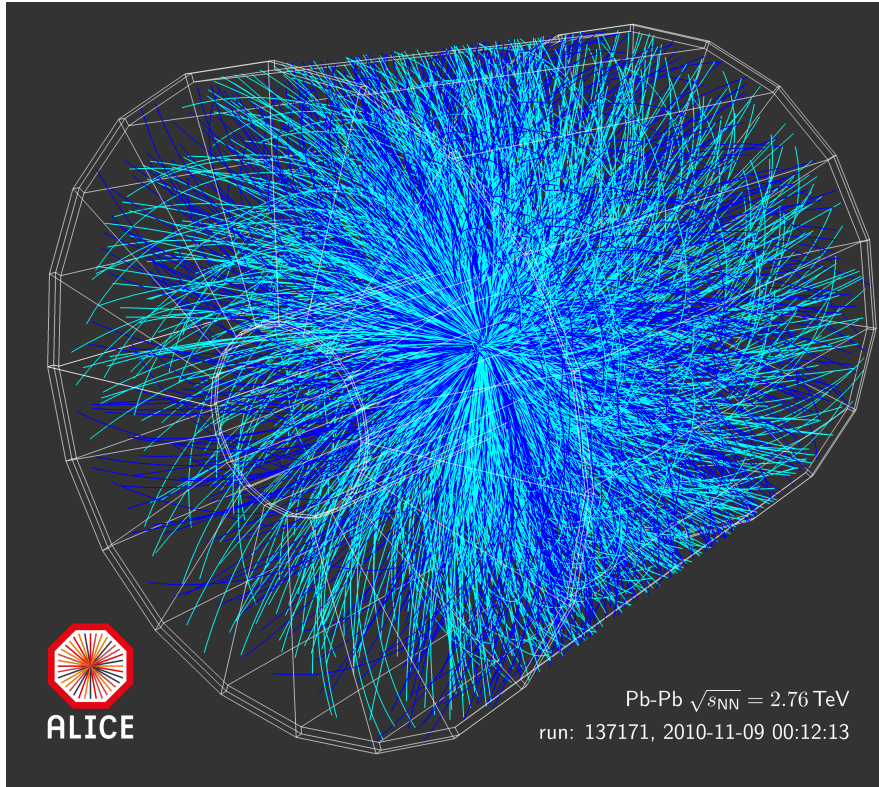


Figure 1.8: Multiplicity in one lead-lead collisions as seen in the Time Projection Chamber of the ALICE experiment.

to provide maximum flexibility for the all subsystems in ALICE. This makes it different from the other LHC experiments, which all use only one hardware trigger level.

2

ALICE EXPERIMENT

This Chapter gives an overview of the ALICE experiment, their physics goals are discussed briefly, while the design, and performance of the Central Trigger Processor during Run 1 and Run 2 is described in detail.

2.1 Introduction

ALICE[6] is a general-purpose, heavy-ion detector at the CERN LHC which focuses on QCD, the strong-interaction sector of the Standard Model. It is designed to address the physics of strongly interacting matter and the quark-gluon plasma at extreme values of energy density and temperature in nucleus-nucleus collisions with purpose of learn more about the conditions that prevailed in the early Universe. The QGP matter is formed in the laboratory by colliding heavy-ions at a speed close to that of light (at ultra-relativistic energies). In the process, it is possible to compress and heat the colliding nuclei in way that the individual protons and the neutrons superimpose with each other. Hence, a region of high energy density is created, in which a relatively large number of de-confined quarks and gluons exist for a brief time. The QGP stage then reverts to the hadronic matter through expansion and cooling. The transition from the QGP state to that of the hadronic matter can be understood in terms of the phase diagram, as shown in the Figure 2.1. ALICE use the high-temperature low baryon-density

regime to study the properties of the QCD.

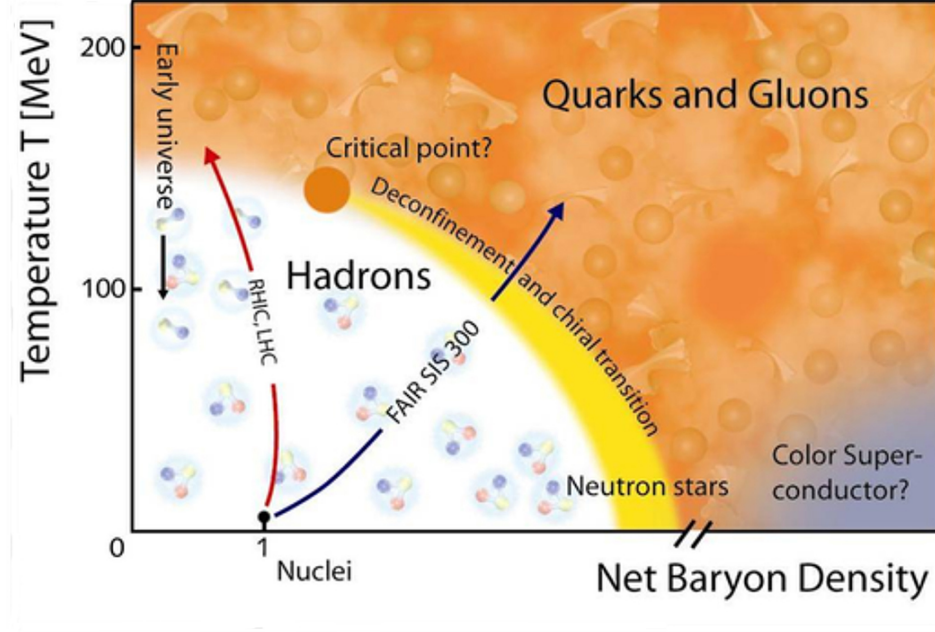


Figure 2.1: QCD Phase Diagram [7].

The physical conditions in ALICE (above mentioned) allow a comprehensive study of hadrons, electrons, muons, and photons produced in the collision of heavy nuclei (Pb-Pb), with highest multiplicities at the LHC. The physics program of ALICE experiment covers different scenarios; Pb-Pb collision, collisions with lighter ions (e.g. Xe), lower energy running and dedicated proton-nucleus runs. ALICE takes data with proton beams at the top LHC energy to collect reference data for the heavy-ion program and to address several QCD topics for which ALICE is complementary to the other LHC detectors [6].

Overall the ALICE dimensions are $16 \times 16 \times 26 m^3$ with total weight of approximately 10,000 t. ALICE is composed of 19 different detector systems each with its own specific technology choice and design constraints, driven both by the physics requirements. ALICE consist of a central barrel part, which measures hadrons, electrons, and photons, and forward muon spectrometer (see figure 2.2). The central part covers polar angles from 45° to 135° . From inside out, the barrel contains an Inner Tracking System (ITS), of six planes of high-resolution silicon pixel (SPD), drift (SDD), and strip (SSD) detectors, a cylindrical Time

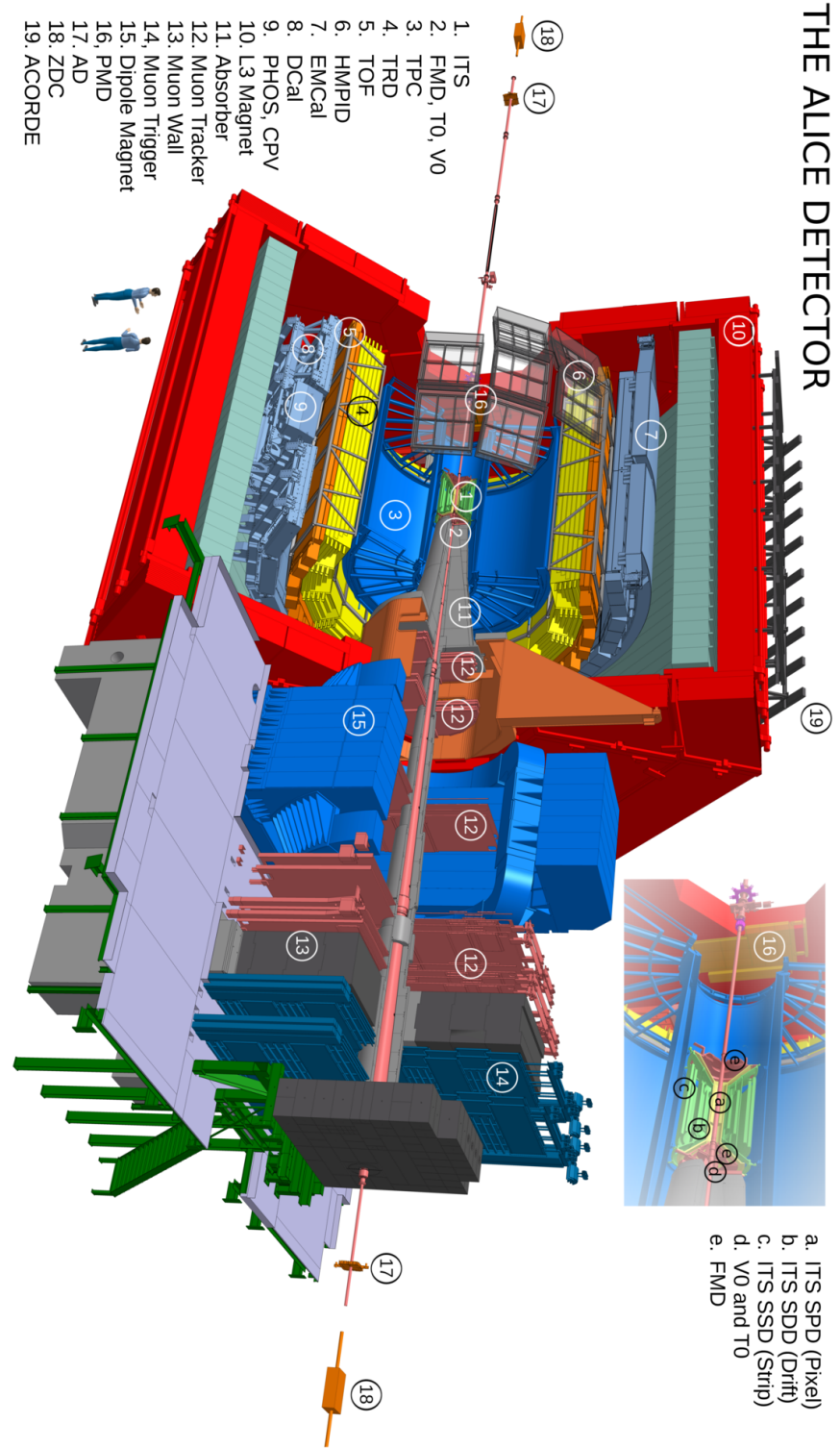


Figure 2.2: ALICE Experiment schematic layout [8].

Projection Chamber (TPC); the TPC has a 90 m^3 drift volume filled with $Ne - CO_2$ and is divided into two parts by the central cathode, which is kept at -1000 kV , and the end plates are equipped with multiwire proportional chambers (MWPC). Together, TPC and ITS provide charged-particle identification via measurements of the specific ionization energy loss dE/dx . In addition ALICE has three particle identification arrays, Time of Flight (TOF), which is based on Multigap Resistive Plate Chamber (MRPC) technology; Ring Imaging Cherenkov (HMPID) which has a liquid C_6F_{14} radiator and CsI; and Transition Radiation (TRD) which consists of six layers of $Xe - CO_2$ filled MWPCs, with a fiber/foam radiator in front of each chamber; two electromagnetic calorimeters (PHOS and EMCal). The forward muon arm ($2^\circ - 9^\circ$) consists of a complex arrangement of absorbers, a large dipole magnet, and fourteen planes of tracking and triggering chambers. In addition several detectors (ZDC, PMD, FMD, T0, V0, AD) for global event characterization and triggering are located at small angles[6]. For studies of cosmic rays, an array of 120 scintillators (ACORDE) on top of the magnet is used. The table 2.1 show different properties of ALICE detectors.

ALICE has an excellent particle identification capability¹ for both hadrons and leptons over a wide acceptance and an extended p_T domain. As a difference from the other LHC experiments, the sensitivity to low p_T particles is relevant for many of topics of physics in ALICE.

2.2 ALICE physics

ALICE is concentrated on physics at or close to mid-rapidity, i.e the region of lowest baryon density and maximum energy density. The acceptance cover a wide range of particle decays even at low momentum, jet fragmentation, and study some variables on an event by event basis, requiring typically several thousand reconstructed particles per event. Therefore the instrumented part is concentrated over 2 units in rapidity around mid-rapidity for the barrel detectors and covers 1.5 units in rapidity at small angles for the muon measurement. The interaction rate with ion beams at LHC is low (10 KHz for Pb-Pb) and the radiation dose is moderate ($< 3000\text{ Gy}$), allowing the use of slow but high-granularity detectors like a TPC

¹Approximately up to $20\text{ GeV}/c$

Table 2.1: Summary of the ALICE detector subsystems. The acceptance in η is calculated from the nominal interaction point and is 360° in azimuth, unless noted otherwise. The detectors marked with an asterisk (*) are used for triggering. Channels is the total number of independent electronic readout channels.

Detector	Acceptance (η, ϕ)	Technology	Main purpose	Channels
SPD *	$\pm 2, \pm 1.4$	Si pixel	tracking, vertex	9.8 M
SDD	$\pm 0.9, \pm 0.9$	Si drift	tracking, PID	133,000
SSD	$\pm 0.97, \pm 0.97$	Si strip	tracking, PID	2.6 M
TPC	± 0.9	Ne drifg+MWPC	tracking, PID	557,568
TRD *	± 0.84	TR+Xe drift + MWPC	tracking, $e^\pm$ id	1.2 M
TOF *	± 0.9	MRPC	PID	157,248
HMPID	$\pm 0.6, 1.2^\circ < \phi < 58.8^\circ$	C_6F_{14} RICH+MWPC	PID	161,280
PHOS*	$\pm 0.12, 220^\circ < \phi < 320^\circ$	$PbWO_4$	photons	17,929
EMCal*	$\pm 0.7, 80^\circ < \phi < 187^\circ$	Pb+scint	photons and jets	12,672
ACORDE*	$\pm 1.3, -60^\circ < \phi < 60^\circ$	scint	cosmics	120
PMD	$\pm 2.3 < \eta < 3.9$	Pb+PC	photons	2.2 M
FMD	$3.6 < \eta < 5.0$	Si strip	charged particles	51,200
	$1.7 < \eta < 3.68$	Si strip	charged particles	
	$-3.4 < \eta < -1.7$	Si strip	charged particles	
V0*	$2.8 < \eta < 5.1$	scint	charged particles	32
	$-1.7 < \eta < -3.7$	scint	charged particles	32
T0*	$4.6 < \eta < 4.92$	quartz	time, vertex	12
	$-3.28 < \eta < -2.97$	quartz	time, vertex	12
ZDC*	$ \eta > 8.8$	W+quartz	forward neutrons	10
	$6.5 < \eta < 7.5 \phi < 10^\circ$	brass+quartz	forward protons	10
	$4.8 < \eta < 5.7 2\phi < 32^\circ$	Pb+quartz	photons	2
MCH	$-4.0 < \eta < -2.5$	MWPC	muon tracking	21 000
MTR	$-4.0 < \eta < -2.5$	RPC	muon trigger	1.08M

and SDD. Rare signals are enriched with selective triggers operating at several levels wherever possible (jets, high p_t electrons, muons, photons). With the integrated Pb-Pb luminosity of (0.5 nb^{-1}) per year, the kinematics reach for example for jets within the acceptance of the EMCAL will exceed 200 GeV and the muon arm will collect thousands of Υ decays. A number of rare signals like heavy flavour decays are however very hard to select at the trigger level in heavy ion collisions: these require then a large sample of minimum bias or central collision and a high bandwidth Data Acquisition system to collect of the order a few 10^7 events [9].

As previously explained, ALICE is the only experiment at LHC dedicated to study the physics of strongly interacting matter and the QGP. During part of the year ($\sim 10^6$ s) the LHC is dedicated to heavy ion physics, with different type of collisions, for example Pb-Pb or pPb.

The ALICE physics goals can be summarized [9] [10] [11], as follows:

- **Global event features.** Multiplicities, very forward energy flow (0 degree) and rapidity distributions allow to determine the centrality, the number of participants in the interaction and to specify the initial energy density,
- **Geometry and space-time evolution of the emitting source.** The space-time structure of the collision fireball is studied with two particles momentum correlations.
- **Degrees of freedom** as a function of temperature. Quantities related to the dynamical evolution of the hadronic phase like p_T spectra and particle ratios of identified hadrons (π , η , ω , ϕ , p , K , Λ , Ξ , Ω) and direct photons are measured.
- **Nonstatistical fluctuations and critical behaviour.** This topic is addressed by event-by-event analyses, including some spectra and particle ratios. Distortions of $N_\gamma - N_{charged}$ correlations will be suitable for the detection of disoriented chiral condensates (DCC).
- **Chiral symmetry restoration.** It is searched through the study of resonance decays.
- **Collective effects** Elliptic and directed flow are investigated by various subdetectors.

- **Hard Probes.** Open charm and beauty, high p_T spectra, jets and jet queching are measured and studied. Spectroscopy of the J/Ψ and Υ families gives us a tool particularly sensitive to deconfinement.

2.3 ALICE Central Trigger Processor (Run 1 and Run 2)

The ALICE Central Trigger Processor (CTP) [12], [13], was designed to select events having a variety of different features at rates which can be scaled down to suit physics requirements and the restrictions imposed by the bandwidth of the data acquisition. The challenge for the ALICE trigger system is to make optimum use of the component detectors, which are busy for widely different periods following a valid trigger, and to perform trigger selections optimized for several different running scenarios: ions (Pb-Pb and lighter species (e.g. Xe)), pA, and pp, varying by almost two orders of magnitude in counting rate. The context diagram of the ALICE CTP is shown in figure 2.3.

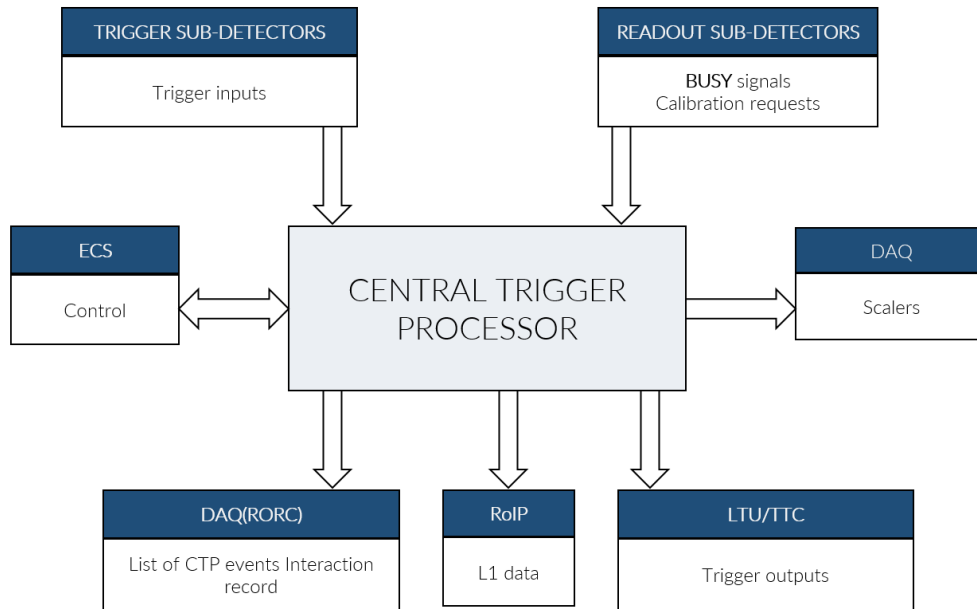


Figure 2.3: Context diagram of the ALICE Central Trigger Processor for Run 1 and Run 2.

The common feature of all detectors of ALICE was the ability to operate in very high multiplicity environment, but the low luminosity meant that the readout of the detectors could be low. For this reason, the read out strategy in ALICE was to avoid the use of the pipeline scheme. There were in addition with other special features of ALICE detectors that led to a different trigger architecture in comparison with the other LHC experiments.

- i The event measurements at mid-rapidity are governed by requirements of the Time Projection Chamber (TPC), which is by its nature a slow detector, with a read out time of around $100\mu\text{s}$. This fits well with the anticipated 8 kHz interaction rate for Pb-P interactions, but means that the TPC would encounter pile-up. As event pile-up in the case of high multiplicity Pb-Pb events was thought to be unmanageable, and would lead to unacceptably low reconstruction efficiency, some form of pile-up protection was deemed to be necessary.
- ii The rapidity coverage for the forward detectors is effectively separated from that of the central detectors, so the two parts of the detector can be usefully used entirely independently. This leads to a requirement for dynamic partitioning of the detector, allowing different parts of the detector to be read out in consecutive events. Because ALICE detectors generate dead time, the requirement for dynamic partitioning implies developing a novel method of dead time management.

In ALICE, the trigger inputs are divided into three different levels. L0, L1 and L2 in Run 1 and four in Run 2 (an additional LM level), which have different associated latencies. The reason for this separation comes from the nature of the trigger inputs, and the requirements of the ALICE detectors. The trigger logic handle trigger, providing windows for sending trigger signals to the detectors at four levels (three levels during Run 1) after the interaction has taken place in the detector.

- **Level minus one (LM).** In order to reduce power consumption, the TRD-FEE remains in a sleep mode when idle and requires a wake up signal before the reception of a level 0 trigger to start the processing. This level is used to provide the wake-up signal to TRD-FEE, and at this level only the T0 and V0 contribution is needed.

- **Level 0 (L0).** As the majority of ALICE detectors do not have pipelined readout, it is necessary to provide a trigger signal early to act as a strobe for the readout electronics. The L0 logic receives trigger input with latencies (at the CTP inputs) of up to 850 ns. The CTP logic has a latency of 115 ns, giving enough time to transmit the trigger signals back to the detectors within the L0 latency target of 1.2 μ s. The L0 trigger is sent as an LVDS signal, or optionally via channel A of the Trigger and Timing Control (TTC) system.[13]
- **Level 1 (L1)** A second stage in the development of the trigger occurs at 6.5 μ s. This is determined by the requirement of the Transition Radiation Detector (TRD). Because the TRD logic depends on a drift time of around 2 μ s, with additional large scale data handling at trigger level, the TRD trigger signals take a longer time to emerge than those for other detectors, with the final decisions not available till 6.2 μ s. after the interaction that produces the tracks.

As transmission of the trigger signals for L1 is by definition not time critical, in this case transmission uses the CERN Timing Trigger Control system (TTC), where single mode optical fibre, allowing transmission at 5.5 ns m^{-1} is used. The TTC system is also used for distribution of the LHC clock to the ALICE detectors, except in the case of the TOF detector, which has very stringent timing requirements and therefore uses a second, undisturbed, TTC system for clock distribution.

- **Level 2 L2** The longest detector sensitive period in ALICE is that of the TPC, which ends when the particles that have travelled the furthest distance arrive at the TPC readout cathode pads. This time depends on the parameters of the TPC gas mixture, but is currently around 96 μ s. The final level of the trigger, L2, waits for the drift time to have elapsed following a triggered interaction, in order to check for subsequent interactions, as part of the past-future protection mechanism, described in the next section.

When the central trigger system was being designed, it was planned that this period,

of order $100\ \mu\text{s}$, could be used for more elaborate trigger algorithms, since it was in any case required for past future protection. In practice, the algorithms that this might have facilitated were eclipsed by the rapid development of *high level* triggers, which use the full information from the data readout and software calculations, and therefore can be much more precise than the rather coarse-grain calculations associated with conventional triggers. For this reason, this trigger level has turned out to be less useful than expected. It serves to provide a signal at completion of the TPC readout to begin in transfer of the data from detector based storage to the data acquisition system.

The list of the trigger capabilities of the ALICE detectors is shown in the table 2.2.

Table 2.2: Trigger capabilities of the ALICE detectors.

Detector	Function	Level
SPD	hit multiplicity based trigger and hit-toplogy based trigger	L0
TRD	electron trigger, high- p_t particle trigger, charged-jet trigger	L1
TOF	multiplicity trigger, topological (back-to-back) trigger, cosmic ray trigger	L0
PHOS	photon trigger	L0
EMCal	photon trigger, neutral-jet trigger	L0/L1
ACORDE	cosmic-ray trigger (single and multiple hits)	L0
V0	coincidence based minimum-bias interaction trigger, centrality trigger	LM/L0
T0	event-vertex selection trigger, interaction trigger	LM/L0
ZDC	minimu-bias interaction and electromagnetic-dissociation trigger in Pb-Pb	L1
MTR	single-muon trigger, dimuon trigger	L0

Owing to the slow readout speed for some ALICE detectors, it was realized that it would be more efficient to treat detector BUSYs individually, so that an event can be triggered provided none of the detectors required by physics analysis for that specific trigger is in a BUSY state; in other words, we give a “required detector” list for each new trigger. Such collections of detectors are described as a trigger cluster. ALICE allows triggers destined to run in different clusters to run independently, but concurrently, the only requirement for a cluster to receive a trigger being that all its detectors should not be BUSY when the trigger is issued.

Another important feature in ALICE trigger system is the implementation of several mechanisms for controlling trigger rates, in order to:

- i Manage the data flow.
- ii Ensure that the selected triggers are not spoiled by rate-related causes.

2.3.1 Classes and cluster

The sensitive periods for different detectors in ALICE, for example runs with a reasonable reconstruction efficiency, can be quite large, and varies a great deal between detectors. As in Pb-Pb running, the number of tracks reaches the maximum for which a good reconstruction efficiency can be maintained, steps must be taken to avoid those events where pileup between different events occurs. The provision is different for each data sample given the multiplicity and interaction rates.

Detectors are read out in groups, known as clusters. The content of each cluster is programmable and is governed by the physics for which the cluster data is used (e.g data from muon arm with rapidity ($2.4 < \eta < 4$)). For the example only the forward trigger detectors (T0, V0 and ZDC) and the pixels are required to give a classification in centrality and determination of the position of the primary vertex, for this reason a special dimuon cluster was defined comprising these detectors, and read out whenever these detectors are not busy, irrespective of the busy status of the rest of the detector.

After several studies it was found that it is sufficient to allow up to six different clusters to be defined simultaneously, both in Run 1 and Run 2.

The trigger class is a basic processing structure in the CTP logic. The number of trigger inputs and classes required for ALICE were 24 L0 inputs, 24 L1 inputs, 12 L2 inputs, and 50 classes in Run 1, while 100 classes in Run 2. Information about trigger classes is used at each level of the trigger decision. The trigger classes are independently programmable, the use of the trigger classes can be understood by considering how the L0 trigger for given class is generated, as shown in Figure 2.4 . The L0 trigger class condition is realized as a logical AND from all L0 trigger inputs, 2 scaled-down BC clocks and 2 random triggers. The two scaled-down BC inputs are 25 ns pulses, synchronous with the BC clock, with a programmable interval between the pulses in a range from 0 to ~ 25 s (a 30– bit counter).

The two random triggers inputs are patterns of 25 ns pulses, synchronous with the BC clock, which are generated by 31 bits linear feedback register. Both types can be used along with the physics input; it defines a trigger class condition, each class has an associated detector cluster. A trigger class is associated with a single cluster; the corresponding cluster BUSY is the BUSY status of all the sub-detectors included in the cluster. In addition DAQ BUSY, CTP BUSY and CTP dead time contribute to the overall BUSY state for a given cluster. They are mandatory vetoes. Test classes also are implemented in the CTP logic, whose parameters can be configured at run time via software. Its principal purpose is to allow detector calibration during physics runs, though in principle it can be used for any software trigger. The four bunch-crossing masks can be used to define which bunch crossing are to be allowed for trigger generation. The class mask disables triggers in beforehand defined BCs. The all/rare signal is used as part of the mechanism to ensure the protection of rare events. It is class dependent. For a non-rare trigger class, the signal is selected, and, if present enables the trigger class. If it is absent, it indicates insufficient buffering in the DAQ system and the class is disabled, allocating only the rare trigger classes. The generation of L1 and L2 triggers is logically similar, but much simpler: more inputs can be received, but the only additional vetos are the corresponding past-future protection circuits for the given trigger level.

2.3.2 Past and future protection

Specifically the purpose of the past future protection circuit is to monitor when an excessive number of interactions (as sensitive periods above mentioned) occur in given interval, normally taken to be twice the drift time of a relevant detector (e.g. the TPC, the SSD or TRD), since these detectors have much longer sensitive time windows than the other detectors.

This is achieved by having a moving time window starting a programmable number of bunch crossings before the interaction of interest, and finishing the same number of bunch crossing afterwards. In this window the total number of interactions that might be detected by a continuously active detector is counted. If the observed number is greater than some (programmable) threshold, the interaction deemed to be unreconstructed, and a veto flag is raised [12].

The block used in Run 1 is shown in fig 2.5. Two types of interaction can be monitored (e.g.

LO Trigger Condition

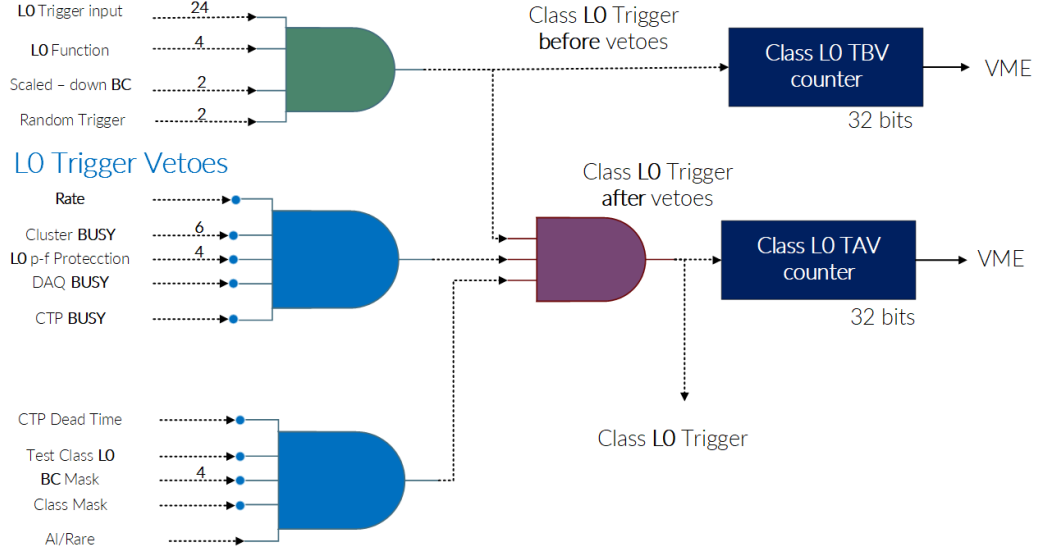


Figure 2.4: L0 trigger class.

minimum bias and semi-central interactions in ion-ion collisions), and different thresholds set for each type ($THa1$, $THa2$, $THb1$, $THb2$) in independent times windows ΔTa , ΔTb each synchronized by the clock BC. Different decisions can be prepared for the a and b blocks, and a veto set according to the AND of their two conditions. The block is quite flexible, and was envisaged to set different thresholds in the same time windows in ion-ion mode (e.g. for tolerating more low multiplicity than high multiplicity events) or different thresholds for one type of interaction in two different time windows in pp mode [12]. The trigger classes are initiated at level 0. All vetos are applied at L0, and the BUSY status is checked. If it is satisfactory, the logic passes to Level 1, then Level 2. In principle, new trigger conditions can be applied at each of these two levels, but only the past-future protection veto is revisited.

2.3.3 Trigger Data

In ALICE the parameters required to make up a trigger selection together define a trigger class. The items needed to specify a trigger class are as follows [14], [6], [12]:

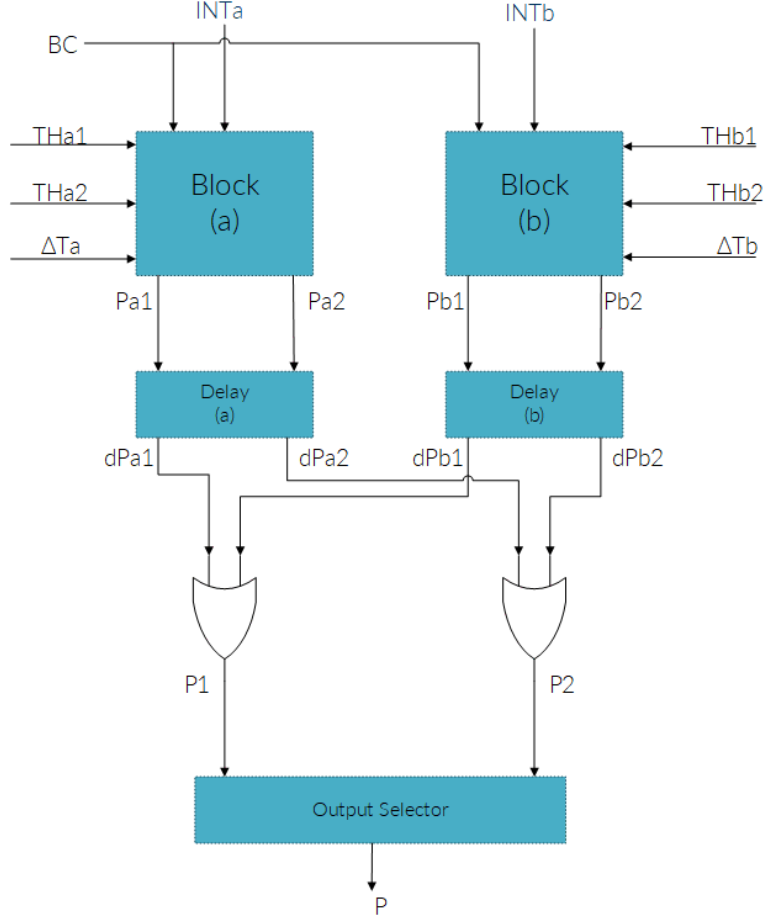


Figure 2.5: Block diagram of Past Future protection logic.

- the trigger logic condition at each trigger level,
- a specification of the trigger cluster to be associated with the trigger class,
- a specification of the downscaling factor to be applied to the trigger class,
- an indication of whether or not the trigger is to be classified as “rare” when DAQ occupancy indicates that certain trigger classes should be disabled.

Downscaling factors are defined such that they pass every n th occurrence of the class trigger, where n is a programmable number in the range from 1 to 1048575, (20 bits). Scaling factors

are applied as L0 veto. This is somewhat counter-intuitive in cases where the main selection occurs at L1, as is the case, for example, for triggers classes where the TRD provides the principal selection. (The TRD triggers are available only at L1). However, the effect of the downscaling factor is to remove a certain proportion of these potential triggers on a random basis, and therefore the scaling works, even if the L1 trigger conditions are not known at that point [14].

The CTP must be able to process triggers for all trigger clusters concurrently and distribute the trigger information to each of the detectors as quickly as possible. For this reason these data are kept to a minimum; for example, all information concerning how a trigger signal was generated must be obtained for the detector which produces it. Several types of data are recorded concerning the operation of the trigger as follow:

Event Data. Trigger data are generated at both L1 and L2, and, are sent to each detector specifying the event identifier (orbit number and bunch crossing number), trigger type (physics trigger, software trigger, calibration trigger), detector set to be read out (given a cluster list for physics data) and the list of active trigger classes. The full list of trigger data bits for L1 and L2 is given in Table 2.3. It amounts to 58 bits for L1 and 97 bits for L2, with the main contribution coming from the transmission of the 50 bits coming from the trigger class description. (In run 2 this number was increased to 100 trigger classes, making a total of 108 bits and 147 bits for L1 and L2 respectively). All of these data are transmitted serially.

Interaction record. All interactions that occur in a given orbit are recorded (giving bunch crossing number, and for Pb-Pb events, a classification into centrality categories: peripheral and semi central). The principal purpose of this record is to aid pile-up correction. Out-of-line events recorded in the TPC will have different apparent origins from triggered events owing to their different drift times. Their apparent origin can be computed using the interaction record, thus aiding their removal from the event data. The data are sent as special records in the data stream, and are collected in DAQ system. A large development between Run 1 and Run 2 was done for interaction record. In Run 2 additional Detector Data Link (DDL) was introduced which allows to transmit and record all CTP input state for every BC and calculate offline any trigger condition. (In Run 2 only two bits corresponding to two trigger

Table 2.3: Trigger L1 Data and L2 Data Serial Data.

(a) L1 Data serial Format				
	<i>Sequence List</i>		<i>L1 Message</i>	
Data	Word	bit	Word	bit
Spare	0	15	1	11
CIT	0	14	1	10
RoC[4..1]	0	13..10	1	9..6
ESR	0	9	1	5
L1SwC	0	8	1	4
	0	7..6	1	3..2
	1	15..14	1	1..0
	1	13..2	2	11..0
	1	1..0	3	11..10
L1Class[50..1]	2	15..16	3	9..0
	2	5..0	3	11..6
	3	15..10	3	5..0
	3	9..0	3	11..2
(b) L2 Data serial Format				
	<i>Sequence List</i>		<i>L1 Message</i>	
Data	Word	bit	Word	bit
L2arF				
BCID[12..1]			1	11..0
OrbitID[24..13]			2	11..0
OribitID[12..1]			3	11..0
Spare	4	14..13	4	11..10
CIT	4	12	4	9
L2SwC	4	11	4	8
L2Cluster[6..1]	4	10..5	4	7 ..2
	4	4..3	4	1..0
	4	2..0	5	11..9
	5	15..7	5	8..0
L2 Class[50..1]	5	6..0	6	11..5
or	6	15..11	6	4..0
Detector	6	10..0	7	11..1
	7	15	7	0
	7	14..3	8	11..0

conditions defined in CTP hardware were available).

Event rates and rare Events When several trigger classes are running concurrently, it becomes necessary to adjust the rates at which they are read out to reflect the physics requirements and the overall DAQ bandwidth. These factors may dictate rates quite different from the natural interaction rates. There are two main mechanisms for controlling readout rates. Downscaling factors may be applied to each trigger class, specifying, for example, that only every n th event should be read out. This mechanism allows gross adjustments to be made, but it is inflexible because the downscaling factors remain in place throughout a physics run. This means that the change in interaction rate as the luminosity decays following each fill can not be followed. For this reason, in addition to downscaling factors, a second method is used. Studies of data flow through the front end and DAQ systems show that with the current choices for number of front end buffers, saturation of front end data storage can be avoided, but without further action temporary data storage in DAQ can become saturated, with a relaxation time of the order of seconds. This phenomenon would particularly affect rare processes, as they would find the available bandwidth for data recording utilized by more common process. To avoid this problem, all trigger classes are classified into two groups:

- Rare Process.
- Common Process.

Initially all activated trigger classes can generate triggers. On a signal from the DAQ, sent when the occupied temporary storage exceeds some preset “high water mark”, the common classes are temporarily disabled, thus ensuring continued available bandwidth for rare processes. When the available temporary storage has gone below some corresponding “low water mark” the common classes are again enabled. Owing to the long relaxation time, timing is not critical, and software signals are adequate for toggling the suppression of common classes.

Scalers. A large number of scalers are recorded. In particular all inputs are counted, and for each trigger class the number of events passing each stage of the trigger (L0, L1, L2, after physics selections, if any and again after the all vetoes have been applied). These data are essential both for on-line monitoring and for subsequent off-line luminosity and cross-section

calculations. Scalers are read at regular intervals (currently every minute) and their values are broadcast to DAQ and to the offline condition database. These ratios can be monitored to check the correct operation of the trigger. At the end of a run, a file containing all values of the scalers and their sums for the run just ended is transmitted to DAQ system. The list of the scalers implemented and their length in words are shown in table 2.4.

Table 2.4: List of quantities counted using the CTP scalers.

Description	Number of words
L0, L1 and L2 inputs	50/100 bits
Interaction signals	2
Interaction test signals	1
<i>For each trigger class</i>	
L0 triggers before vetos	50
L0 triggers after vetos (scaling, past-future, etc.)	50
L1 triggers before past-future	50
L1 triggers after past-future	50
L2 triggers before past-future	50
L2 triggers after past-future	50

Snapshots. The CTP system is able to run “snapshots” in which all steps in the trigger (input and output patterns, busy, status, etc.) are recorded on a bunch-crossing by bunch-crossing basis for a period of about 30 ms in Run 1 and a few seconds in Run 2 (255 times more with respect to Run 1 system [15]), The purpose originally foreseen for this facility is to do agnostic tests of the CTP itself. Snapshots can also be used for checks of correlations between CTP inputs, since an unbiased record of all input data received during the snapshot period can be analyzed. For example, time correlations between a pulse on one input and pulses in other input channels in adjacent bunch crossing can be studied; trigger efficiencies for different inputs can also be studied.

2.3.4 CTP Electronics

There are six board types in the Central Trigger Processor, one each for the functions of BUSY collection and handling, L0 trigger generation (In Run 2 this board was replaced by LM0 board, described in the next section), L1 trigger generation, L2 trigger generation, six fanout (FO) boards to fan out the trigger signals to the different detectors and a board (called the INT board) that handles the transfer of CTP data to the data acquisition system. The layout of the boards is shown in Figure 2.6.

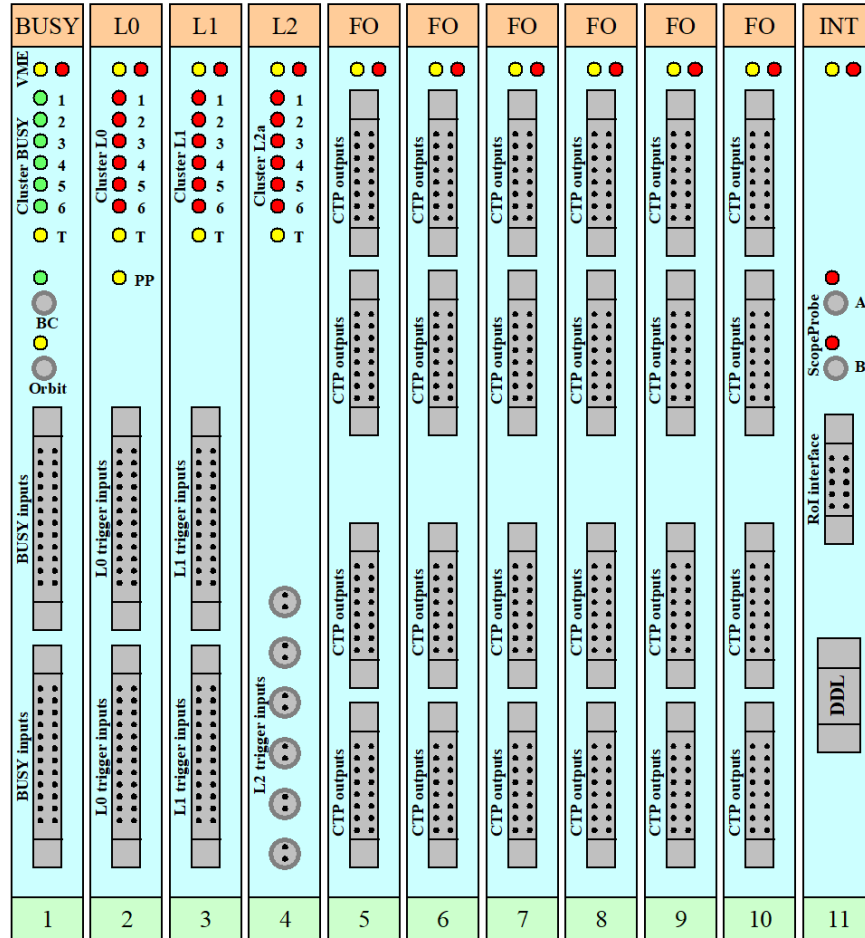


Figure 2.6: Layout of boards in the ALICE CTP during run [13].

The CTP is implemented using six different types of 6U VME board. The CTP system allows dynamic partitioning in order to make optimum use of detector readout. The system provides a flexible past-future protection. Outputs from the CTP go to the Local Trigger Units (LTUs) for each sub-detector. Each detector there has a Local Trigger Unit (LTU) that provides the interface between the CTP and the individual electronics for that detector, as shown in figure 2.8. The LTU serves as an interface between the CTP and the sub-detector front-end electronics. The LTU is also able to run in stand-alone mode of operation; the LTU fully emulates the CTP protocol, thus enabling sub-detectors to carry out development, test and calibration tasks independently of the CTP. The timing of the emulated trigger sequences is identical to the timing during the global run.

The architecture of the boards is very similar for all the boards in the family and is the best explained by the Local Trigger Unit, which served as a prototype for the other boards types. The board is shown in Fig 2.7 (a). There are two FPGAs. An ALTERA EPM2512AFC256-2, situated at the top right-hand side of the board, near the J1 VME connector, governs all VME transfers, including those to program the other FPGA. The full code is transferred to a EP1C20 flash memory, visible to the left of the upper FPGA. Next to this is the main FPGA, controlling all the trigger operations on the board which is an ALTERA CYCLONE EPIC2E324C7; it is fully programmable.

There is a 1M word RAM dedicated to record LTU signals (*snapshots* as explained in previous section), the board also has I^2C capability a Philips PC859IP, 8 bit ADC to monitor 4 voltages (+5V, +3.3V, +1.5V and -5.2V) on the board. The Temperature on the boards is also monitored via an I^2C compatible device, the thermal sensor Philips TC74, but it is read out directly via the VME processor owing to incompatibilities in having the ADC and the thermal sensor on the same I^2C branch.

LM0 board. For LHC Run 2 the CTP group designed a new board. The new board is shown in the figure 2.7 (b) and is called LM0 board. It replaces an old L0 board, and incorporates the new “minus one” trigger level (LM) logic. This uses trigger inputs arriving earlier to make a new earlier decision at 525 ns in addition to L0 one at 950 ns. The LM0 board

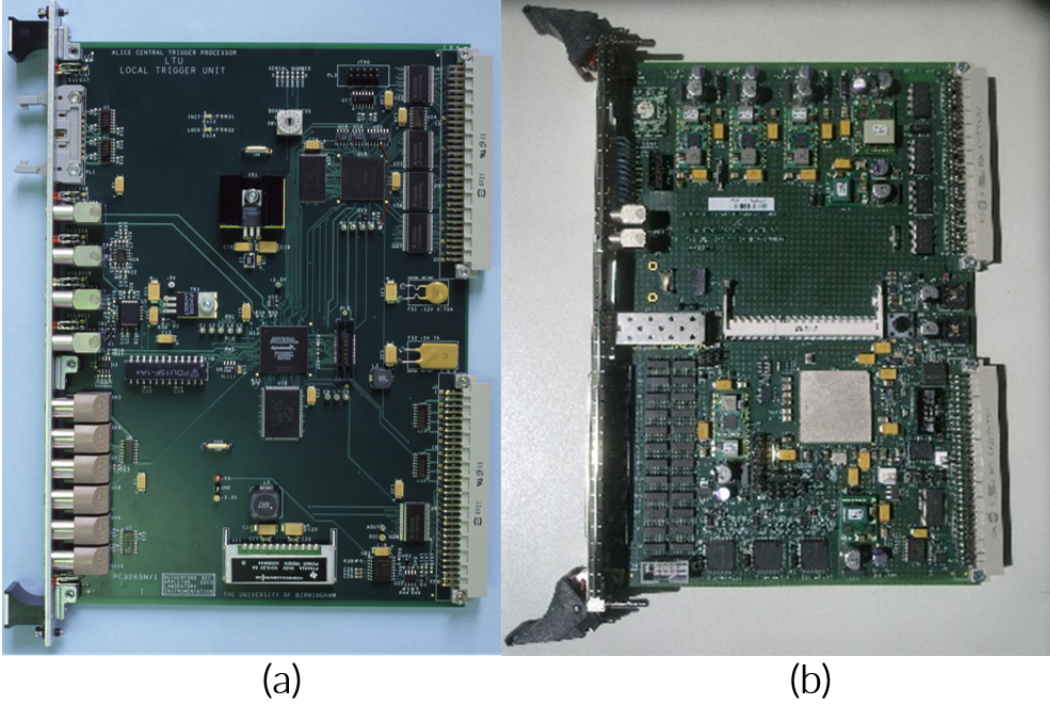


Figure 2.7: ALICE trigger system. (a) LTU board. (b) LM0 board

is based on a Xilinx kintex-7 (XC7K325T-2FFG900C) FPGA. It contains a VME interface, 2GB of DDR3 memory and several data connectivity options (SFP+ cage, Samtec FireFly connector, LEMO input and multi link LVDS connector). In the FPGA design, the required upgrade has been done together with several other improvements: the trigger input switch has been integrated into the FPGA logic, more memory and generator functionality has been allocated and the look-up table based logical blocks called L0 function now has 8 trigger inputs and additional DDL2 read out link.[15].

Data transfer between the boards is done via the J2 connector on the backplane. There is a custom-built Kapton backplane connecting the boards, allowing all and only the connections needed to transfer signals between the boards.

In Run 1, The trigger Input Switch (TIS) was designed in order to select several inputs for CTP and LTUs. As ALICE now has more trigger inputs L0 than were allowed by the original design. The TIS structure is shown in figure 2.9. The TIS consists of four Fanin/Fanout cards, originally designed for distribution of LVDS signals and merging of Low

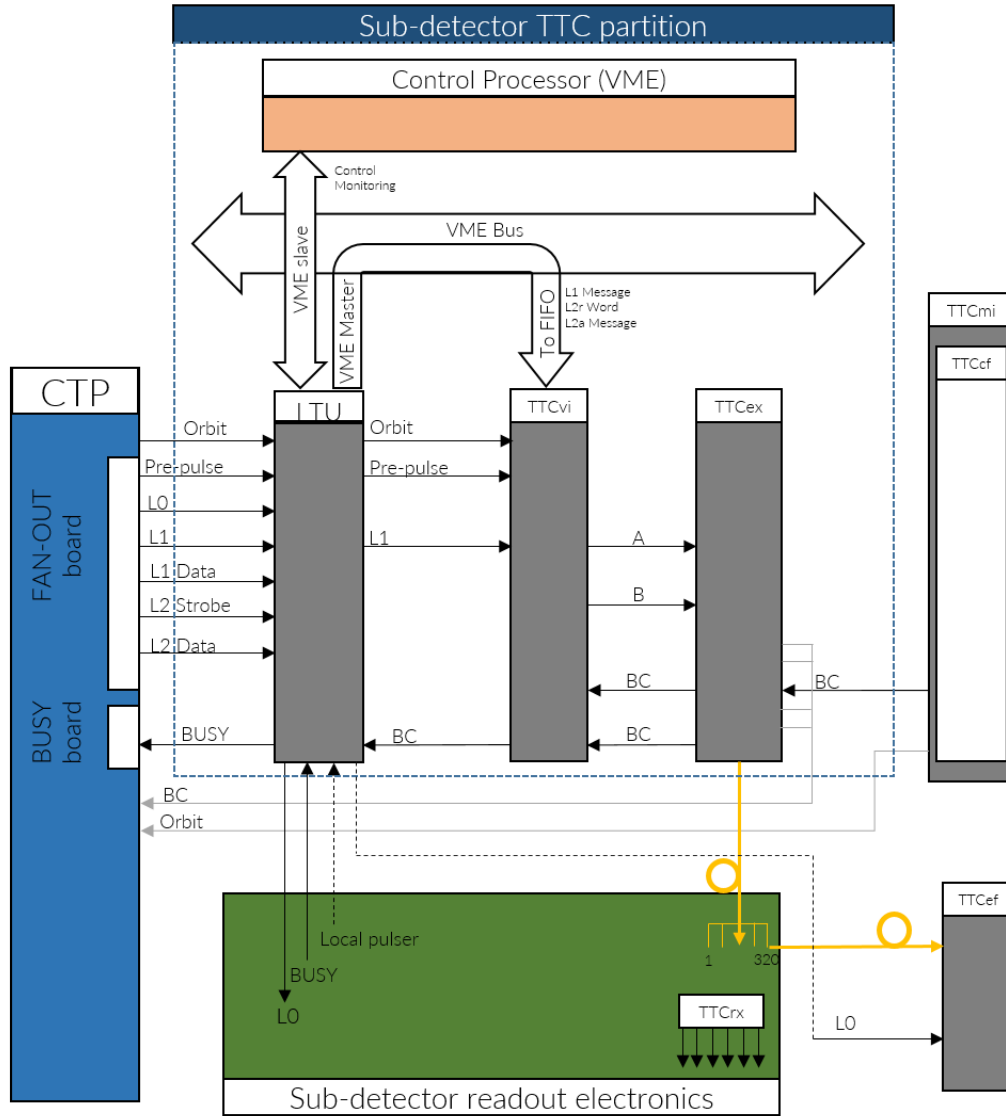


Figure 2.8: LTU block diagram and its position in ALICE Trigger System.

Voltage Differential Signal (LVDS) signals in ALICE, connected together via user defined pins on the VME backplane. The Fanin/Fanout card can be set as fan-in or fan-out by jumpers on the board. The TIS has a monitoring counter for each trigger input. These functionalities were incorporated to LM0 board in Run 2.

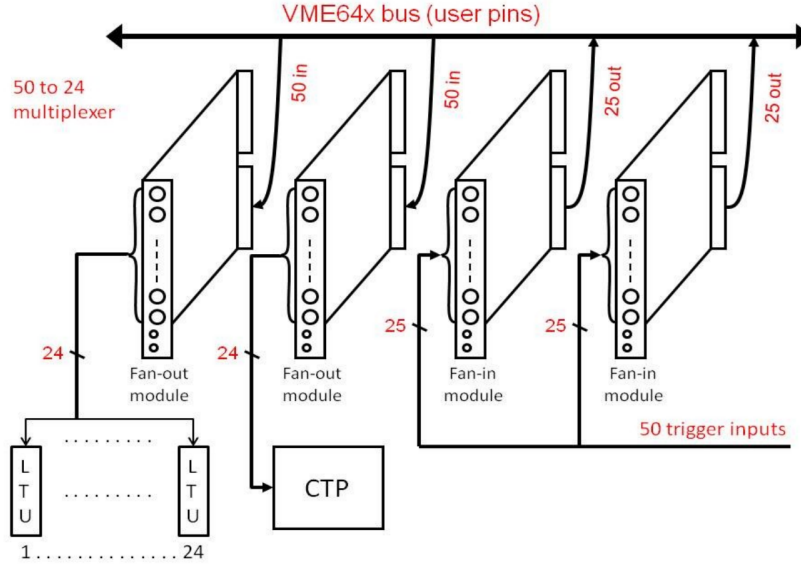


Figure 2.9: Schematic diagram of the Trigger Input Switch.

2.3.5 System Performance

The CTP system has different levels of monitoring to ensure its optimal operation [16].

- **CTP run configuration:** An online monitoring system was developed and implemented to provide immediate basic information for shifters in the control room about the current run i.e. which clock is used (LOCAL or BC1), average busy time for each detector, detector to cluster association, the slowest detector in cluster, 6 selected trigger input rates for last 20 minutes and 2 interaction record rates for last 20 minutes. A snapshot of the CTP run monitoring screen in operation is shown in figure 2.10.

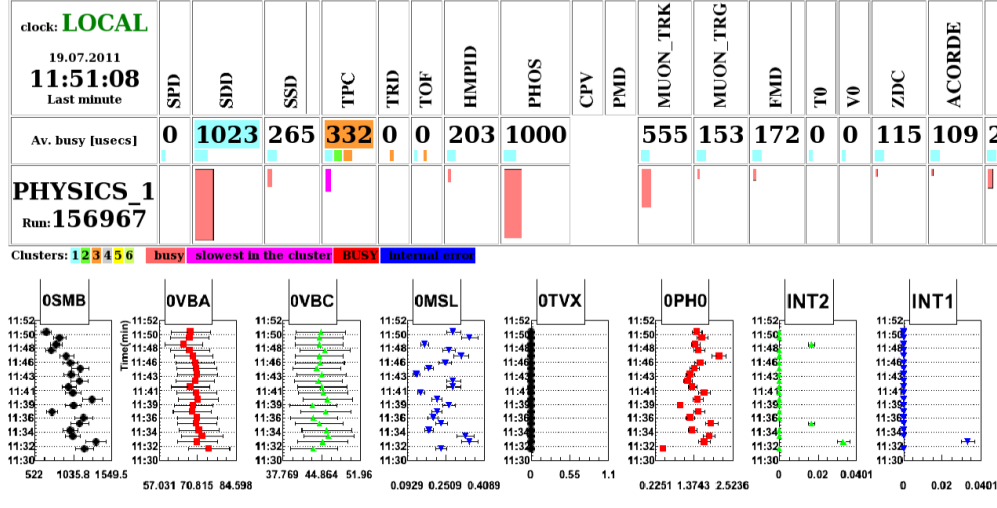


Figure 2.10: Online screen of the CTP run configuration

- **SsM data AcQquisition (SMAQ).** This tool is used for the alignment of trigger inputs. It uses the "Snapshot memory", a facility that allows the activity of selected trigger signals to be monitored of each bunch crossing inside an interval of 1 million bunch crossings, called a "sanpshot". It can also be used to check colliding bunches with respect to the LHC filling scheme, to check whether the correct BC masks have been loaded and other diagnostics of timing problems of trigger inputs.

The SMAQ tool reads several snapshots of trigger inputs from the Snapshot Memory (SSM) of CTP and analyses them. SSM filling is started by any trigger input, usually by the one with the lowest rate. The trigger for SSM filling can be chosen in the control interface for SMAQ. The SMAQ plot for a full LHC orbit with the possibility to have zoomed plots in colliding regions is shown in the figure 2.11.

- **CTP data quality monitor.** In the framework of the ALICE data quality monitor (DQM), a CTP DQM has ben developed. The DQM shifter has the possibility to check for the presence of calibration triggers, the presence of the beam pickup input, the BC schedule, frequencies in each BC, busy times for each detector, class rates, cluster rates and trigger input rates. For each window a threshold can be set to get a warning when it is exceeded.

2. ALICE experiment

2.3 ALICE Central Trigger Processor (Run 1 and Run 2)

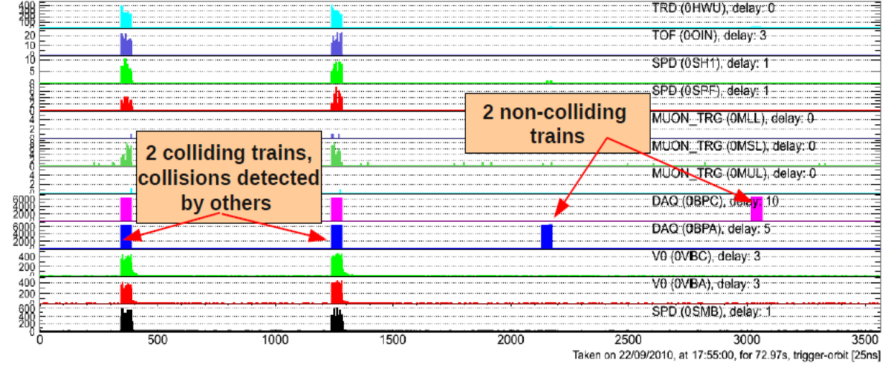


Figure 2.11: SMAQ plot for a full LHC orbit

The CTP DQM is shown in the figure 2.12.

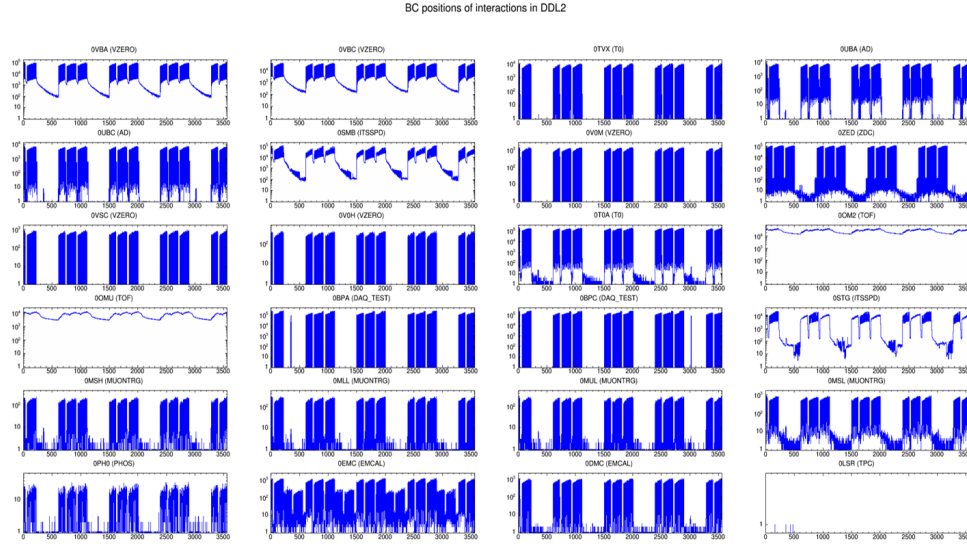


Figure 2.12: CTP Data Quality Monitor DQM

- **ALICE Trigger Configuration.** The ALICE Configuration Tool (ACT) provides sets of reference files, ensuring that the ALICE experiment, including the CTP, can be configured for standard tasks without the presence of experts. The usage of the ACT reduces dramatically the number of people on shift. After choosing a correct configuration files in ACT the following actions are performed:

- download CTP configuration files from ACT to local files.
- Configure CTP and L0 trigger switch.
- A message is sent to Experient Control System (ECS) indicating the end of CTP configuration.

The ALICE trigger system, including the trigger input switch, is installed in the experimental cavern where it is integrated with other subsystems through ECS. The ALICE trigger system has provided stable operation during all type of collisions (pp, p-Pb and Pb-Pb). A variety of monitoring and control options have been prepared.

2.4 Performance of the ALICE CTP during Run 1 and Run 2

As previously commented ALICE takes data in Pb-Pb collisions as well as in pp and p-Pb collisions, in order to provide a reference and cold nuclear matter baseline. During run 1 and run 2 ALICE had different collision scenarios, the summary of these scenarios are shown in the table 2.5.

After those years of operation (2009 - 2018) at the LHC, experience has shown that the maximum pp interaction rate at which all ALICE detectors can be safely operated depends on the CTP configuration, for example for rare trigger configuration the maximum interaction rate is around 700 kHz (including the contribution of both beam-beam and beam-gas collisions) but is, lower for minimum bias trigger due to the pileup restriction. Typical target luminosity values for the ALICE pp data taking range from $\mathcal{L} \simeq 10^{29} s^{-1} cm^{-2}$ (during minimum bias data taking) to $\mathcal{L} \simeq 10^{31} s^{-1} cm^{-2}$ (when accumulating rare triggers). The average number of interactions per bunch crossing varies from 0.005 to 0.3.

The main block of the ALICE trigger system is the Central Trigger Processor (CTP). The CTP evaluates trigger inputs from the trigger detectors every bunch crossing (25 ns). As previously described there are four different hardware trigger levels (LM, L0, L1 and L2) with latencies from 445 ns to 105 μs . During Run 1, all events with L1 were accepted by L2, while during Run 2, different running scenarios (e.g. when taking downscaled minimum bias

Table 2.5: Summary of the ALICE running conditions in 2010 – 2018. The nominal magnetic field was $B = 0.5 T$ except for Xe-Xe system and few pp data samples at $\sqrt{s} = 13$ TeV in 2015-2017

Year	Systems	$\sqrt{S_{NN}/pN}$ (TeV)	Integrated Luminosity (nb^{-1})
Run - 1			
2009 - 2010	pp	0.9	~ 0.5
2011	pp	2.76	~ 1.1
2010-2011	pp	7	~ 4800
2010-2011	Pb-Pb	2.76	~ 0.1
2012	pp	8	~ 9700
2013	p-Pb	5.02	~ 30
Run - 2			
2015	pp	5.02	~ 100
2015-2016	pp	13	~ 14000
2016	p-Pb	5.02	~ 3
2016	p-Pb	8.16	~ 20
2016	Pb-p	8.16	~ 20
2016	Pb-Pb	5.02	~ 0.4
2017	Xe-Xe (B=0.2 T)	5.44	~ 300000
2018	Pb-Pb	5.02	~ 1.1

events in parallel with rare triggers) L2 were used to reject events with multiple collisions from different bunch crossing piled-up in the TPC (past-future protection). The events with L2 are subsequently filtered in the High Level Trigger (HLT).

Information about the LHC bunch filling scheme was used by the CTP to suppress the background. The bunch crossing mask (BCMask) provides the information as to whether are bunches coming from both sides A-side and C-side, or one of them, or neither, at resolution of 25 ns. The beam-gas interaction background was studied by triggering on bunches without a collision partner, and subtracted from physics data taken with the requirement of the presence of both bunches.

The most important trigger configurations used by ALICE are shown in the table 2.6. The minimum bias triggers (MBand and MBor) were used for all pp data taking, as well as in some Pb-Pb runs (2010). The high efficiency MBor trigger was used at low luminosity and with high levels of background while for high luminosity the MBand trigger was used. In the high luminosity Pb-Pb runs, the V0-based trigger was complemented by trigger signals provided by ZDC (MBZ) in order to suppress the electromagnetic interactions between the lead ions. The biased “power-interactions” trigger (SPI) required a certain number of hits in the SPD. With thresholds on the summed-up signals, V0 was also used to generate central 0 – 10% and semicentral 0 – 50% (SEMI) Pb-Pb triggers. The thresholds were applied separately to the sums of the output charges of V0A and V0C, then the coincidence of the two sides was required.

In order to maximize the inspected luminosity without contaminating the sample with multiple interactions events, the trigger strategy for high multiplicity trigger was based on the hit multiplicity in the outer layer of the SPD. The PHOS and EMCal L0 triggers (PH and E0, respectively) required a certain energy deposit within a window of 4×4 calorimeter cells. Using L1 level, EMCal provided triggers on photon/electrons (EGA) and on jets (EJE). The EJE trigger uses window of 32×32 cells and is primarily sensitive to neutral energy but also includes contributions for charged particles.

The instantaneous rate and the total number of collected events in Run 1 are shown for selected trigger in Figure. 2.13. The total number of collected events in 2018 (similar values to the Run 2 data of 2016 and 2017) is shown in Figure 2.14.

During pp runs in 2012 the TRD was introduced into trigger scheme, A fraction (limited to 10 to 25 kHz) of the minimum bias trigger at L0 were subject to a TRD L1 decision, in this trigger level (L1), four algorithms were implemented:

- Jet Trigger (TJE). The jet trigger requires at least 3 charged particle tracks with $p_T > 3$ GeV/c to be detected in one TRD stack.
- Single electron Trigger (TSE). The electron trigger required an electron PID based on a threshold for electron likelihood calculated from the integrated signal of each year.
- Quarkonium electron trigger (TQU). The quarkonia electron trigger required a lower P_T

Table 2.6: ALICE Triggers

Trigger Name	Description	Condition
MB-type triggers		
MBor	minimum bias	signals in V0 and SPD
MBand	minimum bias	signals in V0A and V0C
MBZ	minimum bias	MB and signals in both ZDC's
SPI	multiplicity trigger	n bits in SPD
Centrality triggers		
CENT	Central	V0 based centrality trigger for Pb-Pb (0 – 10%)
SEMI	semicentral	V0 based semicentral trigger for Pb-Pb (0 – 50%)
EMCal rare triggers		
EMC	EMCal L0	EMCal L0 shower trigger in coincidence with MB
EJE	neutral jet	EMCal L1 jet algorithm following EMCAL L0
EJE2	neutral jet	like EJE but with a lower threshold than EJE
EGA	photon/electron	EMCal L1 photon algorithm following EMCAL L0
EGA2	photon/electron	like EGA but with a lower threshold than EGA
TRD rare triggers		
TJE	charged jet	n charged particles in TRD chamber in coincidence with MB
TQU	electron for quarkonia	electron with $p_T > 2 \text{ GeV}/c$ in TRD in coincidence with MB
TSE	electron for open beauty	electron with $p_T > 3 \text{ GeV}/c$ in TRD in coincidence with MB
MUON rare trigger		
MSL	single muon low	single muon in MTR in coincidence with MB
MSH	single muon high	like MSL but with a higher threshold
MUL	dimuon unlike sign	two muons above low threshold, unlike sign in coincidence with MB
MILL	dimuon like sing	two muons above low threshold, same sign in coincidence with MB
Miscellaneous Triggers		
HM	high multiplicity	high multiplicity in SPD in coincidence with MB
PH	photon by PHOS	PHOS energy deposit in coincidence with MB
EE	single electron	electron signal in TRD and EMCAL
DG	diffractive	charged particle in SPD & veto in VO in Run-1 plus AD in Run-2
CUP	barrel ultraperipheral	charged particle in SPD & no signal in V0A, for Pb-Pb and p-Pb
MUP	Muon ultraperipheral	di-muon in MRT & veto in V0A, for Pb-Pb and p-Pb
ZED	electromagnetic dissociation	signal in any of the neutron ZDCs
COS	Cosmic Trigger	signal in ACORDE

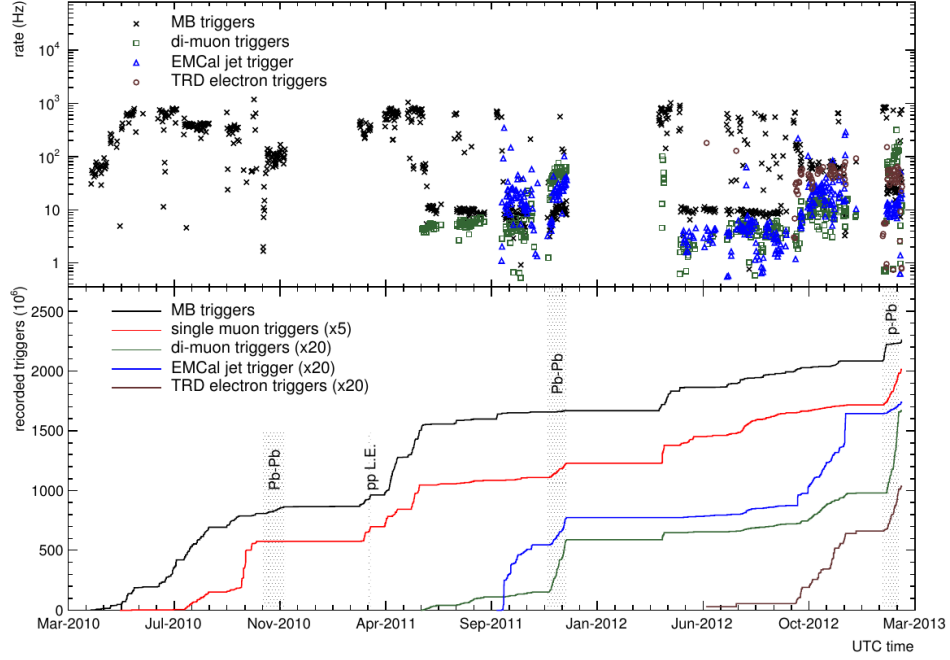


Figure 2.13: Readout rate (top) and number of collected events (bottom) for selected triggers in the running periods from 2010 to 2013. Special running periods (Pb-Pb, p-Pb low energy pp) are indicated by shaded areas; the rest presents pp runs at highest available energy.[11].

threshold of 2 GeV/c with a tighter electron likelihood cut. This enables the detection of low momentum electrons from J/ψ and ψ' decays.

- TRD + EMcal electron Trigger (EE). The high purity trigger EE was inspecting all events with EMCal Level 0 trigger (E0). The TRD trigger condition for EE was the same as for the single electron trigger; however, the acceptance was limited to the TRD sectors that overlap with the acceptance of EMCal. A signal in the innermost TRD layer was required for all TRD electron triggers in order to suppress the background caused by late photon conversions.

In the trigger strategy of ALICE at Level L0 the muon triggers were implemented. There were two single-muon triggers (MSL and MSH) and two dimuon trigger (MULL and MLL), all in coincidence with MB. A low p_T threshold was used for MSL, MUL and MLL, and a high one for the MSH trigger. The low-threshold single muon trigger MSL was downscaled when used

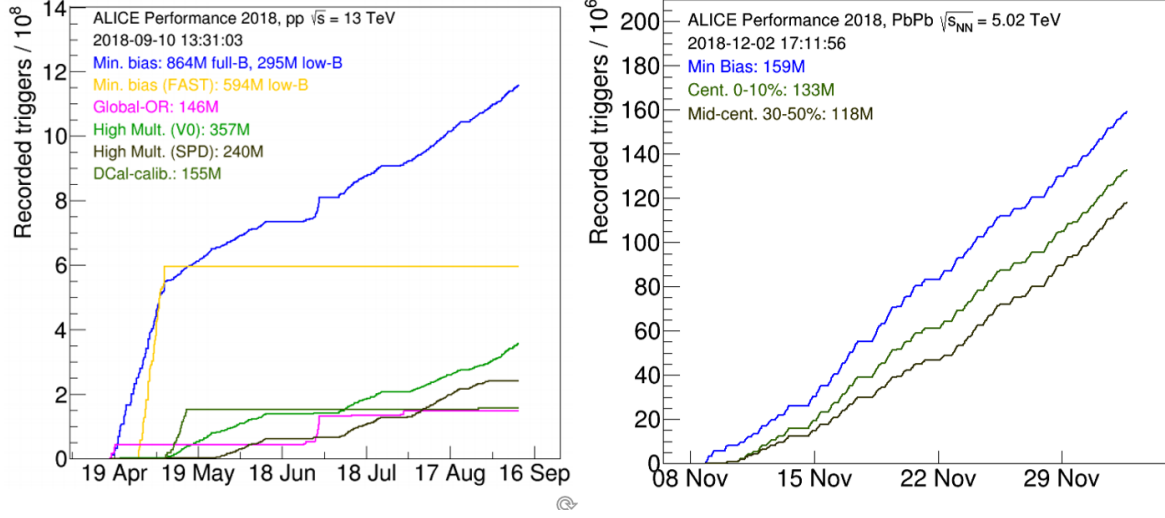


Figure 2.14: Total recorded trigger for 2018, proton-proton period (left) lead-lead period (right).

in parallel with MSH. The unlike-sign muon-pair trigger MUL, used for measuring mesons, was completed by the like-sign (MLL) one for the combinatorial background estimations. The low p_T thresholds were $0.5 - 10$ GeV/c and $1.7 - 4.2$ GeV/c respectively, adjusted according to the run type.

Several additional triggers were implemented in order to enhance events related to diffractive physics in pp and ultraperipheral nuclear collisions, and to measure cosmic rays. The DG (double gap) trigger in pp required a particle at midrapidity and no particles within the intermediate pseudorapidity ranges covered by the V0 detector. The CUP (Central-rapidity ultraperipheral) trigger performed a similar selection in collision system involving ions. An analogous condition, but with a forward muon rather than a midrapidity particle, was named the MUP (muon ultraperipheral) trigger. Finally, a cosmic trigger defined by ACORDE (COS) was implemented to collect high muon multiplicity cosmic events. The minimum bias and rare-triggers running modes are illustrated in detail for the p-Pb data taking in 2013 in Figure 2.15, and for 2018 in Figure 2.16 is shown.

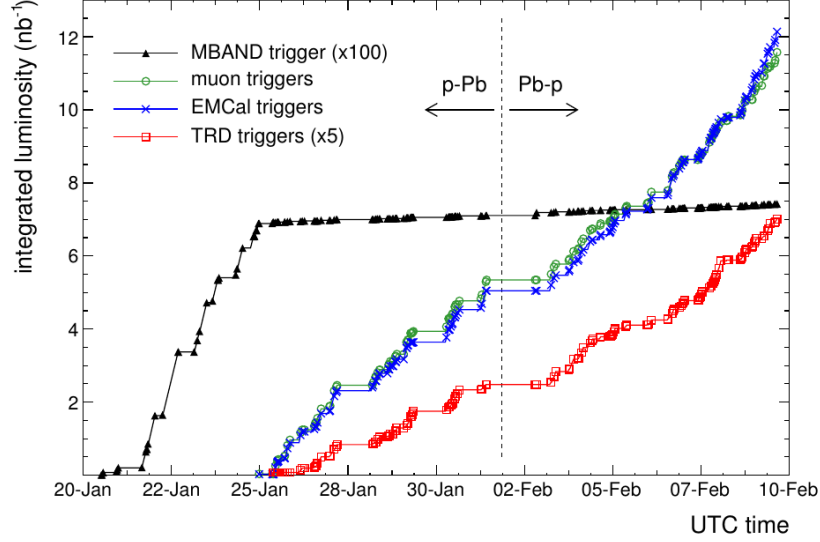


Figure 2.15: Integrated luminosity in 2013 proton-lead run, collected in the minimum bias and rare-trigger during 2013. [11].

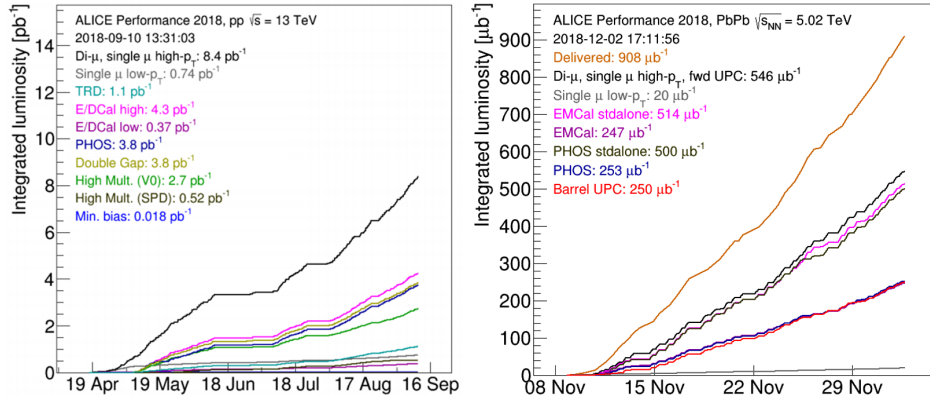


Figure 2.16: Integrated luminosity in 2018, proton-proton period (left), lead-lead period (right)

3

ALICE UPGRADE

This Chapter gives an overview about the ALICE upgrade plans for LHC Run 3, a full description of the Central Trigger System design is given including a brief description about the trigger strategy that will be used.

3.1 Introduction

3.1.1 Physics Programme

The LHC is going for its next major upgrade from 2018 to 2020 as is shown in figure 3.1. The LHC has already attained the maximum energy of 13 TeV centre-of-mass energy in 2015 for proton-proton collisions and 5.02 TeV per nucleon in the case of Pb-Pb collisions. From the year 2020 onwards, a High Luminosity Collider (HL-LHC) will be operational whose main objective is to increase the luminosity of the machine by a large factor.

During LHC-Run 3, the ALICE collaboration plans to extend its physics programme, in order to fully exploit the scientific potential of the LHC for fundamental studies of QCD, with the main emphasis on heavy-ion collisions. The proposed enhancement of the ALICE detector performance will enable detailed and quantitative characterization of the high density, high temperature phase of strongly interacting matter, together with the exploration of new phenomena in QCD [18].

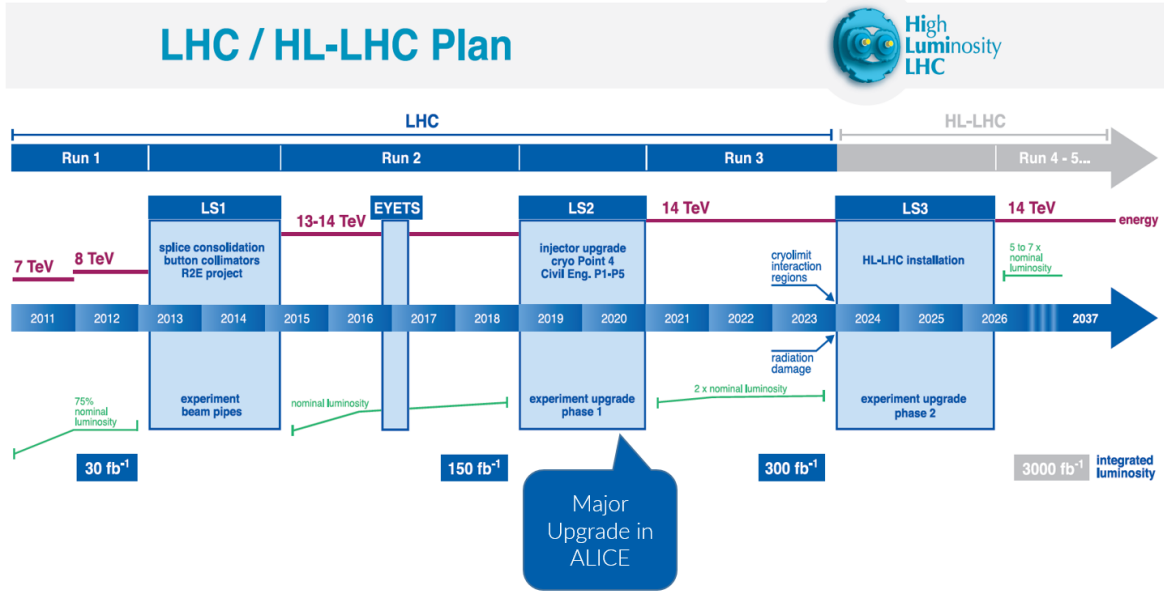


Figure 3.1: Major upgrade in ALICE during phase 1 of the HL-LHC plans (from [17]).

The study of the strongly-interacting state of matter in the second generation of LHC heavy-ion studies following LS2 will focus on rare probes, and the study of their coupling with medium and hadronization processes. These include *heavy-flavour particles*, *quarkonium states*, *real and virtual photons*, *jets and their correlations with other probes*. The interaction with the medium of heavy-flavour probes is better controlled theoretically than the propagation of light partons. All these investigations should involve soft momentum scales, and thus benefit from the ALICE detector strengths: excellent tracking performance in high-multiplicity down to low p_T and particle identification over a large momentum range. Major highlights of the proposed programme focus on the following physics questions [18]:

- Study of the thermalization of partons in the QGP, with focus on the massive charm and beauty quarks. Heavy-quark azimuthal-flow anisotropy is especially sensitive to the partonic equation state. Ultimately heavy quarks might fully equilibrate and become part of the strongly-coupled medium.
- Study of the low momentum quarkonium dissociation and, possible regeneration pattern, as a probe of deconfinement, and an evaluation of the medium temperature.

- Study of the production of thermal photons and low-mass dileptons emitted by the QGP. This should allow to evaluate the initial temperature and the equation of state of the medium, as well as to shed light on the chiral nature of the phase transition.
- Study of the in-medium parton energy-loss mechanism that provides both a testing ground for the multiparticle aspects of QCD and a probe of the QGP density. The relevant observables are: jet structure, jet-jet and photon-jet correlations, and jet correlations with high-momentum identified hadrons and heavy-flavour particle production in jets. In particular, it is crucial to characterize the dependencies of energy loss on the parton colour-charge, mass, and energy, as well as on the density of the medium.
- Search for heavy nuclear states such as light multi- Λ hyper-nuclei bound states of $(\Lambda\Lambda)$ or the H dibaryon, (Λn) bound state, as well as bound states involving multi-strange baryons; a systematic study of light nuclei and anti-nuclei production.

3.1.2 Detector Upgrade

To achieve the best description of the physics topics described above, high statistics and high precision measurements are required, which will give access to the rare physics channels needed to understand the dynamics of the condensed phase of QCD. Many of these measurements will involve complex probes at low transverse momentum, where traditional methods for triggering will not be enough, for these reasons, the ALICE collaboration is planning to upgrade the current detector by enhancing its low-momentum vertexing and tracking capability, and allowing data taking at substantially higher rates.

The ALICE upgrade strategy is therefore based on collecting $> 10 \text{ nb}^{-1}$ of Pb-Pb collisions at luminosities up to $\mathcal{L} = 6 \times 10^{27} \text{ cm}^{-2}\text{s}^{-1}$ corresponding to collision rates of 50 kHz, where each collision is shipped to the online systems, either upon a Minimum Bias trigger or in a self-triggered, continuous trigger. In addition the ALICE collaboration expect the collection of 6 pb^{-1} of pp collisions at the equivalent Pb-Pb nucleon energy as well as 50 nb^{-1} of p-Pb collisions, both at a levelled collision rate of 200 kHz. With this program, the statistics for the above mentioned physics topics will be increased by a factor of 100 over

the numbers achievable with the present ALICE detector. The upgrade plan of the ALICE detector preserve the excellent particle identification capability while enhancing the vertexing and tracking capabilities, and include [18] [19]:

- A new, high-resolution, low-material-thickness Inner Tracking System (ITS). This detector will consist by 7 layers of monolithic silicon detectors. With this new detector the resolution of the distance of closest approach between a track and the primary vertex will be improved by a factor about 3, and the standalone ITS tracking performance will be significantly enhanced.
- The Time Projection Chamber (TPC) upgrade is based in the replacement of the readout multi wire proportional chambers with GEM (Gas Electron Multiplier) detectors, that allow continuous operation to read out 50 kHz Pb-Pb collisions. The TPC electronics will push the digitized and time-stamped TPC data to the online systems in a triggerless mode. For calibration and commissioning purposes, a triggered mode of operation will be implemented as well.
- The Muon Forward Tracker (MFT) consists of several discs of monolithic silicon pixel sensors located in the forward region between the ITS and the front absorber. The sensors and read-out will exploit a maximum synergy with the ITS detector.
- The Muon Chamber System (MCH) consists of a sequence of 5 wire chambers stations in the forward region of the experiment. It is presently limited to 1 kHz read-out rate and will change the entire read-out electronics using the SAMP4 chip to digitize the detector signals. It will ship the data to the online system, either upon an interaction trigger or in continuous mode.
- The Muon Trigger detector (MTR) is at present providing the selection of high p_T single muon and di-muon events with a maximum trigger rate of 1 kHz. As the upgrade trigger strategy does not foresee a muon trigger, all events will be read upon the interaction trigger and the data are used offline for hadron rejection. The detector will be called Muon Identifier (MID).
- The Transition Radiation Detector (TRD) is presently limited to a few kHz read-out rate. Reducing the data volume from the detector by using tracklets and increasing

the data throughput of the off-detector electronics, a trigger rate of 100 kHz for Pb-Pb and pp can be achieved. Since the front-end electronics does not support the use of the multi-event buffers, a 100 kHz trigger rate corresponds to $\approx 60\%$ of events being read out. At 50 kHz Pb-Pb collisions $\approx 75\%$ of the events will be read out. Going beyond this number is not possible, because a change of the on-detector electronics would be needed, which requires a removal and disassembly of all TRD modules.

- The read-out of the Time Of Flight detector (TOF) is at present limited to 40 kHz by the throughput of the VME system located in the crates at the end of the detector modules. The upgrade strategy of TOF is focused in this element that will allow the detector to read out at rates greater than 200 kHz in Pb-Pb collisions.
- The V0,T0 and FMD detectors will be replaced by a Fast Interaction Trigger (FIT) detector, which will provide the Minimum Bias interaction trigger for the experiment. The FIT will consist of a new assembly of Cherenkov and scintillator detectors with $> 99\%$ efficiency and < 30 ps time resolution for Pb-Pb events. The excellent time resolution is used for vertex selection with 1 cm resolution as well as start time for the TOF detector. Due to its proposed granularity, the detector will be also able to provide event plane determination. The ZDC will change the read-out electronics to accept the increased trigger rate. It will also provide trigger information that can be used to clean the interaction trigger.

The schematic layout of ALICE for LHC Run 3 is shown in the figure 3.2.

The detector electronics, the trigger and the online computing system are designed to keep the nominal performance, even if noise or background is larger than anticipated.

The high interaction rate and the large event size result in a data flow of ≈ 1 TB/s from the detectors to the online system. Partial event reconstruction and data reduction in the online system results in a peak data rate to storage of 80 GB/s [19]. ALICE will use standard system interfaces for the upgrade. The Detector Data Link (DDL) will be upgraded to a higher bandwidth link and complemented with a common read-out unit (CRU). The CRU forms the interface between the detector front-end links and the DDL connecting to the online computing system (O^2). The CRU also receives the trigger and timing distribution signals from the Central Trigger System (CTS). Depending on sub-detector specifications, detector

3. ALICE UPGRADE

3.1 Introduction

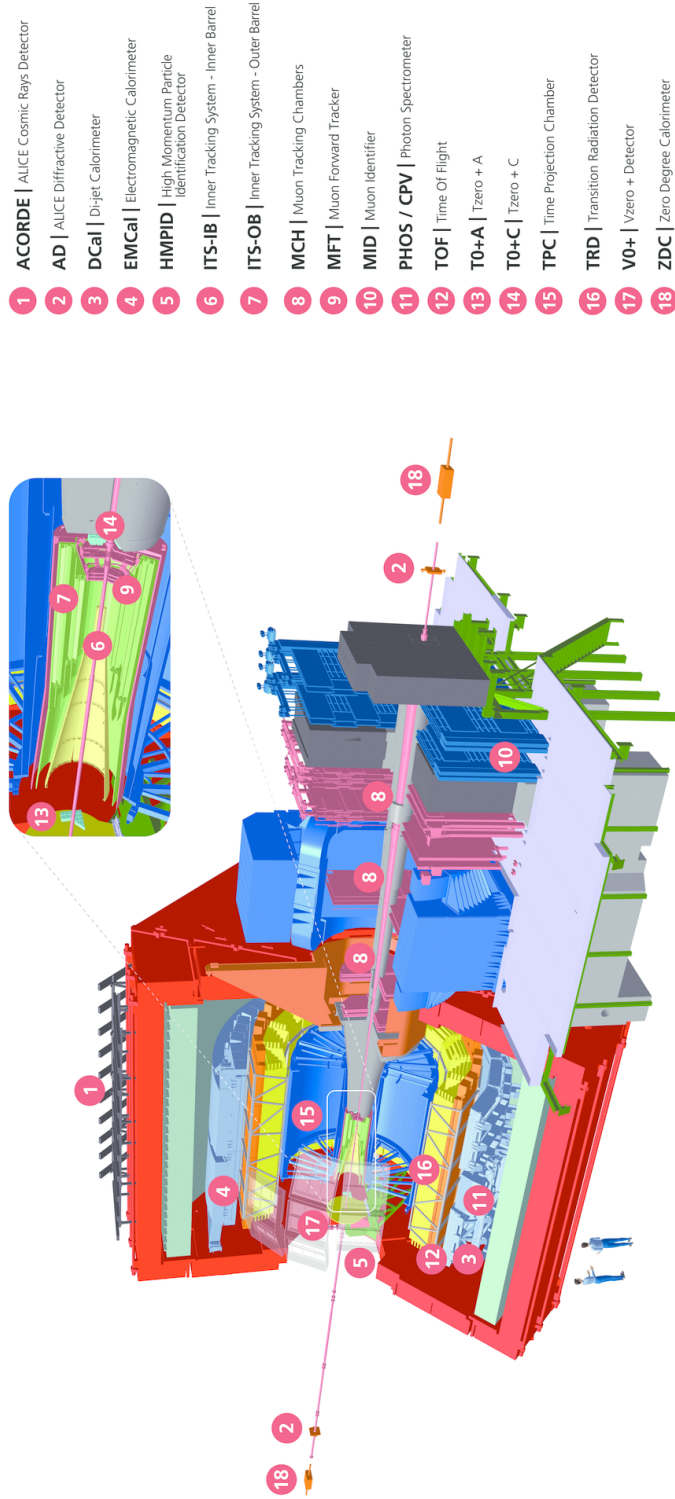


Figure 3.2: ALICE Experiment schematic layout for LHC Run 3 [8].

data sent to the CRU are multiplexed, processed and formatted. The CRU on-detector interfaces is based on the Giga Byte Transceiver (GBT) protocol and optical versatile link. For upgrading detectors the CTS will provide trigger information via Timing Trigger Control - Passive Optical Network (TTC-PON) links and GBT for special detectors. For detectors not upgrading their interfaces, backwards compatibility to Run 1 and Run 2 systems is provided.

3.2 Trigger Architecture

The ALICE Upgrade will require a very different triggering strategy from the current one and hence a new Central Trigger System (CTS). The CTS will manage a system of detectors with very different properties. The majority of detectors, which will read-out the nominal interaction rate, are dead-time free. However, in order to provide backwards compatibility to detectors not being upgraded, the CTS must cope with detectors which will have dead-time during the read out. For Run 3 the CTS will keep the concept of a Central Trigger Processor (CTP) and Local Trigger Units (LTUs) as detector interfaces but advances in FPGA technology mean it is now possible to have all the functionality of the CTP on a single 6-U board. Figure 3.3, shows the six detectors that will deliver trigger inputs to the CTP and the three ways the trigger data will be distributed to the detector FEE. As previously commented, detectors not upgrading their FEE will have trigger data sent via the TTC system, directly to their FEE. Most of the detectors being upgraded will receive trigger data via a TTC-PON optical link to their Common Readout Units (CRUs) but some will require a direct link via GBT.

The strategy for selecting event or readout will also be different from that employed in previous runs, for example in previous runs, despite the fact that ALICE events are highly complex, the trigger strategy was to combine a Minimum Bias sample with one selected according to thresholds in high E_T (calorimeter triggers), high p_t , or high multiplicity. As was previously mentioned the strategy for the ALICE upgrade system is to read out all interactions and apply an online filtering in the high level trigger (HLT). During Run 3 the interaction will increase to ~ 50 kHz for Pb-Pb, and 200 kHz for p-p and p-A. The main goal

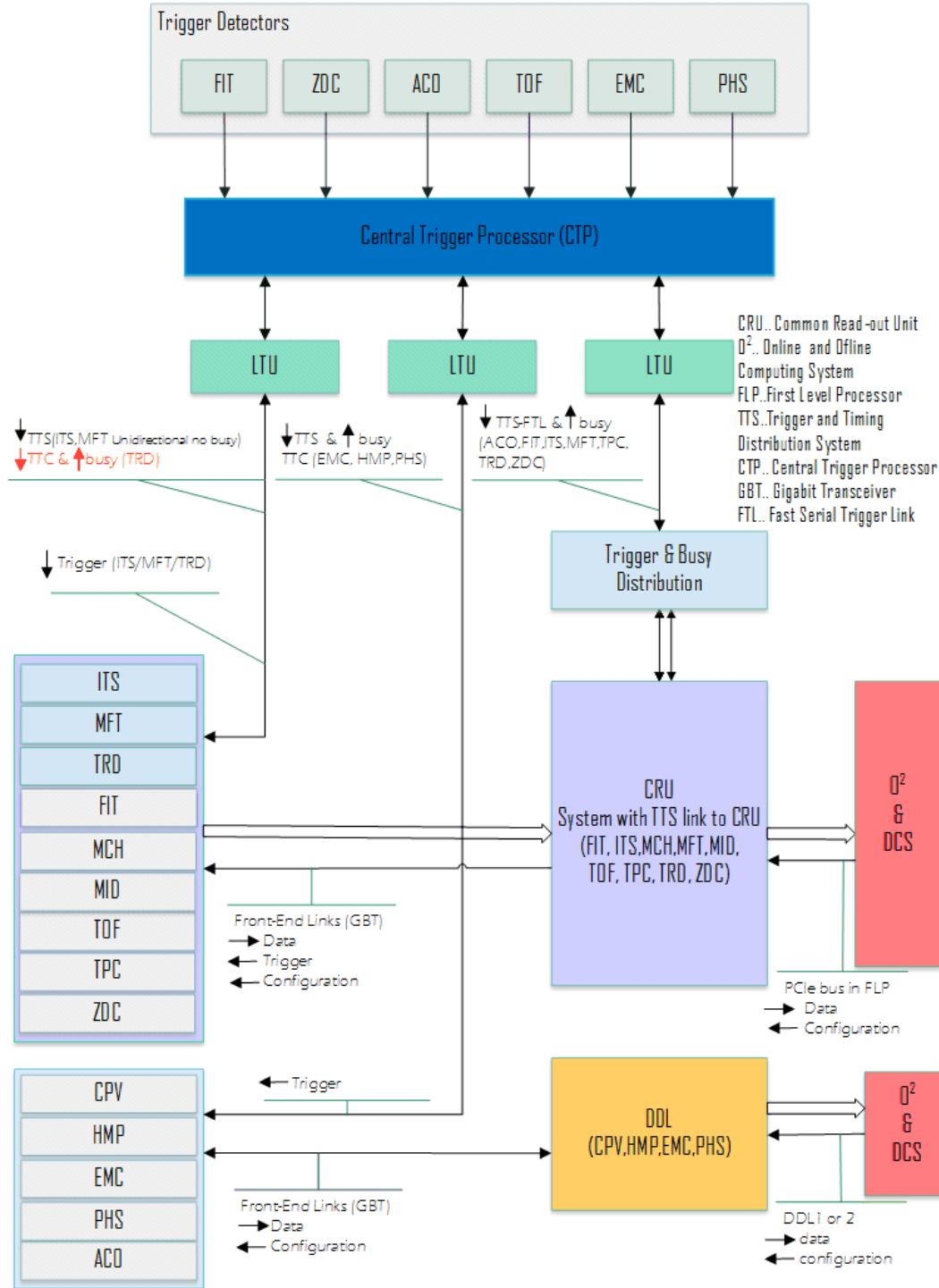


Figure 3.3: Summary of trigger distribution.

of the ALICE trigger system is to select essentially all of these interactions. To achieve this, a novel trigger strategy will be applied; the combination of continuous readout detectors and minimum bias trigger using the new trigger detector (FIT), with a few additional inputs to allow for cosmic triggers and calorimeter based triggers to enhance rates for some types of events where the minimum trigger is inefficient.

The CTS will collect the trigger inputs in different latencies, giving hardware triggers at three different latencies known as LM , $L0$ and $L1$. The maximum latency for the trigger input signals to reach the CTS are summarized in Table 3.1.

Table 3.1: Summary of trigger inputs

Input Latency	Input to CTP [ns]	Contributing detectors
LM	425	FIT
L0	1200	ACO, EMC, PHOS, TOF, ZDC
L1	6100	EMC, ZDC

Table 3.2, gives a summary for all detectors stating which trigger they require, their maximum readout rate, the trigger distribution method, whether they will use the CRUs and how they deliver their BUSY signal. In the strategy of the CTS for Run 3 the LM latency will be similar that used in Run 2, and is suitable for generating a fast trigger signal for both the TRD and ITS/MFT electronics FEEs. In addition an electrical LM signal will be used by CPV and HMPID detectors; meanwhile the ITS will receive its LM trigger via a GBT link. However, it will not be possible to generate an Electro-Magnetic Calorimeter (EMC) signal early enough for the LM trigger, and for this reason the $L0$ is retained, The FIT detector is not suitable for cosmic ray triggers, and in this case the TOF and ACORDE detectors will be used. The ZDC is optionally available to clean the minimum bias trigger provided by the FIT. Trigger signals go to every detector, since it is a requirement for each detector, even those where continuous readout is foreseen as the norm, that it should also be capable of reading out in triggered mode [20].

Due to the new trigger strategy including continuous readout, there will be relatively few

physics conditions defined as combinations of trigger inputs (trigger class), with most events selected by Minimum Bias trigger with subsequent filtering in the HLT. During Run 3 if a single trigger condition is satisfied, the event is read out with the full set of continuous readout detectors, plus all other available detectors. This strategy in effect treats each detector as a separate cluster, so any combination of detectors could be read out for a given event. At the same time the BUSY requirements of every detector (old readout detectors) can be treated independently of other detectors. It could turn out that this strategy would lead to insufficient numbers of events being read out with useful combinations of detectors. To allow for this possibility, the trigger logic can, in addition, define further clusters consisting of groups of detectors, as at present, and balance the bandwidth between a free selection of all available detectors and a restricted choices requiring a given combination [20].

Table 3.2: Summary of detector requirements

Detector	Triggered by () = optional	Pb-Pb RO Rate[kHz]	Trigger	CRU used	BUSY IN
TPC	(L0 or L1)	50	PON via CRU	yes	PON/CRU
MCH	(L0 or L1)	100	PON via CRU	yes	PON/CRU
ITS	LM	100	GBT	yes	PON/CRU
MFT	LM	100	GBT	yes	PON/CRU
MID	LM	100	PON via CRU	yes	PON/CRU
TOF	L0 or L1	>100	PON via CRU	yes	PON/CRU
ACO	L0	100	PON via CRU	yes	PON/CRU
TRD	LM	39	TTC	no	PON/CRU
EMC	L0 & L1	42	TTC	no	LVDS
PHO	L0 & L1	42	TTC	no	LVDS
CPV	L0	50	TTC	no	LVDS
HMP	L0 & L1	2.5	TTC	no	LVDS

3.3 Continuous Readout

The continuous readout of the majority of the detectors is the main change in the trigger strategy point of view. The data are not delimited by physics triggers but are composed of several constant data streams that will be transferred from the detectors to the computing system. Dedicated time markers the heart beat trigger (HB), will be used to chop the data flow to the First Level Processor (FLP) into manageable pieces called HB frames (HBF). The HBFs are assembled in Sub-Time Frames (STF) and then Time Frames (TF) by computing system as shown in the figure 3.4. All FLPs produce STFs, which could be empty for those FLPs receiving data from triggered detectors inactive during the corresponding time period. The STFs are then dispatched to the Event Processing Nodes (EPNs) for aggregation. The STFs related to the same time period and from all FLPs are received by the same EPN and aggregated into a complete time frame (TF). The STF and TF duration of 22 ms is chosen to minimise incomplete data at the TF boundaries for the collisions producing tracks spanning across the TF boundaries. The LHC clock will be used as a reference to synchronize, aggregate and buffer the data. The time between two HB is $89.4\mu\text{s}$; that time is equivalent to one LHC orbit period, and the duration of a TF is of the order of 20 ms, both are programmable parameters. The data from triggered read out are assembled into trigger data fragments and transferred to the FLPs [20], [21].

The ALICE continuous readout mode is designed to operate in nominal conditions without data loss. In this context data loss is considered a rare exception and thus missing HBF in the reconstruction are either considered negligible and are ignored or the full TF with missing data is discarded at the time of reconstruction. Under the previous conditions no coordinated approach between read out modules to discard data fragments would be required. However, we are providing some: HB reject. It is important to know that the detector also need to take samples without data compression during commissioning or for calibration runs. In those cases, the continuous read out detectors will continue to work with individual read out modules which discard any excess of data and inform the O2 system [21].

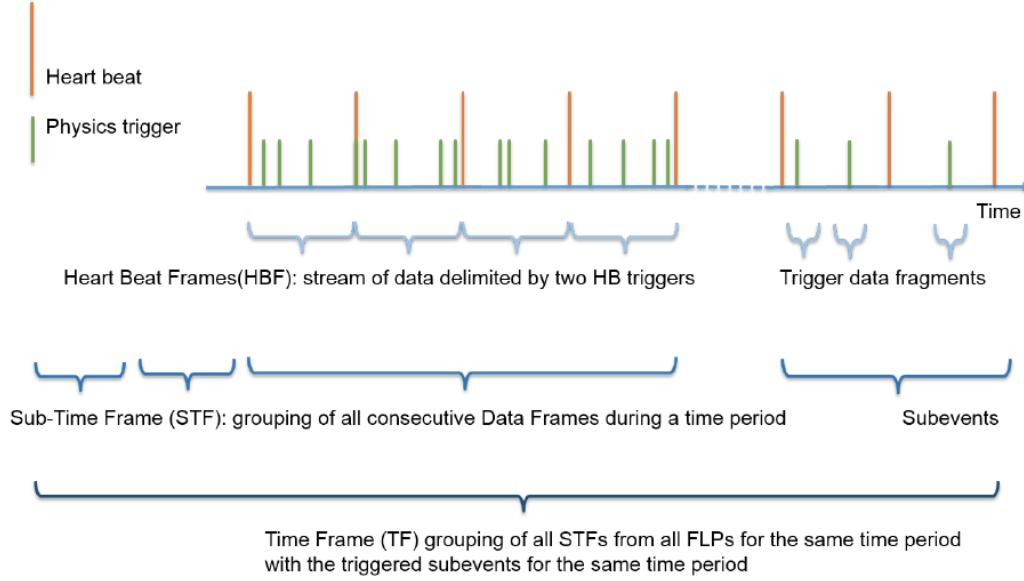


Figure 3.4: The usage of physics and heartbeat triggers for the continuous and triggered readout [21].

Each detector readout module sends information, the so-called HB, to the CTS on acknowledge. whether data has been discarded, where geographically in the detector and which HBF is affected. In triggered mode, the HB information does not refer to the HBF but to individual triggers. In continuous and in triggered mode the CTS takes the HB information to assemble a HB map covering the whole detector and forward it to the O^2 system via the CTS readout. Furthermore, the CTS applies pre-defined algorithms on the HB map and if needed takes action to reduce the data throughput. As previously commented the CTS in trigger mode will provide one trigger signal with several latencies ($LM L0 L1$), in this mode each detector needs to respond and send the data corresponding to the triggered time period. In special case for detectors, with the exception of the TPC, the trigger refers to the read out data of a given bunch crossing. The TPC needs to provide the data of the $102.4 \mu s$ following this bunch crossing.

During Run 3 the CTS will operate without dead time, which means that it can assert a subsequent trigger in the following bunch crossing. The control loop (detector gets full, sends HB information to CTS, CTS sends trigger to detector) is longer than 25 ns and might be longer than $10 \mu s$. As a result, a new trigger might have been released from the CTS to the

detector before the corresponding message indicating that the detector cannot read out any more events arrives at the CTS. Therefore, the detectors need to be able to process a trigger signal, even though they are full and need to send an empty data packet as acknowledge of the trigger reception with the trigger information to the FLPs. Not upgraded detectors with a minimum read out time longer than the control loop cycle can be protected by the CTS from triggers once they are full.

3.3.1 Heart beat map

The new trigger strategy for the Run 3 will include the concept of the Heart Beat Map, this concept has been introduced in order to allow throttling the data throughput in case the detector data throughput exceeds the system instantaneous bandwidth. The HB map is representing the read out buffer states of the entire ALICE detector with a granularity of one HBF and one CRU. However, it needs to be foreseen that one CRU is divided into several geographical regions in order to increase the HB map granularity. In that case the CRU will not deliver only one bit to the HB map, but one bit for each of its geographical regions, stating whether the corresponding HBF has been read out successfully or whether data is missing and has been deleted. The readout process of the HBF data will be successfully once all data corresponding to one HBF has left the PCIe buffer in the CRU. In that case the CRU sends a positive HB message containing the HB ID to the CTS via TTC-PON links. In case data of this HBF is fully or partially missing the CRU will autonomously delete data of that HBF and send a negative HB acknowledge message. The CTS will assemble all HB message of a given HBF, after all CRUs have replied with a positive or negative message or after a programmable time-out, in case the HB map message is missing or delayed for too long. Once the HB map has been fully assembled, the CTS applies one out of a pre-defined set of algorithms to evaluate whether the corresponding HBF is considered useful or should be deleted. This decision, called the HB map decision, will be transmitted via TTC-PON links to all CRUs which will forward it to the FLPs between the transmission of a HB trailer and the HB header of the next HBF. In case of a negative decision, those HBFs still in the buffers of CRU and FLP, and which have not yet been forwarded to the EPN, will be deleted. The CTS also will transmit the full HB map and decision via the CTS read out to the CTS-FLP and

3.3.2 Data Format in continuous readout

In continuous mode the detectors receive the HB triggers a timing reference only. As a result, HBFs sent from the CRU to the FLP are referenced to HB triggers, that process is shown in figure 3.6. A data transmission must not span over two HBFs. Scheduled data transmissions spanning over two HBFs must be broken in two packets. The reception of the HB trigger must be followed by the transmission of a HB header followed by the detector data and a HB trailer or if there were no hits in the corresponding HBF by transmission of a HB header and trailer only. Additional detector status information can be sent in the HB header or trailer.

Some detectors will require a sequence of auxiliary triggers to initiate a constant stream of read-out transfers. Throttling of these detectors by changing the auxiliary trigger pattern is not foreseen. These detectors are throttled switching to triggered mode or using the throttling techniques in the CRU described previously.

The HBF transmission can be split into several sub HBFs and each of the sub HBF data headers indicate the corresponding HB ID. The HBF transmission is terminated with the HBF trailer, which contains the number hits in a HBF and the information whether this HBF transmission has been completed successfully or whether data has been deleted due to buffer overflow. This information is sent in the trailer as the CRU might not know the number of hits or whether the buffer will overflow at to begin of the data transmission. It can be considered that the FLP extracts the HBF trailer information and moves it to the HBF header to facilitate further data processing. In case no hits were recorded during a HBF, the HBF trailer indicating zero hits will be transmitted [21].

The CTS transmits the HB map decision to the CRUs for each HBF whenever they are available. After each HBF trailer and before the next HBF header the CRU transmits the HB map decisions of all HBF received in the meanwhile to their FLPs, the scenario is described in figure 3.7.

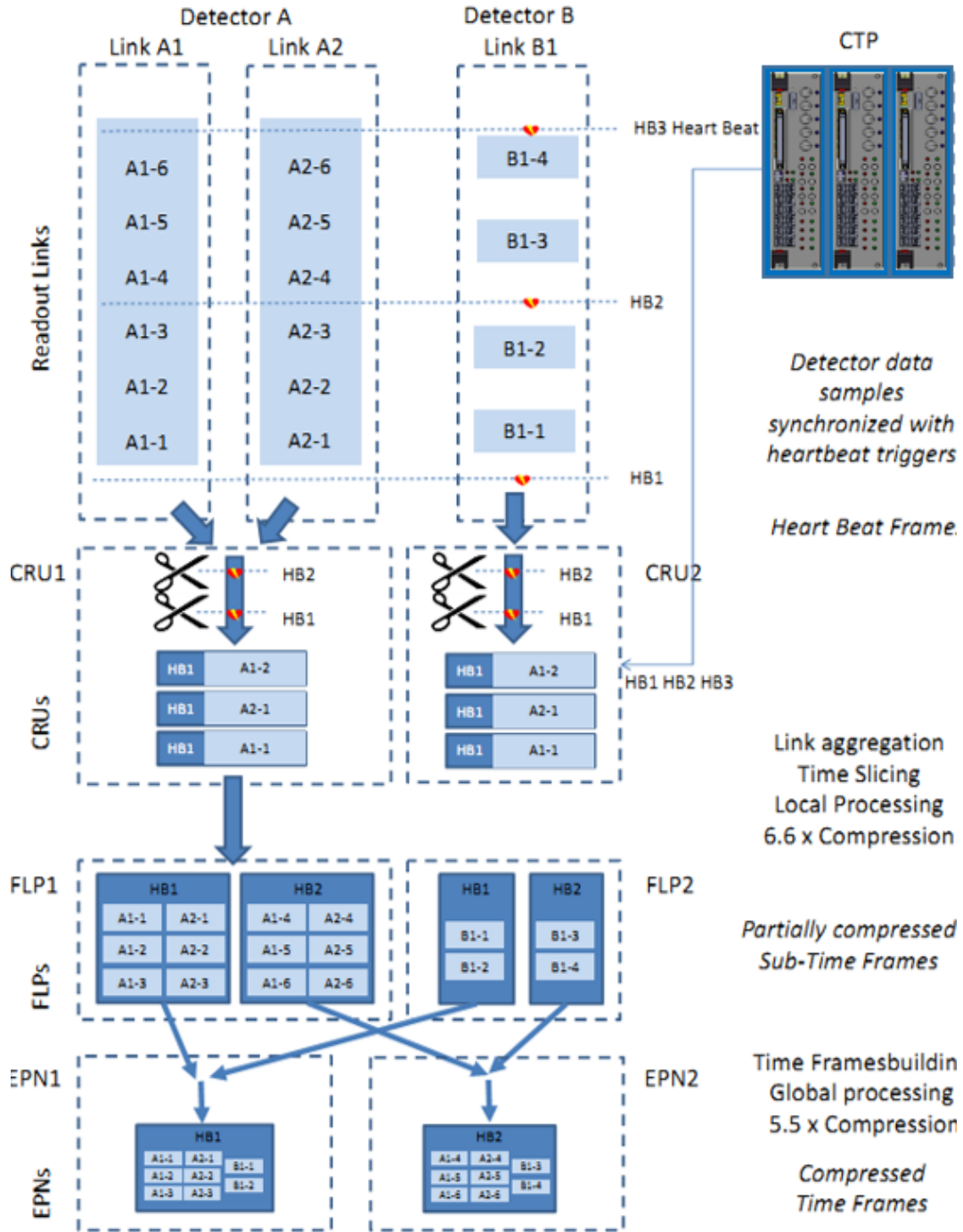


Figure 3.6: Data aggregation along the data flow from continuous data streams from the detectors up to the full TFs in the EPNs

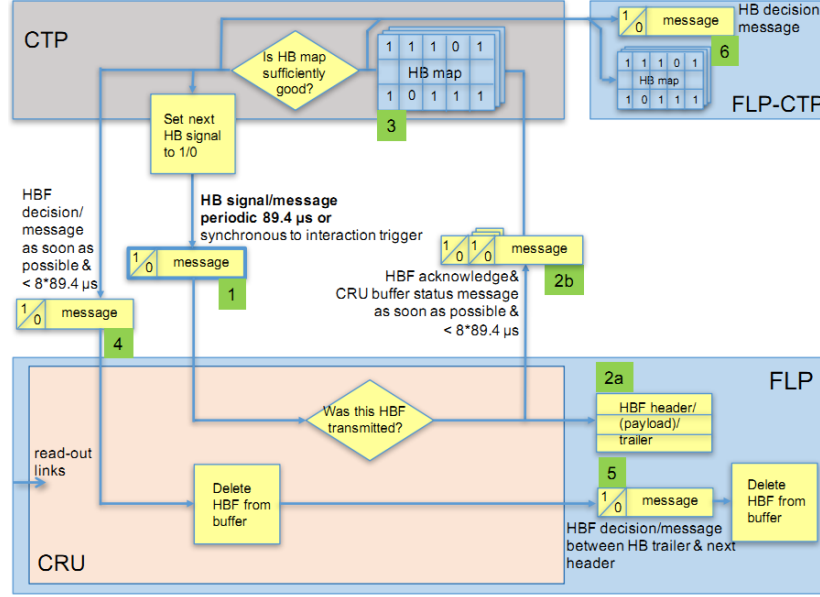


Figure 3.7: Signal and Data flow (from [21]).

3.4 Interface to Detectors

As shown in figures, 3.8 and 3.9, and as previously described, triggers and trigger data will be distributed to detectors using three different protocols: TTC-PON from LTU to the CRUs, GBT for upgraded detectors receiving triggers directly, and TTC for detectors that are not being upgraded. The table 3.3 show full information about the trigger data. Only part of this information is sent to detector with every trigger. The trigger data sent to detectors consists of *Trigger Type (TType)*, *Bunch Cross Identification (BCID)* and *Orbit number (ORBIT)*, 76 bits in total. The rest of the data from Table 3.3 are sent to O^2 system only via the CTP readout.

The communication between CTS and CRU is similar for both modes (trigger and continuous). The flow of the data is shown in figure 3.7 and can be explained as follow:

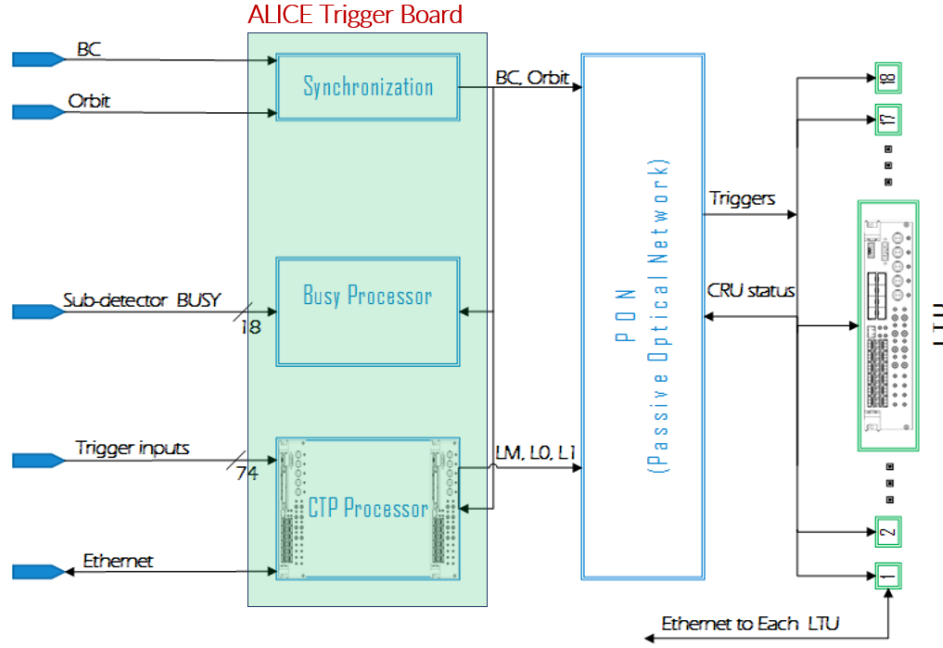


Figure 3.8: Block diagram of CTP and LTU system.

1. The CTP transmits a TTC-PON message of 77 bits every Bunch Crossing (BC).
- 2b. For the message marked as Heart Beat (HB), the CRU responds with an HB acknowledge message (HBAm) acknowledging that data have been successfully collected from the FE and transferred to the FLPs. A timeout for receiving HBAm on the CTP side is a programmable parameter of order $T_{HBAm} 8 * 89.4 \mu s$.
3. After a time T_{HBAm} the CTP evaluates the HB decision (HBd) for a given HB frame. The decision is based on a predefined function of HBAm message from all CRUs. The CTP modifies the HBaccept/HBreject flag in the trigger type in the TTC-PON messages.
4. The CTP collects all HBd for a given Time Frame (TF) creating the Heart Beat Decision Map of the Time Frame (HBDMTF) and transmits then asynchronously to the CRU.

In case of the CTS and FEE communication where the latency is important (LTU to FEE part in the figure 3.9), the CTP transmits every BC a message of 77 bits using GBT protocol, the payload of the message is identical to the TTC-PON message. No upstream

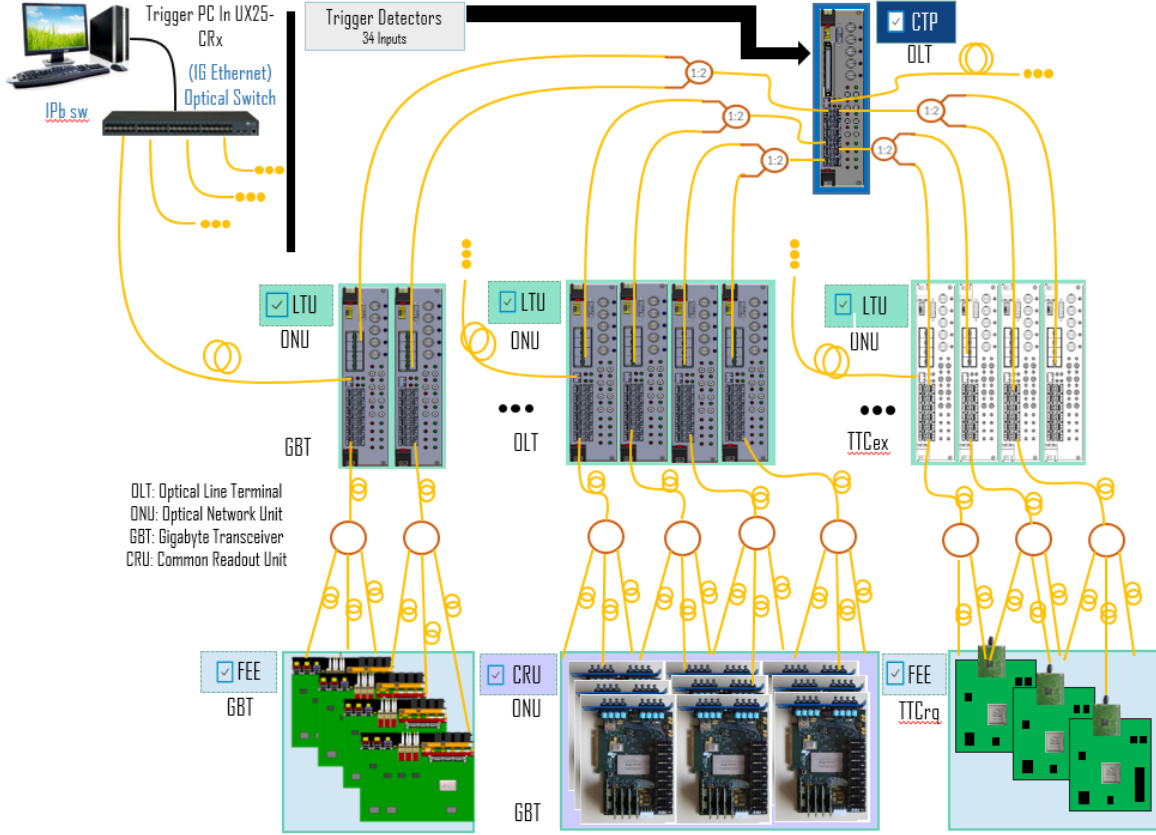


Figure 3.9: Schematic layout of the Central Trigger System for Run 3.

communication from the FEE to the CTP is expected.

3.4.1 Trigger Message

As previously described, the trigger message transmitted to the CRUs and the detector FEE consists of 77 bits arranged as follows: trigger type (TTYTYPE) (32 bits), event identification (44 bits), trigger type data valid bit (TTValid). The event identification consist of an LHC orbit counter ORBIT (32 bits) and Bunch Cross (BC) counter BCID (12 bits) (see table 3.3). Trigger Type Valid is a special bit in the payload and is interpreted as follow:

Table 3.3: Summary of the trigger data.

Data Name	Acronym	No. of Bits	Description
Trigger Type	TType	32	Trigger Type e.g. physics, calibration heartbeat, etc.
Bunch Cross No	BCID	12	Event ID: ORBIT + BCID equates to 4.4 days.
Orbit Number	ORBIT	32	
Trigger input mask	TIM	74	Trigger inputs activated.
Detector Mask	DM	18	Detectors included in event.

- **Trigger Type Valid** (TTValid) = '1' indicates that the order 3 fields (ORBIT, BCID, TTYPE) are valid.
- **Trigger Type Valid** (TTValid) = '0' indicates that the bits occupied by the 3 fields can be used for other communication purposes e.g slow control.

Software Triggers (Trigger Types): Including calibration triggers, are recognized via Trigger Type (TType) of 32 bits. The current trigger types are summarized in table 3.5. The bit HB = '1' indicates that the message is of Heat Beat (HB) type and the corresponding ORBIT and BCID are the identification of the HB. The HB frequency is defined to be equal to LHC orbit frequency and is synchronized with the LHC orbit, i.e BC = 0 in trigger messages with HB = '1'.

Throttling, Busy, and Heartbeat (HB) triggers: Heart-Beat (HB) triggers, containing the HBid, are sent to all detectors in all modes of operation, even when their status is full/busy, nominally every LHC Orbit.

Two types of HB triggers are envisage, HB-accept (HBa) and HB-reject (HBr) depending on the status of CRUs. The HBa and HBr triggers will contain the HBid and a bit to signify whether it is a HBa or HBr. The CTP will send Heartbeat (HB) triggers, nominally every LHC Orbit (98 μ s), to the CRUs via the LTUs. The HB period, however, will be a programmable parameter.

Table 3.4: Trigger Types.

Bit	Name	Comment
0	ORBIT	ORBIT
1	HB	Heart Beat Flag
2	HBr	Heart Beat Reject
3	HC	Health Check
4	PhT	Physics Trigger
5	PP	Pre Pulse for calibration
6	Cal	Calibration Trigger
7	SOT	Start of Triggered Data
8	EOT	End of Triggered Data
9	SOC	Start of continuous Data
10	EOC	End of continuous Data
11	TF	Time frame delimiter
...	...	Spare
29	TPCsync	TPC synchronization
30	TPCrst	TPC Reset
31	TOF	TOF special trigger

3.5 CTS Logic and readout

The trigger logic of the CTP is similar to that in Run 2 (explained in chapter 2). It keeps options for: *several trigger levels (e.g CPV), different trigger input conditions, the clustering of detectors*. Therefore the concept of trigger class defined as combination of trigger input condition and group of detectors to be read out is also kept at least in internal CTP logic. However, the expected number of classes is less than in Run 2, i.e. ~ 20 . However, the extension of classes in the CTP is fully transparent for the rest of the system.

For the CTS read out, the data will be send from CTP or LTU to O^2 system, including the following information :

- copy of all triggers,

- TIM (64 bits) and DM (18 bits) for every bunch crossing,
- HB map with payload of
 - HB id - Orbit + BC id.
 - 1 acknowledge bit and 2 buffers status bits per CRU.

In the CTS readout strategy, the CTP behaves with respect to O^2 almost as a normal detector. The strategy is represented in figure 3.10. The CTP transmit, at every bunch crossing, the data containing the TIM, DM and HB mask via links R1, R2, R3 to the O^2 CTP CRU over link R.

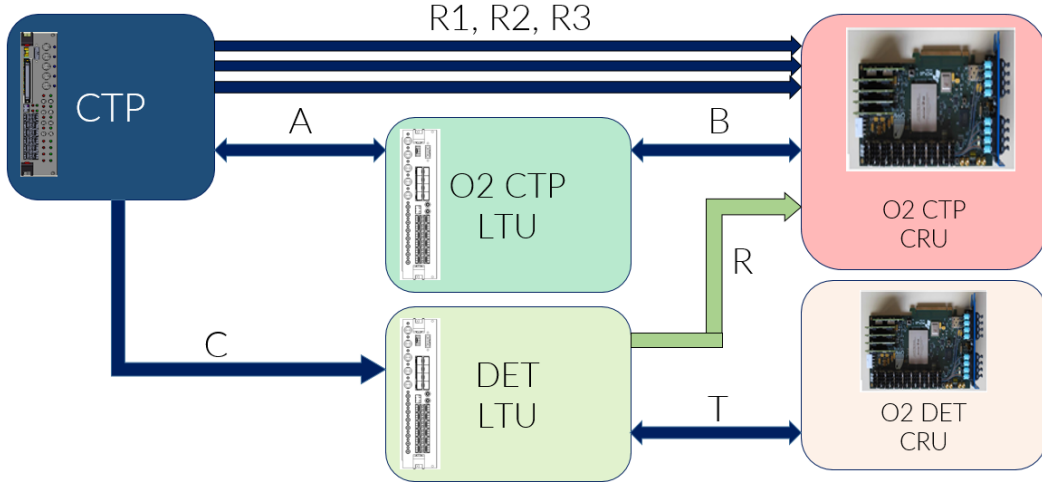


Figure 3.10: Scheme of the CTP readout.

The status of the CRU as seen by the LTU is also sent on the same link R. Other possible implementation is that the status of the CRUs are sent from LTU to CTP over link C where they are collected and sent to O^2 over link R3. In this baseline solution the links A, B, C and T are TTC-PON R1, R2, R3 and R are GBT.

The data format for TTC-PON links is summarized in the table 3.5, data on links R1, R2, R3 and R are in table 3.6, 3.7. In the following the upstream data rate is estimated and compared with TTC-PON bandwidth. The status of CRUs is transmitted from CRU to O^2

in three steps. First it goes from detector CRU to detector LTU (link T), then from detector LTU to CTP (link C) and finally from CTP to O^2 (links A,B).

As discussed previously each CRU sends HBid and CRU status bits corresponding to $(44 + 48)$ bits per $100\mu s$ assuming 10 kHz HB frequency resulting in about 1 Mb/s data rate. The upstream TTC-PON bandwidth is 48 user bits per Optical Network Unit (ONU) per 125 ns, corresponding for 64 *ONU* per splitter to 6 Mb/s data rate giving us safety margin of six for upstream traffic on link T. In the next step, the LTU collects the status of all the detector CRUs and sends it to CTP via link C. The maximum number of CRUs per detector is 360 (TPC), so maximum upstream traffic on link C, is $360 \times 1 \text{ Mbps} = 360 \text{ Mbps}$ just below 384 Mbps maximal rate over one TTC-PON upstream link, i.e. the TPC LTU will be a sole LTU connected to the corresponding CTP OLT. Finally the links A,B from CTP to O^2 are downstream links, with, a bandwidth higher than 1 Gbps and thus do not create a bottleneck.

Table 3.5: TTC-PON data format Trigger Message.

TTC-PON Bit	TTC-PON byte	Payload	Payload
31:0	0-3	31:0	Trigger Type
43:32	4-5	11:0	BCID
47:44	5	3:0	Spare
79:48	6-9	31:0	ORBIT
118:80	10-14	38:0	spare
119:119	14	0:0	TTC Valid
120:120	15	0:0	Header Flag
127:121	15	6:0	Word Count
167:128	16-20	39:0	HBDM Payload
198:168	21-24	30:0	Spare
198:199	24	0:0	HBDM Valid

Table 3.6: CTP readout GBT format: Detector Record.

Data	GBT Frame	GBT word	Payload	Content
0:3	1	G0	0:3	Header
4:15		G0	0:11	BCID
0:15		G1	0:15	Orbit
0:15		G2	16:31	Orbit
0:15		G3	0:15	DM
0:1		G4	16:17	DM

Table 3.7: CTP readout GBT format: Detector Record.

Data	GBT Frame	GBT word	Payload	Content
0:3	1	G0	0:3	Header
4:15		G0	-	Spare
0:15		G1	0:15	Orbit
0:15		G2	16:31	Orbit
0:15		G3	-	Spare
0:1		G4	-	Spare
0:3	2	G0	0:3	Header
4:15		G0	0:11	BCID
0:15		G1	0:15	TIM
0:15		G2	16:31	TIM
0:15		G3	32:47	TIM
0:15		G4	48:63	TIM
...	...	...	...	...
0:3	N	G0	0:3	Header
4:15		G0	0:11	BCID
0:15		G1	0:15	TIM
0:15		G2	16:31	TIM
0:15		G3	32:47	TIM
0:15		G4	48:63	TIM

4

ALICE CENTRAL TRIGGER SYSTEM (HARDWARE IMPLEMENTATION)

In this Chapter the design of the electronic board for the ALICE-CTS, called ALICE Trigger Board (ATB) is described, at the end of this chapter the test results of the evaluation of this board are then given.

4.1 Introduction

As described in the previous chapter, in Run 3 of the LHC, it is envisaged that the luminosity for Pb-Pb collisions will increase significantly, leading to a ~ 50 kHz interaction rate for Pb-Pb, while in p-p and p-A mode the interaction rate can be kept to 200 kHz. The physics signals of interest for ALICE are in general complex to separate, and therefore not amenable to hardware triggers. For these reasons ALICE will require a very different triggering strategy from the current one and hence a new Central Trigger Processor is needed. Custom instrumentation of the CTS is required to cover all of the ALICE experiment requirements, (e.g. select all possible interactions). The new design of the CTS must have a combination of continuous readout and minimum bias trigger. However, there will be some detectors that will not be upgraded, so the CTS will provide backwards compatibility, making the CTS more complicated.

For Run 3 the CTS will keep the concept of a CTP and LTUs as detector interfaces. The electronics of the CTS will be based in a new universal board, called ALICE Trigger Board

(ATB), which can be used in both the LTU and CTP roles. The ATBs of the CTS will be placed in the ALICE experimental cavern in a site with radiation (AUX25-CRX), therefore the components of the CTP could be devices with a moderate radiation tolerance.

4.2 ALICE Trigger Board Design

After several discussions, the ALICE-CTP group decided to design a universal electronic board, which can be used as CTP or as LTU, depending of the role of the ATB. The design of the Printed Circuit Board (PCB) of the ATB is quite complex (almost 40 pages of schematic capture), and is based on 20 layers with following properties:

- I-TERA MT40 material (Special for high-speed digital multilayer).
- No blind vias
- All clocks traces from PLL to FPGA with same length
- All high speed links designed with 100 Ohm characteristic impedance.
- FMC links designed according to Faster Technology recommendations.
- Maximum 500 ps difference for all high speed links.
- The routing of the DDR 4 memories was designed according to Xilinx recommendations[22].
- High speed links with minimum through hole vias and track stubs.
- The transition points placed as close as possible to existing ground vias.

As shown in figures 4.1 and 4.2, the ATB is based on a Kintex UltraScale (XCKU040-2FFVA1156E) FPGA as main device, including 2 GB of DDR4 memory, portioned so as to allow adequate storage of snapshot data, a universal FMC connector (using a custom mezzanine card for 96 LVDS inputs/outputs in the CTP case or to a commercial mezzanine card with and additional eight optical connections in the LTU case), a 12 slot cage for optical input/output. These slots will be used according to the user requirements (e.g typical

4. ALICE Central Trigger System (Hardware Implementation)

4.3 ALICE Trigger Board Design (Mechanical Design)

configuration to detector in the lab are; 1 GBT, 1 ONU and 1 OLT), an optical SFP+ link to O² (or dedicated Trigger) PC using IPbus protocol for monitoring and control. An electronic Ethernet SFP+ module, instead of an optical module, will be used for IPbus communications when using the ATB in the lab, 2 external PLLs (Si5345) which provide excellent jitter reduction, useful to provide a clean LHC clock to detectors, are fully programmable via a serial interface link (I²C or SPI), including two Texas Instrument power controllers (UCD90120A).

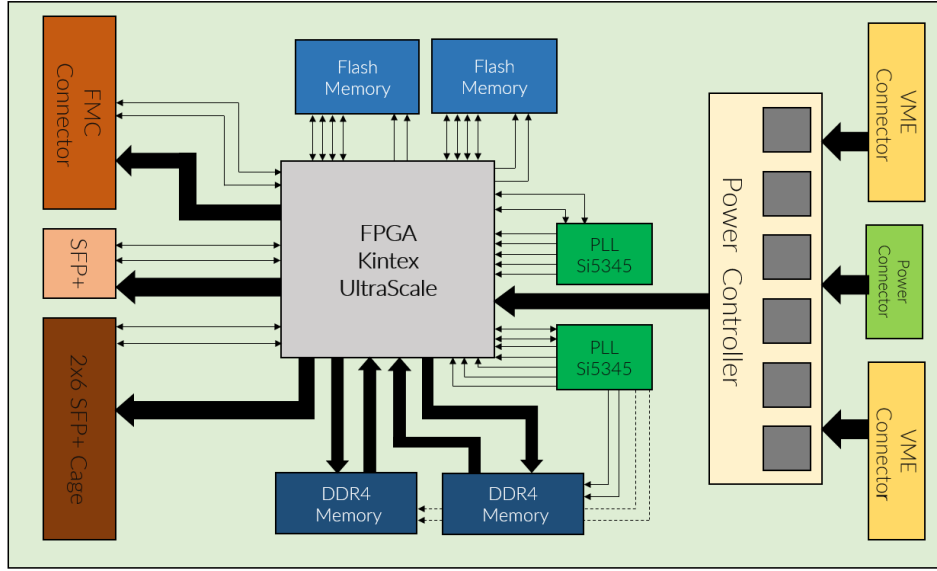


Figure 4.1: ALICE Trigger Board (Simplified Block Diagram).

4.3 ALICE Trigger Board Design (Mechanical Design)

In parallel with the PCB design of the ATB, the mechanical design was started, the main task in the stage, was to elaborate the mechanical drawings of the front panels for both roles (CTP and LTU) of the ATB.

At the beginning of the design the use of the CAD software was extremely useful to give us a clear idea of how the ATB would look like. To allocate all functionalities and indicators of the ATB, the front panel has a size of 3 VME slots (see figure 4.3). The table 4.1 show the

4. ALICE Central Trigger System (Hardware Implementation)

4.3 ALICE Trigger Board Design (Mechanical Design)

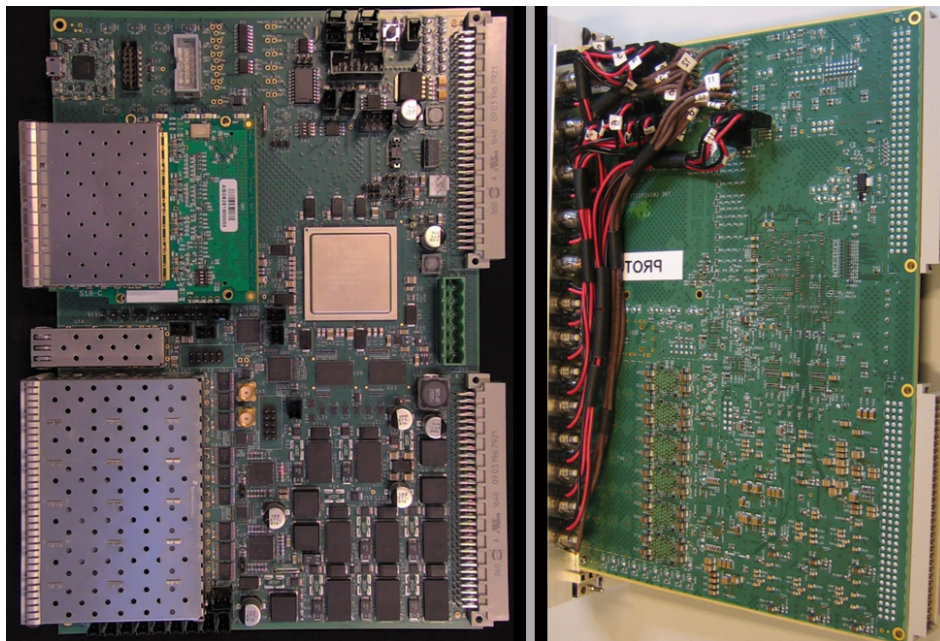


Figure 4.2: ALICE Trigger Board, Top view (left). Bottom view (right)

list of the components of the front panel.

As is shown in the CAD drawing (figure 4.4), the ATB is a 6U VME-type board a will use the existing CTP/LTU VME backplane is used only for powering of ATB. (It will not be to program or communicate with this board via VME), with the board using $+5V/10A$ and $\pm 12V/1A$, and any other required voltages being generated on the board using DC-DC converters. The ATB can be reconfigured remotely via a USB-JTAG connector.

All inputs/outputs to or from the ATB are performed via the front panel, the connections can be summarized as :

- A USB-JTAG connector for configuring the FPGA. When using this device in the ALICE cavern, the JTAG will be connected to a Trigger PC located on the surface via USB to Ethernet module (Anywhere© USB), which makes an interface between USB and Ethernet.
- Twelve optical connections, (can be used as OLT, ONU or GBT).
- One single optical connector (special to control and monitoring).

4.ALICE Central Trigger System (Hardware Implementation)

4.3 ALICE Trigger Board Design (Mechanical Design)

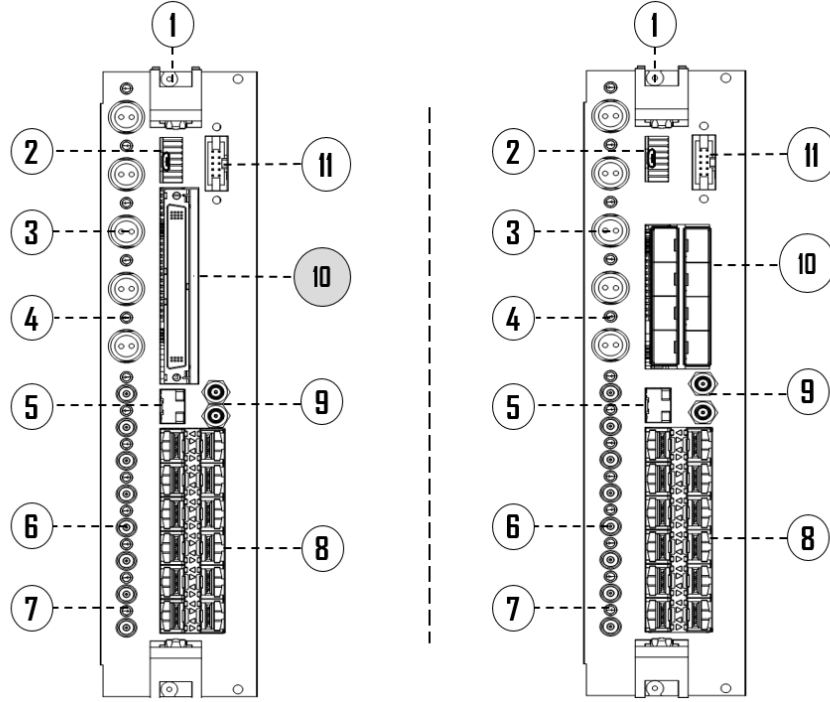


Figure 4.3: Front Panel of the ALICE Trigger Board. CTP (left), LTU (right)

Table 4.1: ALICE Trigger Board Components

N°	Description
1	Handles (ELMA 81-096)
2	USB-JTAG module (Diligent JTAG-SMT2)
3	LEMO 00B (LEMO.EGG.00.302CLL)
4	LEDs 3 mm (panel Mount)
5	SFP Cage (Molex 7441-10001)
6	LEMO 00B (LEMO.EGG.OB32)
7	LEDs 3 mm (panel Mount)
8	2x6 SFP Cage (TE connectivity 20007562-5)
9	SMA connectors (LHC Clock)
10	FMC CTP Card
	FMC Card (FM S-18)
11	PM Bus Connector

4. ALICE Central Trigger System (Hardware Implementation)

4.3 ALICE Trigger Board Design (Mechanical Design)

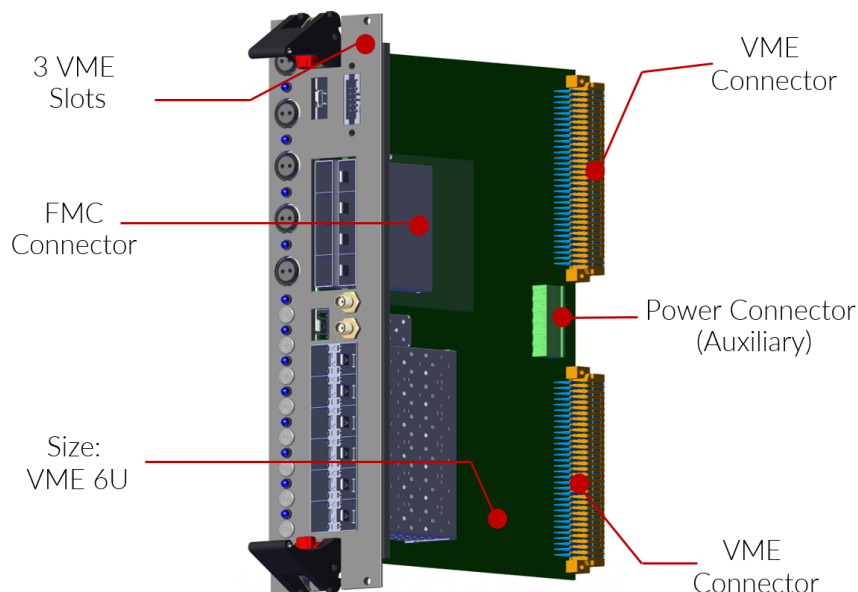


Figure 4.4: ALICE Trigger Board as LTU (Isometric view)

- One FMC-HPC connector
- Eight LEMO 00B ECL connectors
 - One for the LHC bunch-crossing (BC) signal
 - One for the LHC Orbit signal
 - Two outputs for scope
 - TTC channel A and B outputs to TTCex board (for detectors using the existing TTC system)
 - Pulser input (for pulser trigger input in *stand-alone*)
 - Spare i/o
- Five LVDS LEMO connectors
 - Two for LM and L0 outputs which can be used for detectors requiring LM or L0 trigger via LVDS copper cable, e.g. CPV, HMPID, ZDC.
 - One for BUSY in signal from detector.

4.ALICE Central Trigger System (Hardware Implementation)

4.3 ALICE Trigger Board Design (Mechanical Design)

- One for BUSY out to be sent to CTP board.
- One for FAST LM trigger input, direct from CTP. (ITS, TRD, CPV, HMPID, ZDC).

The ATB in LTU role, has two different modes of operation:

- **Global**, in this configuration, the ATB serves as interface between the CTP and detector readout electronics; the board performs the necessary conversion of signal levels and provides some on-line monitoring options.
- **Stand alone**, in this configuration, the ATB fully emulates the CTP protocol and enables detectors to carry out development, test and calibration tasks independently of the CTP, at remote sites, or at times when the CTP is either not available or not required.

During the design process, the CTP group decided to provide the ALICE community with a portable version of the ATB, which can be used for the ALICE detector in their laboratories, this ATB portable is based on an ELMA Guardbox 33 case and two AC-DC power supplies +12V/10A and $-5V/3A$. plus an internal Fan for cooling, the case design of the ATB in its portable version is shown in figure 4.5.

The ATB in CTP mode has to receive up to 34 trigger inputs in LVDS format, so a custom FMC-CTP has been designed and developed for this purpose. The design of the FMC-CTP is in compliance with the dimensions of the FMC VITA 57 standard [23]. In the CAD drawing of the FMC-CTP (figure 4.6) a Samtec SEAF type connector can be seen which has been chosen for the input cable as its size fits the FMC card. A corresponding SEAC connector is used on the cable which brings the trigger inputs from a patch panel to the CTP board, the second end of the SEAC cable is a customized cable with the differential LEMO connectors.

Using the ATB capability to support up to 20 high speed links, compatibility tests of FM S-18 card with ATB have been performed. The FM-S18 Octal SFP/SFP+card provides the following capabilities:

- Utilizes the high speed differential pair channels of the HPC connector.

4.ALICE Central Trigger System (Hardware Implementation)

4.3 ALICE Trigger Board Design (Mechanical Design)

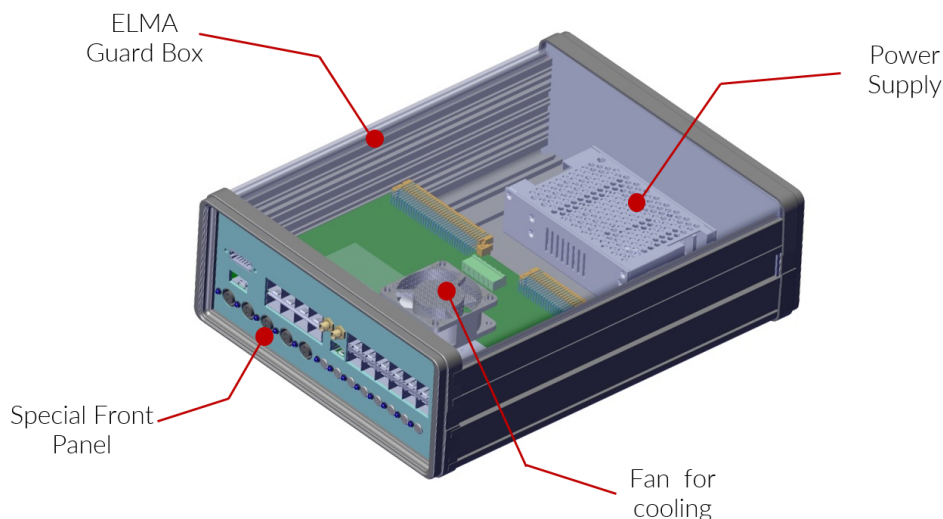


Figure 4.5: ALICE Trigger Board portable version (CAD Drawing)

- Supports up to 8 SFP/SFP+ modules
- Connects high speed serial I/O directly into multi-gigabit transceivers of supported FPGAs on compatible carrier cards
- Support either 2.5 volts or 1.8 volt FMC signaling
- Two programmable reference clocks
- 8 host controlled LED status indicators
- 4 host readable switches
- Host accessible serial EEPROM

It is important to mention that the company does not have access to the CAD drawing; therefore, in collaboration with them we made the CAD drawing according to the specifications that were provided to us. The CAD drawing of the board (FM-S18) is shown in figure 4.7. This drawing helped us to visualize the ATB (LTU role) in a configuration that the ITS and MFT detectors could use.

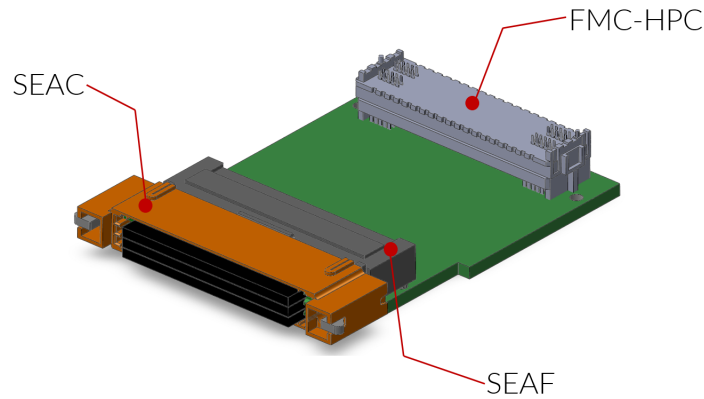


Figure 4.6: FMC-CTP card (CAD Drawing)

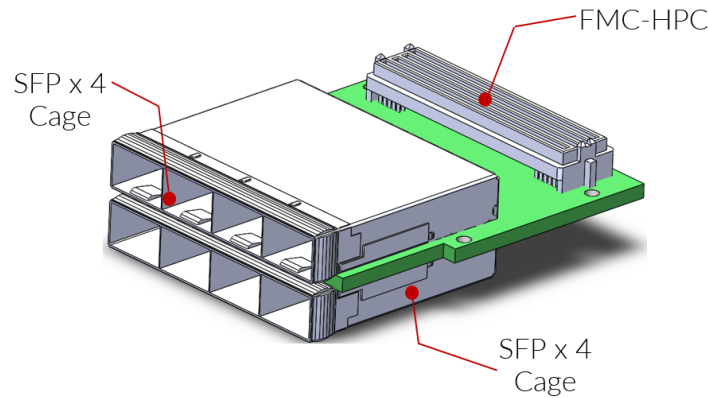


Figure 4.7: FMC-SFP card (CAD Drawing)

4.4 Field Programmable Gate Array

The main component of the ATB is a Kintex UltraScale (XCKU040-1FFVA1156C) Field Programmable Gate Array (FPGA). A FPGA [24] is an advanced, configurable semiconductor device whose final functionality is defined after its manufacturing. Its simplified architecture is shown in Figure 4.8. It consists of a logic fabric, global routing network, a ring of I/O blocks, and various functionality predefined components (FPC). A logic fabric contains a matrix of logic blocks (LB) that can be configured to execute combinational functions of different levels

of complexity. A global routing network connects various FPGA components together, and it usually occupies about 80 % of the total device area.

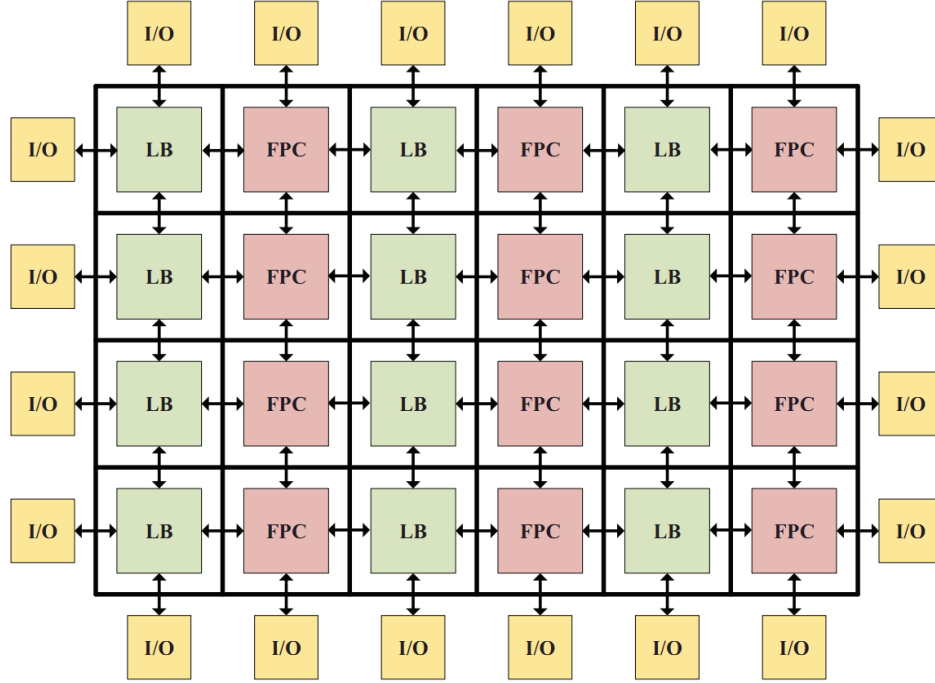


Figure 4.8: Simplified FPGA architecture (from [24]).

The I/O blocks interface off-chip signals operating in different I/O standards to the internal FPGA routing network. The FPGA can include some extra functionality predefined for example: a built-in memory block or external memory controller; and embedded Digital Signal Processor (DSP) block, multiplier or processor; clock Phase-Locked Loop (PLL) or Delay-Locked Loop (DLL); high-speed serializer-deserializer, data transceiver; analog-to-digital converter. Frequently, these components are optimized for high speed performance. Currently FPGAs are widely used in High Energy Physics, the FPGAs are often the alternative of using Application Specific Integrated Circuit (ASICs). For example some differences between FPGAs and ASICs are:

- **Advantages**
 - reconfigurability
 - fast implementation

- low cost for small quantities

- **Disadvantages**

- lower clock frequencies
- lower density of logic blocks
- higher power consumption at comparable functionality

Kintex UltraScale FPGAs [25] are High-Performance FPGAs with a focus on price/performance, using both monolithic and next-generation stacked silicon interconnect (SSI) technology. High DSP and block RAM-to-logic ratios and next-generation transceivers, where high-speed transceivers operates at TTC-PON frequency (9.6 Gbps). The resources of the Kintex UltraScale FPGA is shown in table 4.2.

Table 4.2: Kintex UltraScale Resources

	Kintex UltraScale FPGA
System Logic Cells (K)	318-1,451
Block Memory (Mb)	12.7 - 75.9
DSP (Slices)	768 - 5,520
DSP Performance (GMAC/s)	8,18
Tranceivers	12 - 64
Max. Tranceivers Speed (Gb/s)	16.3
Max. Serial Bandwidth (full duplex) (Gb/s)	2,083
Memory Interface Performance (Mb/s)	2, 400
I/O Pins	312 , 832

4.5 Testing and Results

In the first production of ATB modules, 25 ATB modules were produced, including 8 VME boards (2 prototypes) and 17 portables (ELMA boxes) and they have been extensively tested. For this task my contribution can be divided in 3 stages.

- Development of the firmware for qualification of the high speed links on ATB for different bandwidths, using the IBERT functionality available in the Xilinx FPGAs. To qualify the high speed links of the ATB connected to FMC-HPC connector two different mezzanine cards, The KYA card and the FM-S18 Octal SFP/SFP+ FMC mezzanine card were used, comparing the behaviour between ATB and KCU105 evaluation card.
 - 1 Gbps. Operational bandwidth of the IPbus protocol.
 - 4.8 Gbps. Operational bandwidth of the GBT protocol.
 - 9.6 Gbps. Operational bandwidth of the TTC-PON protocol.
- Testing of the all ATBs using a special firmware called IBERT+.
- Design, implementation and testing of IPbus slaves in ATB for the next interfaces:
 - Firmware to activate the Internal Configuration Access Port (ICAP) functionality
 - Access to Flash memories via IPbus - Serial Peripheral Interface (SPI)
 - Configuration and control of the PLLs and reading of the status of all SFPs via IPbus- I^2C
- Design, implementation and testing of IPbus slaves for DDR4 interface.

4.5.1 Evaluation of the high speed links in ATB

It is well known that a primary and effective measure of data integrity is the so called Bit-Error-Rate (BER). In electronics and in digital communications systems BER can be defined as the estimated probability that any bit transmitted through the system will be received in error. In practical tests, the BER is measured by transmitting a finite number of bits through the system and counting the number of bits received. The ratio of the number of bits received erroneously to the total number of bits transmitted is the BER (eq 4.1). This measured ratio is affected by many factors including: signal noise, distortion, and jitter. It is important to take care of the quality of the BER estimation, because the ratio increases as the total number of transmitted bits increases. In the limit, as the number of transmitted bits approaches infinity, the BER becomes a perfect estimate of the true error probability [26], but

for the most of cases the test is defined only if the BER is less than a predefined threshold.

$$BER = \frac{N_{Err}}{N_{bits}} \quad (4.1)$$

An important parameter in the BER estimation is the confidence level (CL), which can be defined as the percentage of tests that the system's true BER is less than the specified BER. It is possible to calculate the confidence level using the equation 4.2 [26].

$$CL = 1 - \exp^{-N_{bits} \times BER} \quad (4.2)$$

4.5.1.0 IBERT Evaluation

For the first test of the ATB prototype, a special firmware called “IBERT_test” was developed; the basis of this firmware is the Xilinx IP Integrated Bit Error Ratio Tester (IBERT), which is designed for evaluating and monitoring the GTH transceivers. This firmware includes pattern generators and checkers that are implemented in FPGA logic, as well as access to ports and the dynamic reconfiguration port attributes of the GTH transceivers. The IBERT eye scan provides a picture of the serial signal error distribution. To cover the bandwidths of the TTC-PON and GBT protocols, the IBERT_Test was running at 10 Gbps, 9.6 Gbps, 4.8 Gbps and 1 Gbps. In figures 4.9 and 4.10, the clock scheme and GTH channels distribution of the IBERT_test is shown. The parameters of the BER measurements are shown in table 4.3. All of the GTH channels in ATB (20 High speed links), were checked for errors by transmitting and receiving PRBS-31 pattern data and different bandwidths, no errors was detected and the maximum BER reached was lower than 6.12×10^{-15} , with confidence level of $\sim 99\%$.

An eye diagram is a common indicator of the quality and signal integrity in high-speed digital transmissions. The signal to noise ratio of this high-speed data signal is directly indicated by the amount of eye closure or eye height. Due to the very high number of eye diagrams (2 ATB prototypes x 4 Tx Diff Swing x 4 bandwidth = 620 Eye diagrams), a collection of TCL scripts were written to automate the test. The figure shows the eye diagram of 20 GTH links at 4.8 Gbps (GBT bandwidth), with an excellent eye opening.

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4.5 Testing and Results

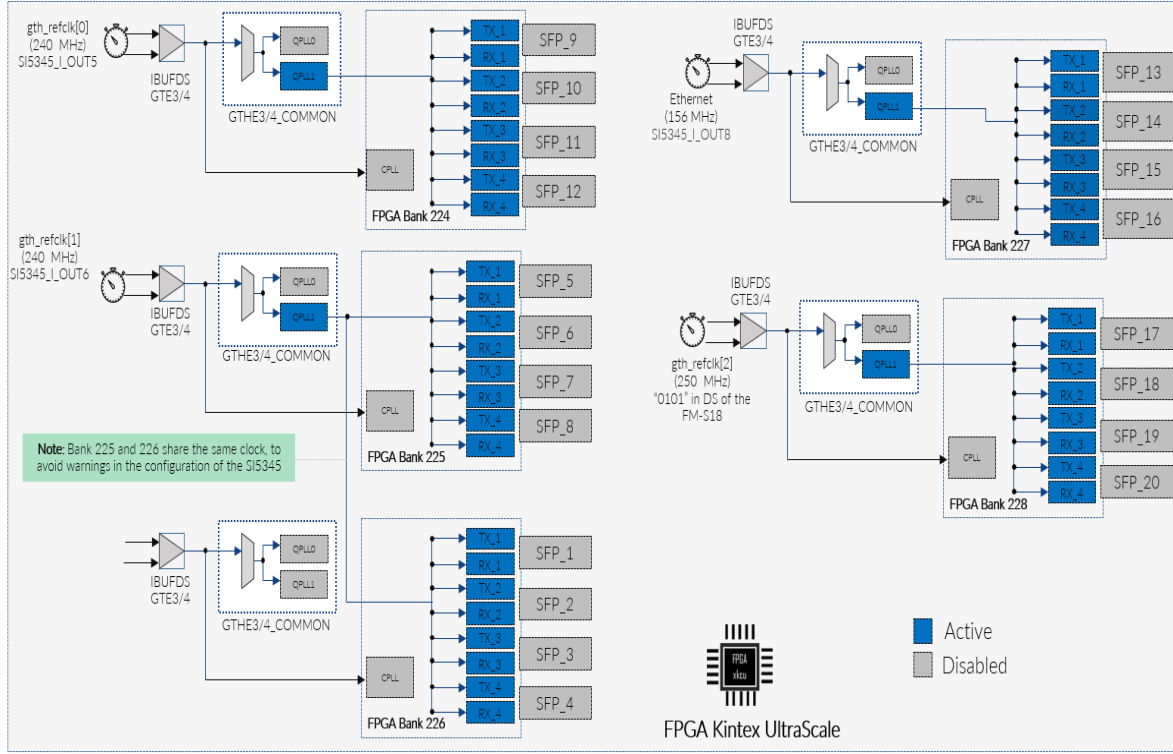


Figure 4.9: Clock scheme of the IBERT_test firmware.

Table 4.3: BER Measurements

Parameter	Value	Units
Bandwidth	10, 9.6, 4.8, 1	Gbps
PLL Reference	240, 250	MHz
Scan Type	2D Full Eye Scan	
TX Pre Cursor	0.00 to 12.96	dB
TX Post Cursor	0.00 to 6.02	dB
TX Diff swing	1080, 880, 660, 390	mV
DFE Enable	ON	
Test Pattern	PRBS-31	
BER	$10E^{-15}$	

4. ALICE Central Trigger System (Hardware Implementation)

4.5 Testing and Results

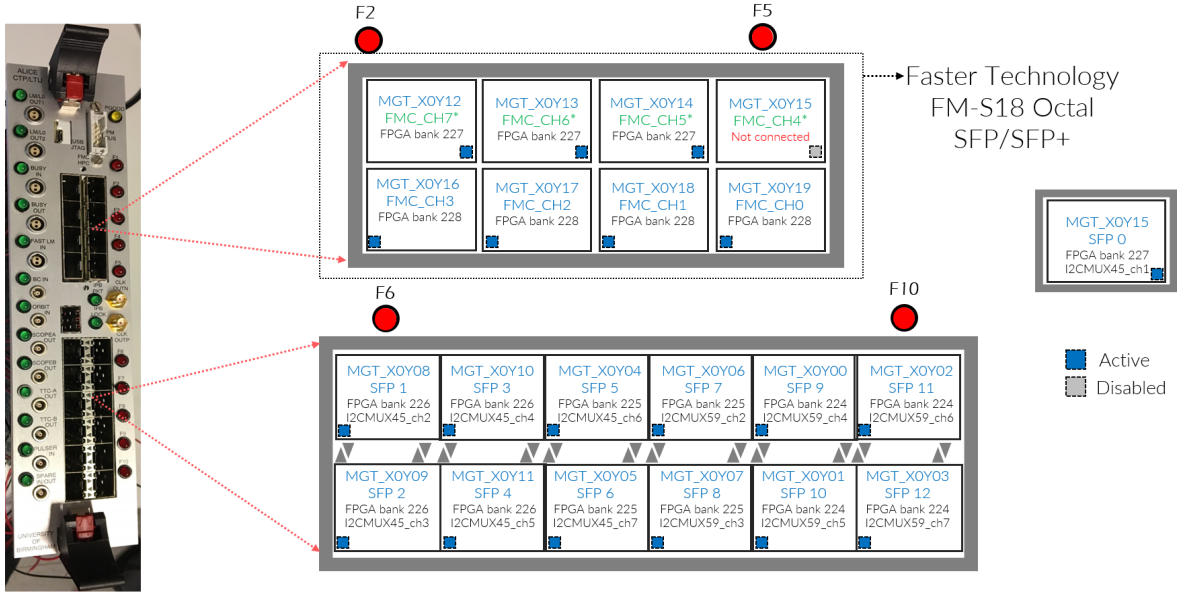


Figure 4.10: Channels distributions of the IBERT_test firmware.

During the test, the results indicated that some attenuation problems are present in the ATB in the GTH channels of the FMC connector (X0Y12 to X0Y19). In order to prove that problem is not located in the design of the ATB, different mezzanine cards were tested, and at the end, for comparison, the Xilinx evaluation card (KCU105) was included in the test. In Figure 4.13 it is clear to see that the FS-S18 mezzanine card has attenuation problems; this behaviour was reported to the Faster Technology company.

The results of this test give us a first approximation about the performance of the GTH channels in the ATB prototypes (see figure 4.14), the GTH links showed an excellent performance at different bandwidths with a very good eye opening, but we have to do a more stringent test (BER 10E-20) to ensure the correct behaviour of the ATB high speed links during LHC-Run 3.

4. ALICE Central Trigger System (Hardware Implementation)

4.5 Testing and Results

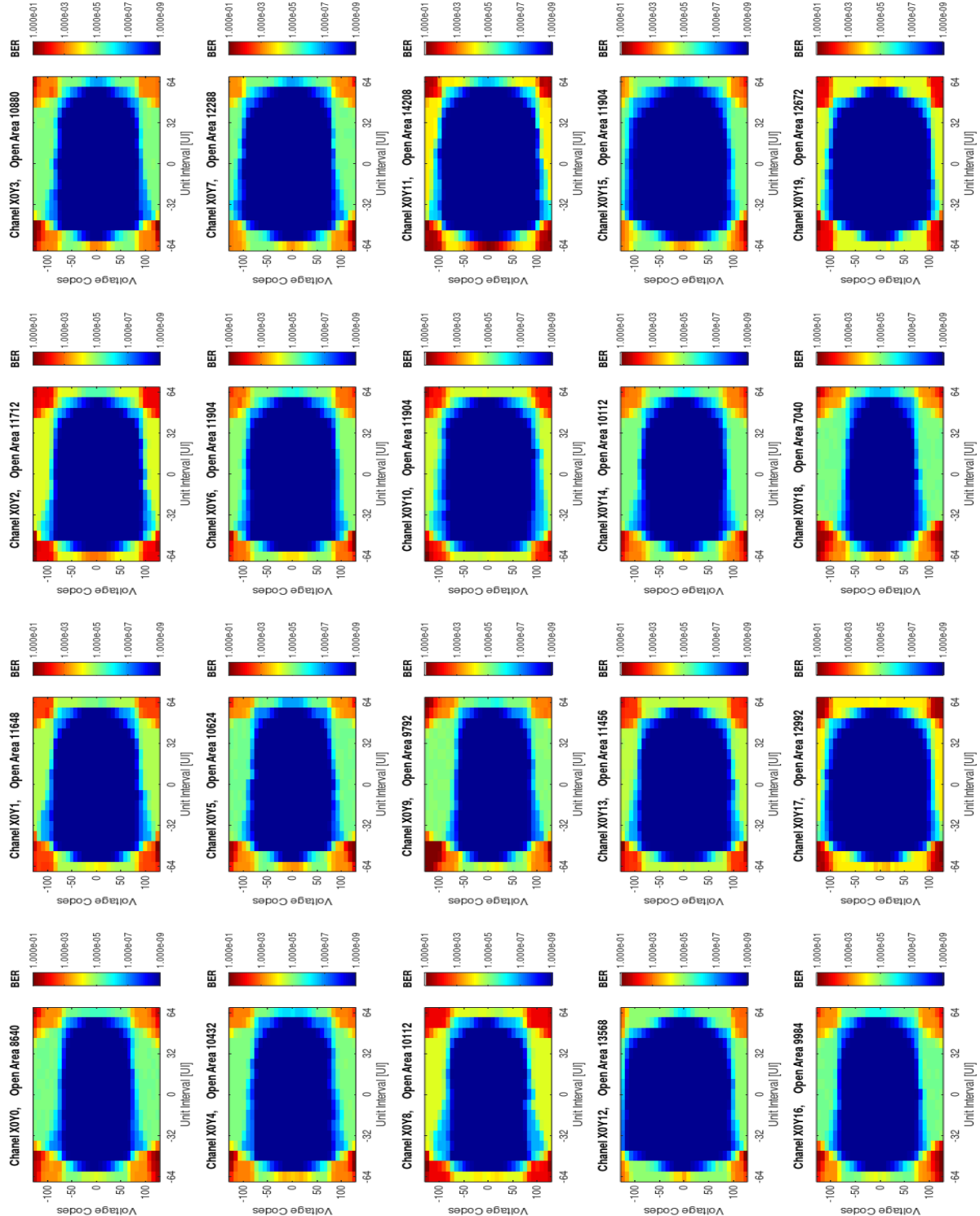


Figure 4.11: Eye diagram of 20 GTH links in ATB, running at 4.8 Gbps (GBT bandwidth).

4. ALICE Central Trigger System (Hardware Implementation)

4.5 Testing and Results

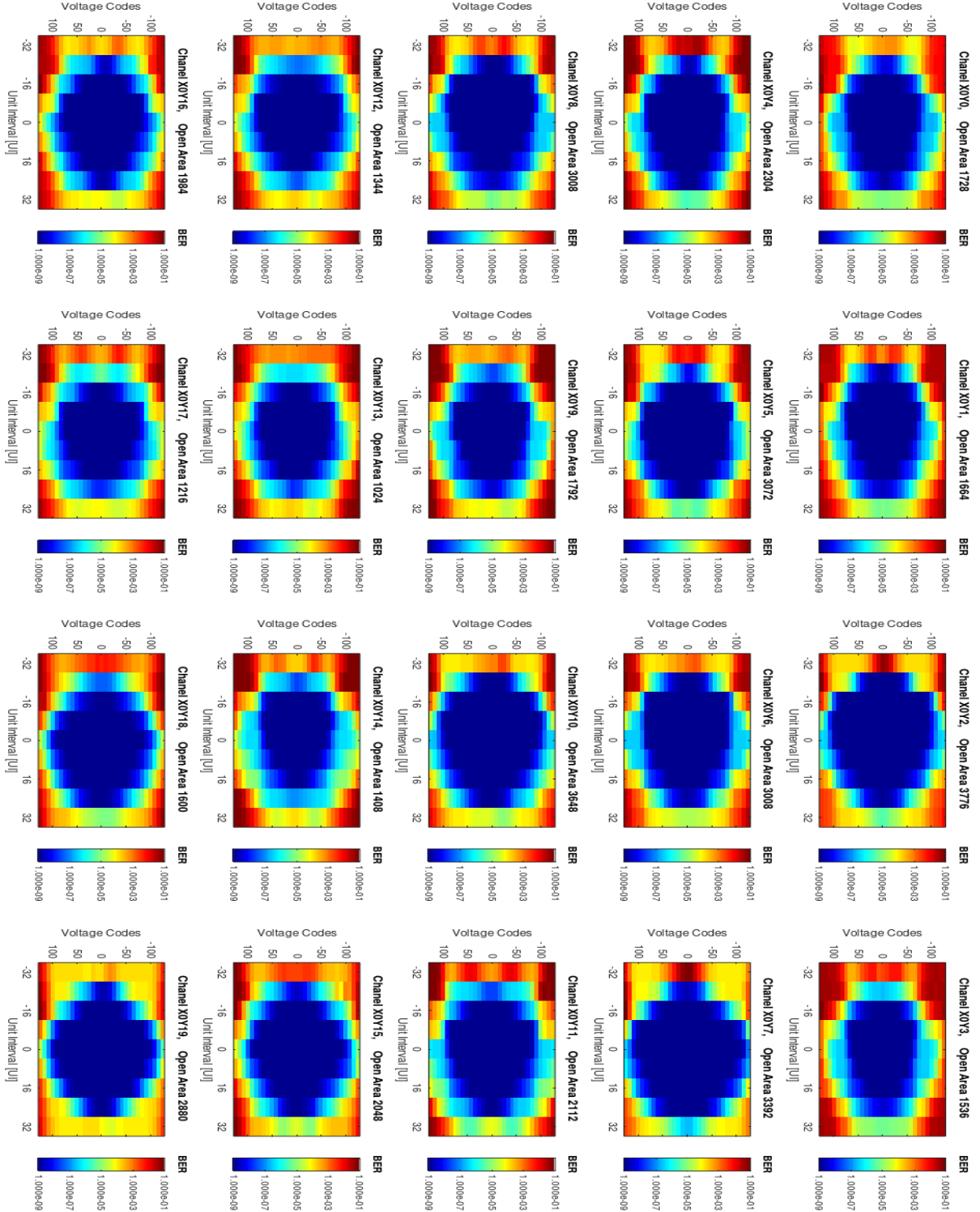


Figure 4.12: Eye diagram of 20 GTH links in ATB, running at 9.6 Gbps (TTC-PON bandwidth).

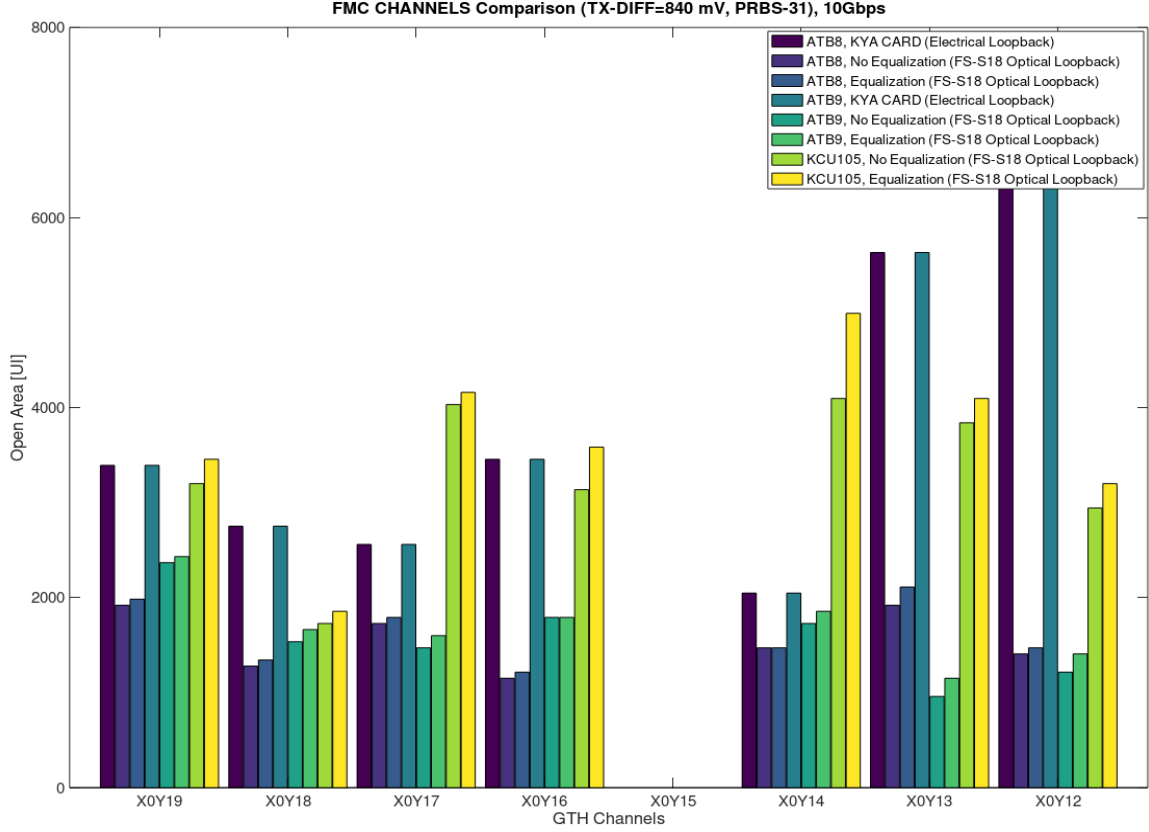


Figure 4.13: Eye aperture of GTH channels using KYA card, FS-S18 card and KCU105 board, (Channel X0Y15 in ATB is dedicated to IPbus). These results are subject to FPGA configuration.

4.5.1.0 IBERT+

To cover all requirements of the new ALICE-CTS described in previous chapters (e.g high interaction rate) the high speed links of the ATBs must have an excellent performance. The second stage in the evaluation of the ATBs, was to evaluate the high speed links (GTH channels) with a more robust firmware called “IBERT+ ¹”. This firmware is an extended version of the Xilinx IBERT design using a GT debugger software. The GT debugger is a powerful set of Tcl procedures allowing a low-level transceiver debug without adding any

¹Developed by ALICE-CTP group and Xilinx experts.

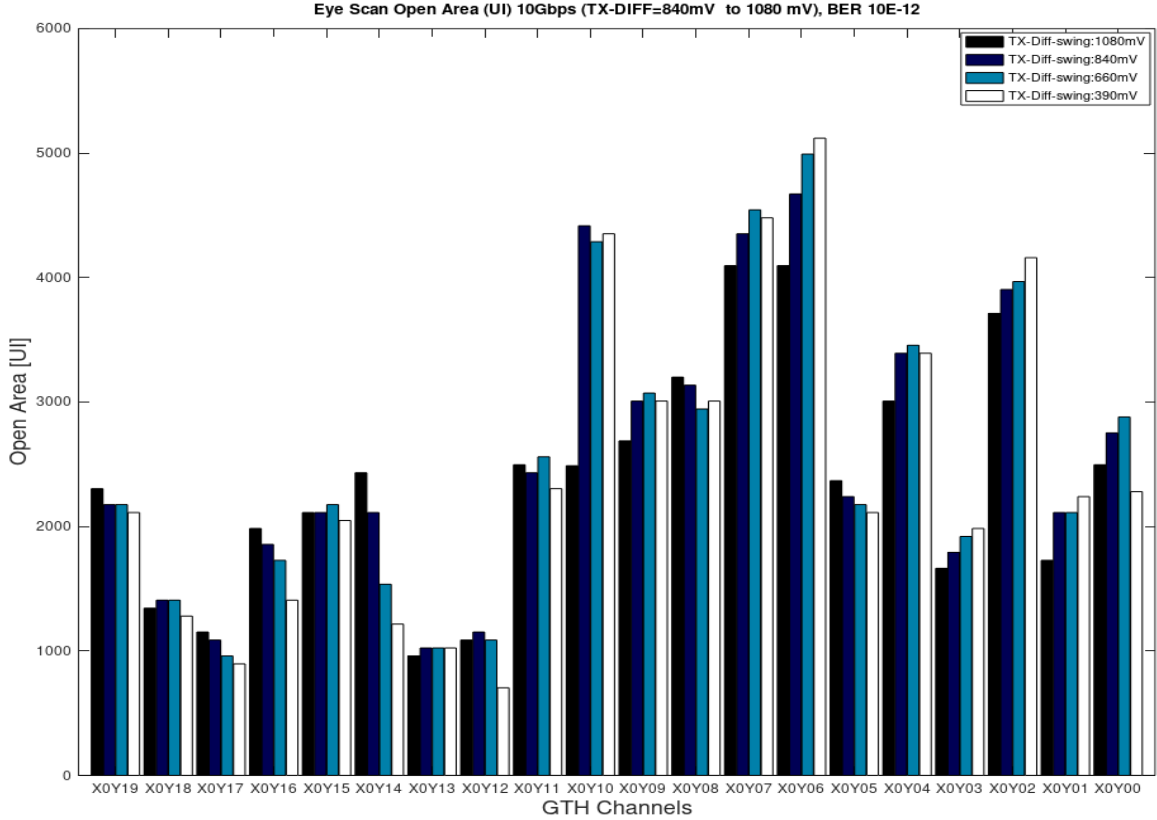


Figure 4.14: Eye Aperture in GTH channels in ATB prototype, Estimation BER 10E-12, TX_Diff_Swing scan from 390mV to 1080mV, Channels X012 to X019 connected to FM S-18. These results are subject to FPGA configuration.

additional HDL code to the design under test [27]. The GT debugger provides scripts with the methodology for the best equalization setup, power reduction and crosstalk analysis. For the BER estimation, the GT debugger uses a data sample equal to 10^{-9} , but the IBERT+ procedure involves a special algorithm for the study of the eye diagram and gives us a BER $< 10^{-20}$, by extrapolation, with CL = 99%. The setup of the IBERT+ used is shown in figure 4.15.

The record file provided by IBERT+ shows some important parameters such as estimated BER, vertical (Voltage) and horizontal (Time) aperture. These information allows a better qualification of the GTH channel. In order to have a better understanding, of the parameters

IBERT Configuration: Loopback

Data: PRBS 31

Bandwidth: 10Gbps

CL = 99 %

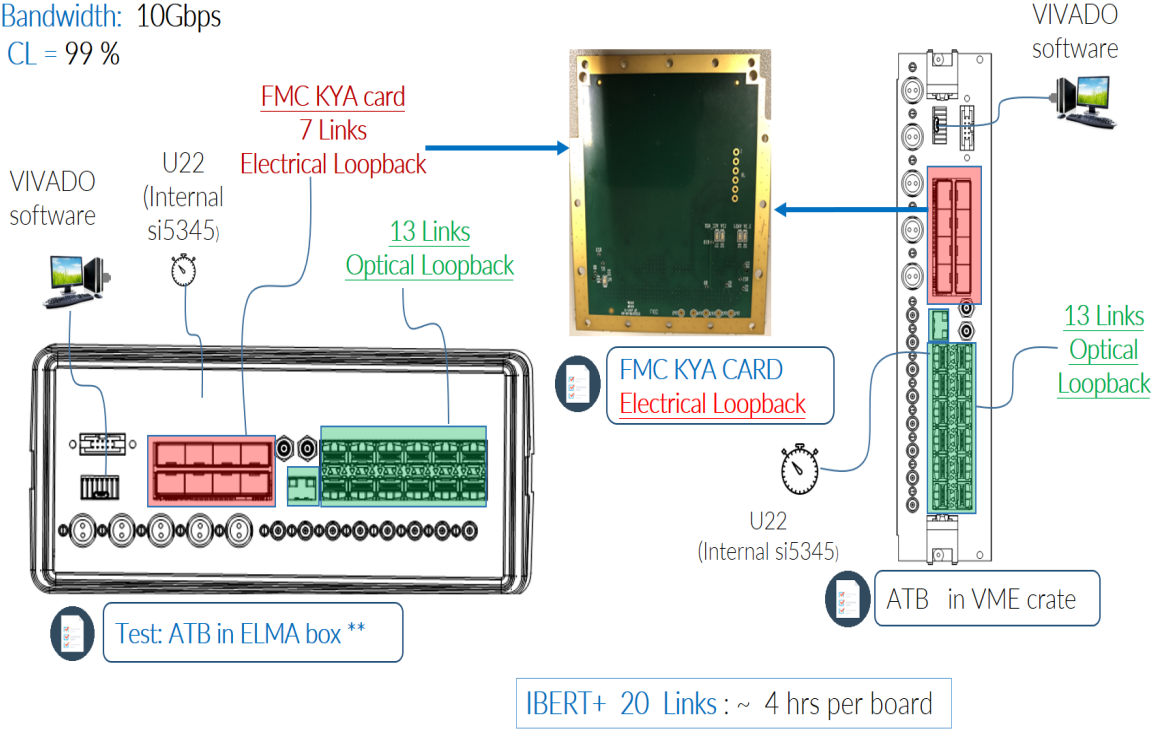


Figure 4.15: Block Diagram of IBERT+ setup, KYA card was used.

presented in the record files generate by IBERT+; in the figure 4.16 a eye diagram mesured in ATB using a Lecroy Serial Data Analyser (SDA) oscilloscope is presented. All ATB evaluated with IBERT+ have a plot, where the performance of their high speed links is presented; for example in figure 4.17 the result of the IBERT+ in ATB_14 is shown, but all ATBs were evaluated, see figures 4.19, 4.20.

The IBERT+ firmware was extremely useful in the evaluation of the all ATBs, during the first production phase (23 ATBs), because to get a BER equal to 10^{-16} using standard IBERT firmware could take almost 36 hours, while with IBERT+ an estimated 10^{-20} it took takes less than 4 hours. Two boards were found to have faulty channels giving a higher BER.

In summary, the high speed links of the ATBs (~ 400 links) were tested with an estimated

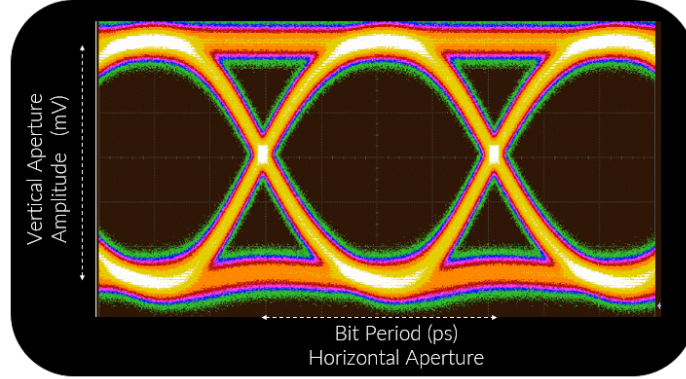


Figure 4.16: Eye Diagram measured in ATB using SDA, 10 Gbps, The signal to noise of the link is directly indicated by the amount of eye closure or Eye Height.

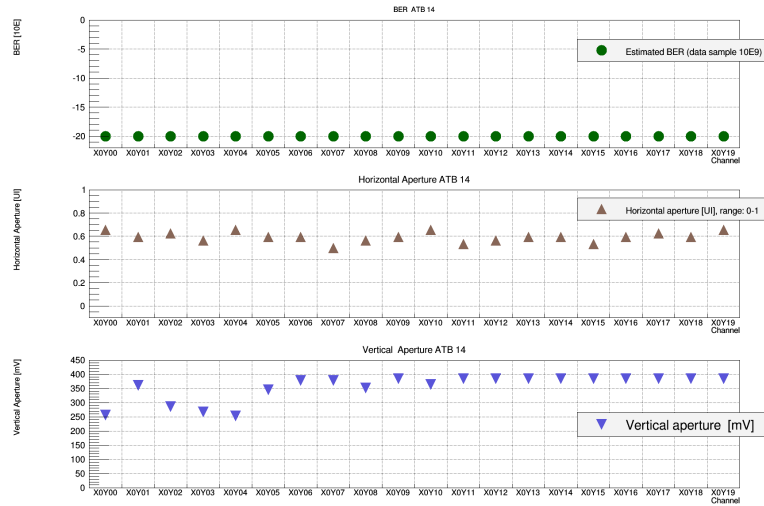


Figure 4.17: IBERT+ result in ATB.14, Estimated BER (Up), Horizontal Aperture (Mid), Vertical Aperture (Low).

Estimated BER based on data sample 10E9

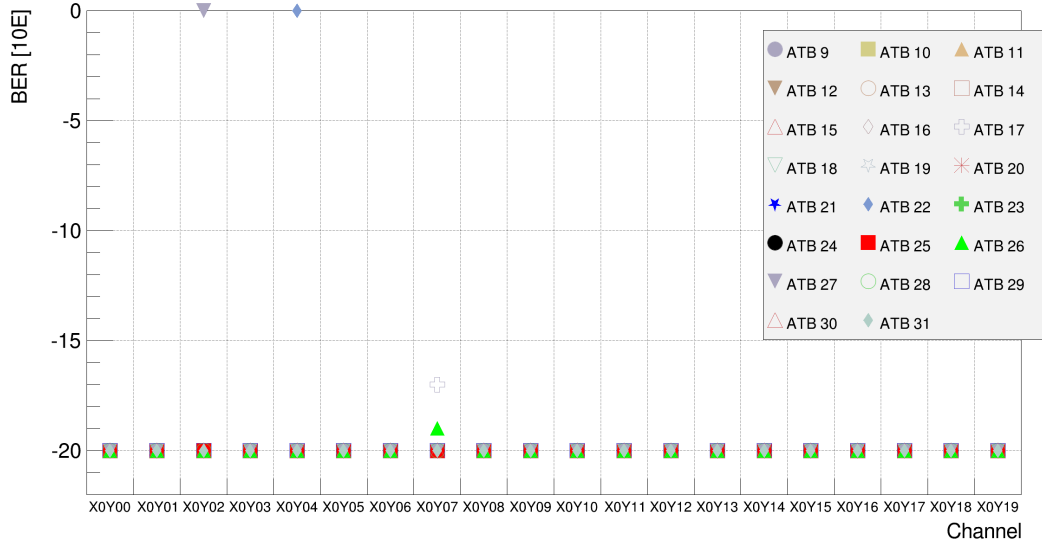


Figure 4.18: IBERT+ result Estimated BER for all ATBs.

Vertical Eye Aperture [mV]

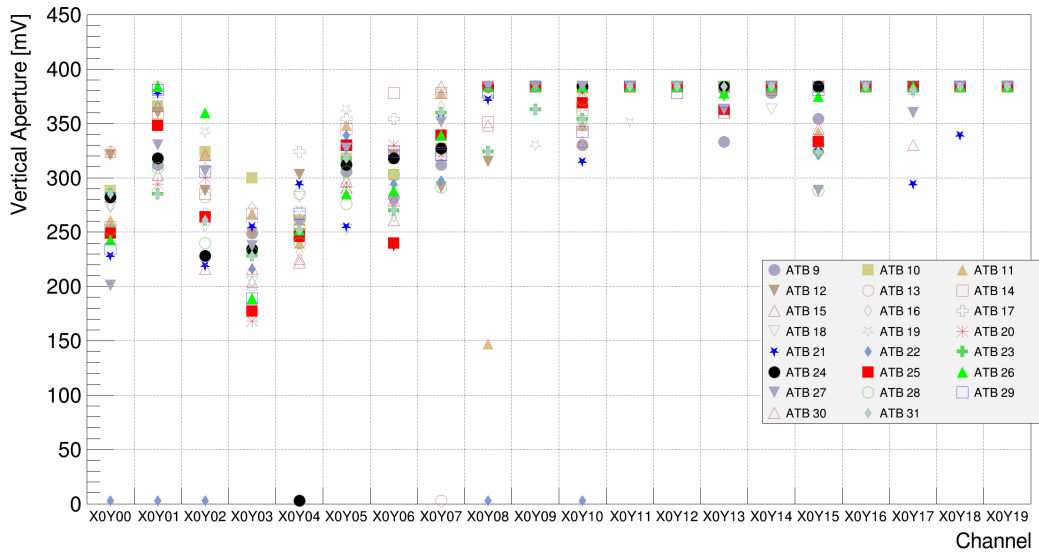


Figure 4.19: IBERT+ result vertical aperture (mV) for all ATBs.

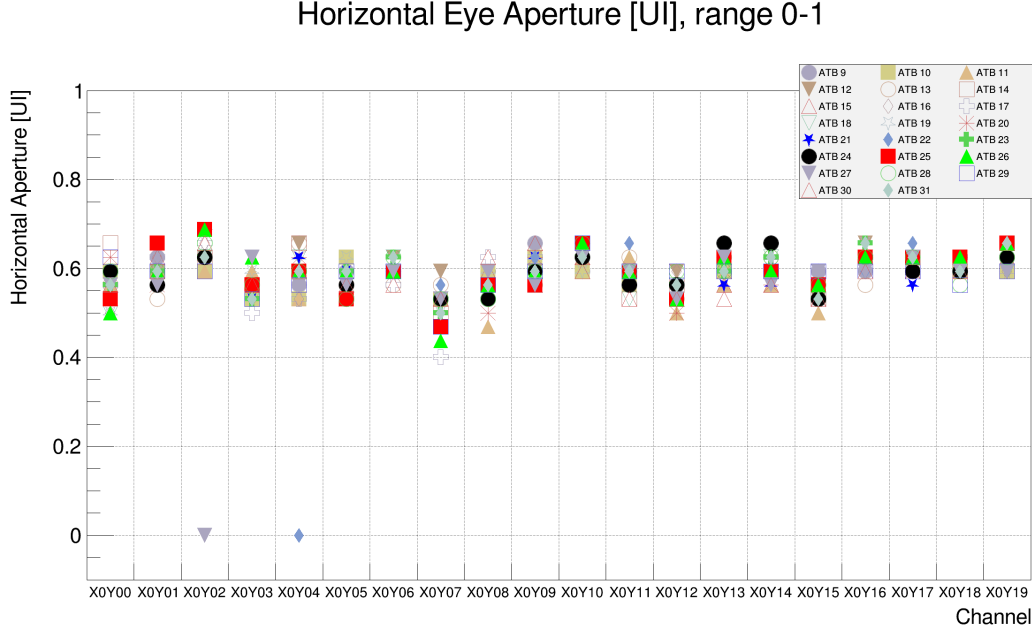


Figure 4.20: IBERT+ result horizontal aperture (UI) for all ATBs.

BER equal to $10E-20$ (by extrapolation), and the results of the test indicate that the high speed links fulfil the required specifications of ALICE for LHC-Run 3.

4.5.2 IPbus in ATB

The new CTS will re-use the water cooled VME crates used for the CTS during the LHC-Run2, and as described in the previous section, the ATB is a 6U-VME board but the VME connector is used only for power supply connector; for this reason the IPbus system will be the main interface to control and configure the complete CTS.

The IPbus system allows the control of hardware via a “virtual bus”, using a standard IP over-gigabit-Ethernet network connection. IPbus specifies a simple transaction protocol between the hardware and a software controller, which assumes an A32/D32 connection to slave devices connected to the hardware endpoint [28]. The current IPbus firmware implementation uses a UDP/IP protocol and a simple synchronous bus. Table 4.4 lists the

main IPbus operations.

Table 4.4: Operations supported by the IPbus protocol

Operation	Explanation
Single Write	Writes a single 32 bits in a location pointed by a 32 bits address
Single Read	Reads a single 32 bits value from a location pointed by a 32 bits address
Block Write	Writes N 32 bits values in N memory contiguous locations
Block Reas	Reads N 32 bits values from N memory contiguous locations
FIFO Write	Writes N 32 bits values in a single memory location
FIFO Read	Reads N times a 32 bits value from the same memory location.

This protocol is based upon the Wishbone protocol, and is compatible with Wishbone cores. However, there are two important differences:

- The master is not required to explicitly deassert strobe between cycles. However, it is guaranteed to deassert strobe or being a new cycle on the clock cycle following acknowledge (ack).
- Slaves are not allowed to tie ack high, and must deassert ack on the same clock cycle that strobe is deasserted. However, it *is* allowed to tie ack to strobe, if a zero-wait-state response is always possible.

The IPbus read and write transactions for a slave with and without wait states are shown in figures 4.21, 4.22.

Diagram 4.21 illustrates a write cycle to slave with one wait state; the bus idle for two clock cycles; then a read to a slave with zero wait states. Diagram 4.22 illustrates a Read Modify-Write transaction with a slave with zero wait states, followed immediately by two reads from a slave with one wait state.

The IPbus protocol has been already adopted by the CMS and ALICE experiments for current upgrade projects and it is being considered for a future ATLAS upgrade.

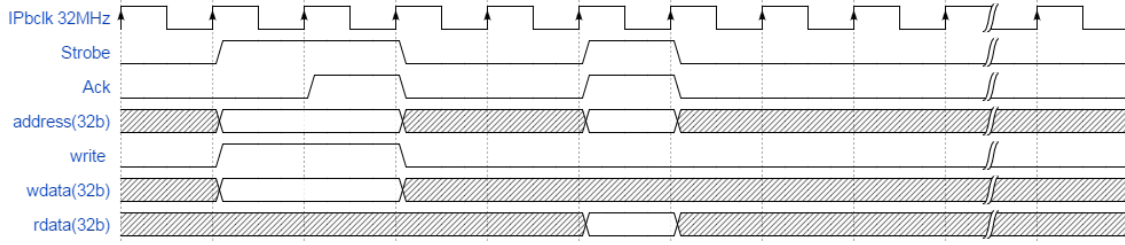


Figure 4.21: Standard IPbus transaction.

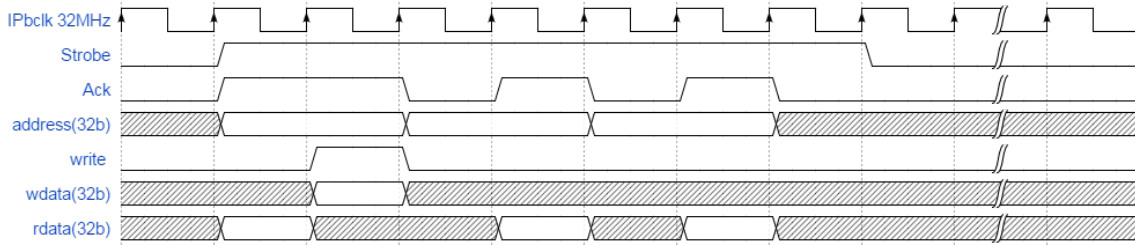


Figure 4.22: Zero delay IPbus transaction.

4.5.2.0 Test Logic Firmware

In order to cover all requirements of the CTS in ALICE for the LHC-Run 3, the ATB is equipped with several devices, each with the specific purpose of exploiting the full physics topics offered by the ALICE upgrade. For example the ATB include two PLLs (Si545) to deliver to detectors (FIT and TOF) an LHC clock signal as clean as possible. These PLLs are fully programmable via the I^2C interface; the ATB includes a flash memory (N25Q128A11) to store the FPGA firmware and can be accessed via SPI interface.

To evaluate the correct functionality of the devices connected to the FPGA in ATB, a special firmware was developed. This firmware allows to qualify the communication between IPbus and the devices (e.g PLLs, flash memories) using IPbus as a bridge to other interfaces (e.g I^2C , SPI). Figure 4.23 shows the simplified block diagram of the firmware.

I^2C Interface

The verification plan began with the evaluation of the IPbus to I^2C interface. A dedicated

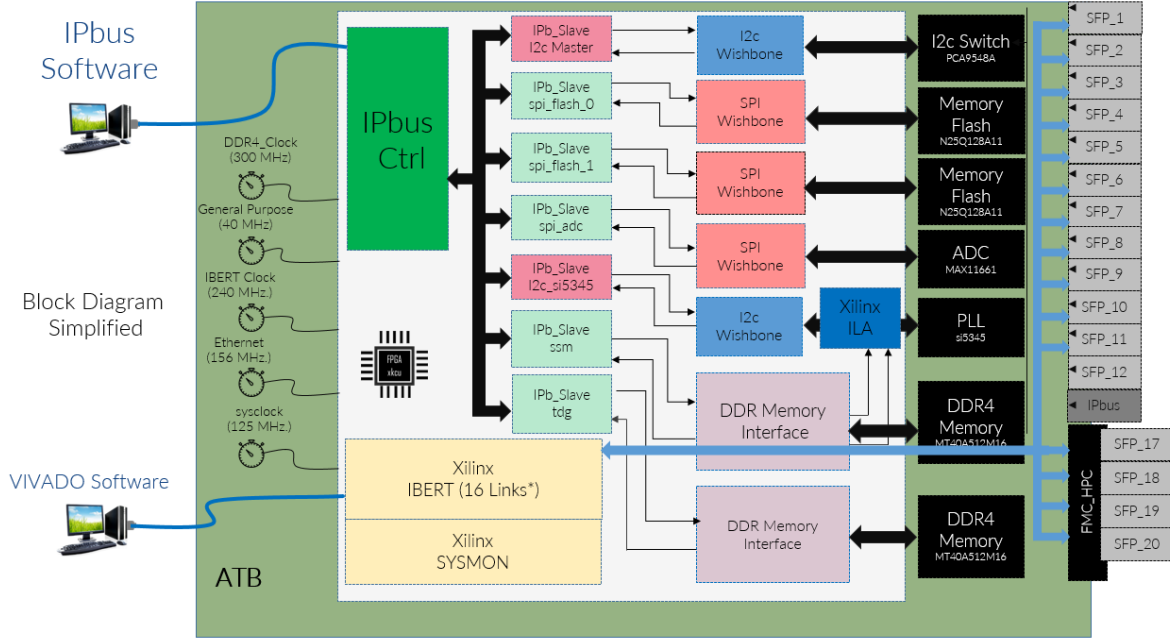


Figure 4.23: Block Diagram of the Test Logic Firmware.

IPbus slave was implemented, the IPbus slave support the WISHBONE I^2C interface [29]. The design responds to the read and write cycles initiated by the IPbus slave through the WISHBONE interface. It provides the correct sequences of commands and data to the I^2C slave device and then transfer the required data from the I^2C slave device through the two open drain wires. The configuration of the PLLs (Si5345), the access of the identification parameters and the read of the temperature of all SFP+ connected in the ATB were made. The result of the IPbus- I^2C interface is shown in figure 4.24.

Serial Peripheral Interface (SPI)

Since the location of the ATB in ALICE will not have free access, the remote configuration of the FPGA is crucial to keep the CTS working correctly. The ATB was designed with direct connection to the standard, four pin SPI interface of a serial NOR flash memory (N25Q128A11) for reading a store bitstream. As remote access of SPI flash memory, the ATB has routed dedicated pins to the FPGA primitive STARTUPE3. This primitive allows access to the flash memory.

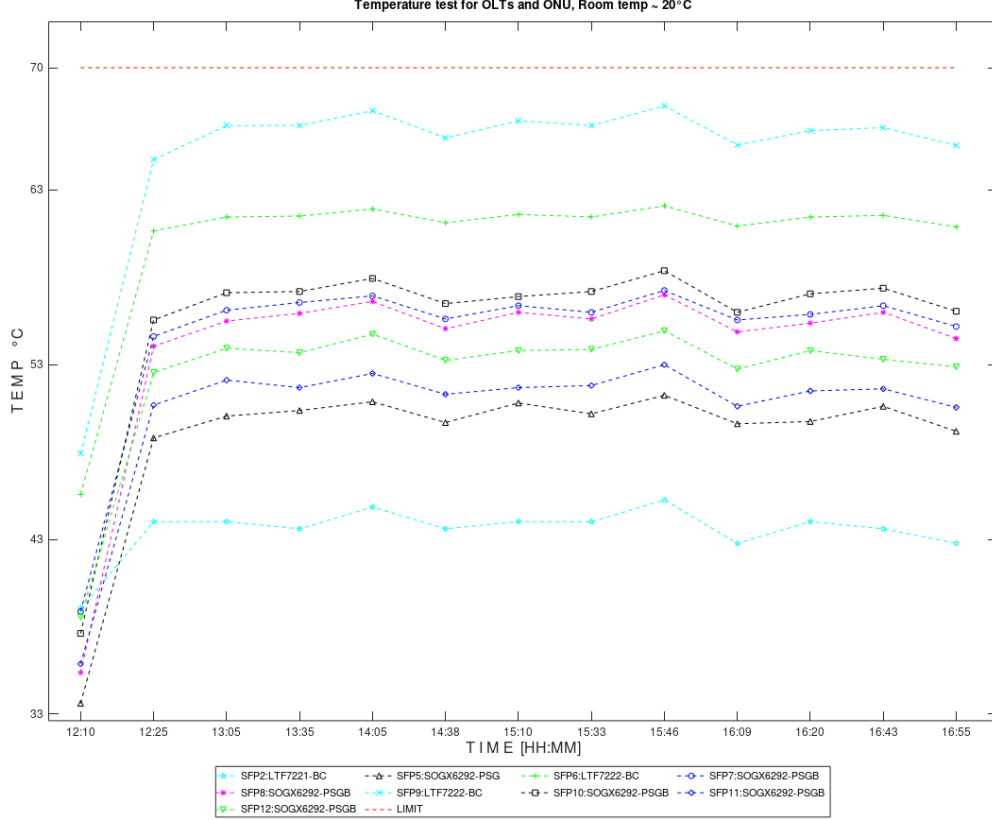


Figure 4.24: Temperature test on SFP+ connected in ATB , accessed via IPbus- I^2C interface.

To qualify the access of such flash memories a secondary firmware was added in test logic firmware, the basis of this firmware is the IPbus to SPI interface. Figure 4.25 shows the block diagram and log file.

Internal Configuration Access Port

Dynamic and partial reconfiguration are key differentiating capabilities of FPGAs. The FPGA in ATBs (Xilinx UltraScale) also support the partial reconfiguration at runtime, the handling of this reconfiguration in ATB can be done through the Internal Configuration Access Port (ICAP). Figure 4.26 shows the interface between IPbus and ICAPE3. ICAPE3 provides post-configuration access to the configuration functions of the FPGA from the FPGA logic.

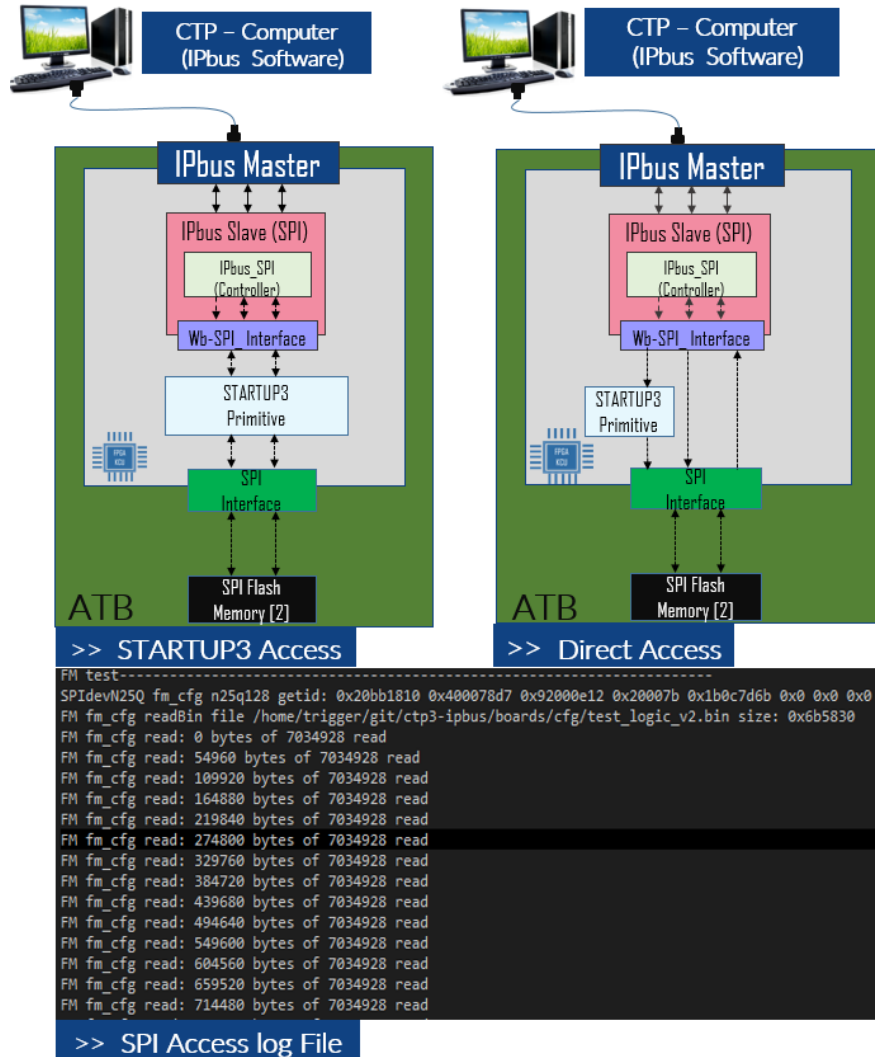


Figure 4.25: Block Diagram of the IPbus to SPI interface, (right) STARTUPE3 access, (left), log file of the IPbus to SPI interface (bottom).

Using this component, commands and data can be written to and read from the configuration logic.

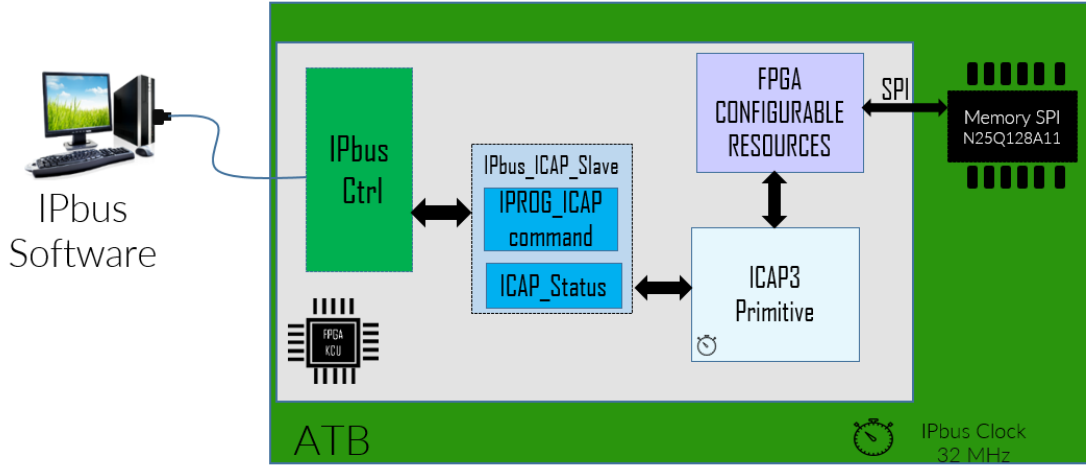


Figure 4.26: Block Diagram of the IPbus to ICAP interface

The commands (IPROG commands) necessary to active the reconfiguration process are listed in table 4.5. The interface IPbus to ICAP must follow the time diagram shown in figure 4.27 to activate the reconfiguration.

Table 4.5: IPROG commands to activate the ICAPE3 primitive.

Configuration (Hex)	Explanation
FFFFFFFF	Dummy Word
AA995566	Sync Word
20000000	Type 1 NOOP
30020001	Type 1 Write words to WBSTAR
00000000	Warm boot start address (Load the desired address)
30008001	Type 1 Write 1 words to CMD.
0000000F	IPGROG Command
20000000	Type 1 NOOP

The IPbus to ICAP interface works properly. The time to boot the FPGA is around 2 seconds working at 106 MHz.



The CTS for LHC-Run 3 has to cover special requirements, for example the CTS must record all interactions selected. The ATBs use DDR4 memories for the interaction record, trigger data generator (TDG) and snapshots memories. To implement these functionalities, the memories must be accessible from two sides: externally read and write through the IPbus interface, and externally the write process is from the TTC-PON or GBT interface.

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4.ALICE Central Trigger System (Hardware Implementation)

4.5 Testing and Results

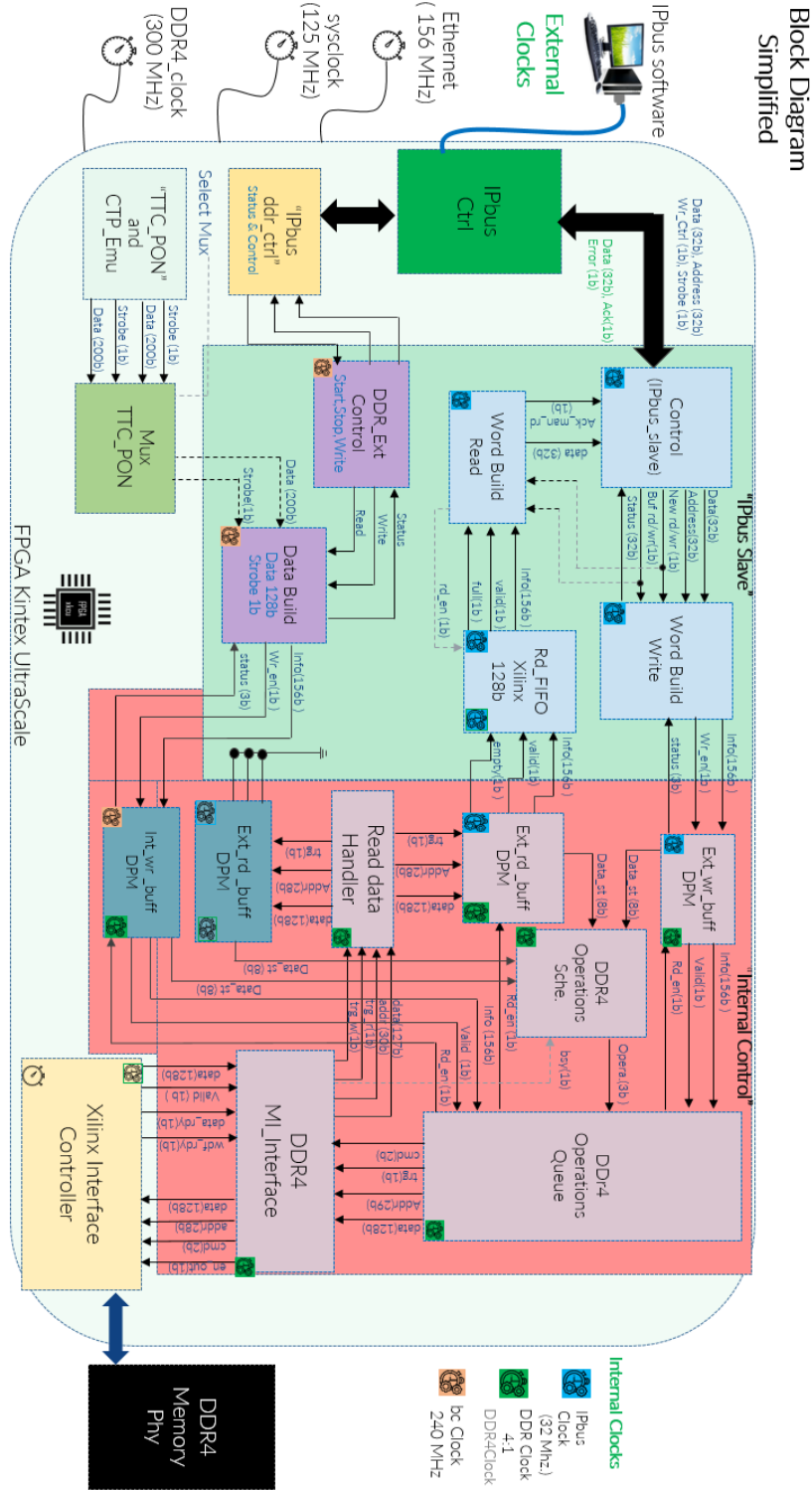


Figure 4.28: Block Diagram of the DDR4 interface in ATB

The DDR4 controller implemented in ATB have been extensively tested, using the concept shown in figure 4.29, where the every location of the memory is double checked, leaving 26,8435,456 of IPbus access, and no problems were detected.

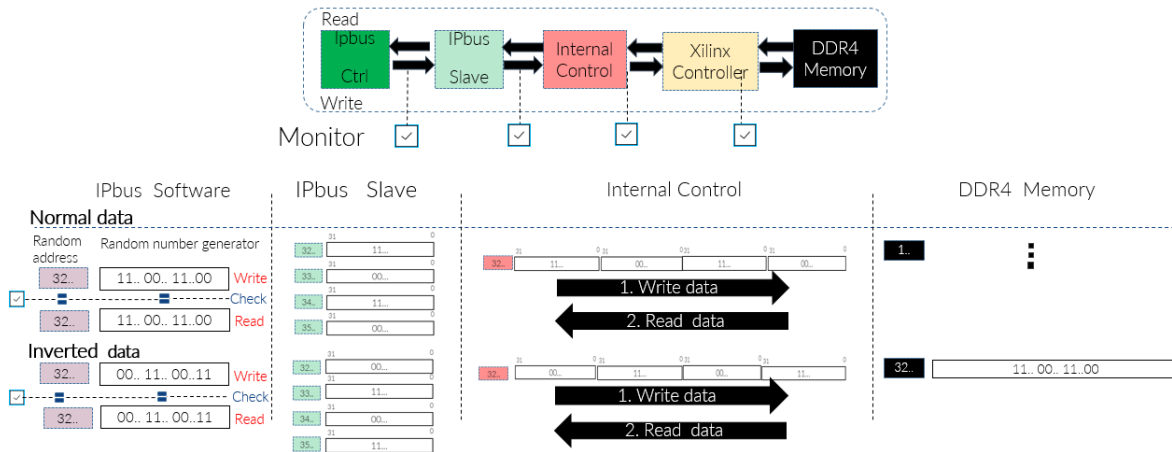


Figure 4.29: Block Diagram of the DDR4 interface in ATB

5

ALICE CENTRAL TRIGGER SYSTEM (INTERFACES)

The implementation and qualification in ALICE trigger board of the novel Timing and Trigger Control system based on Passive Optical Networks (TTC-PON) and the Giga Byte Transceiver (GBT) protocol is described in this chapter.

5.1 Introduction

The Central Trigger Processor (CTP) in ALICE manages the trigger decisions globally and supervise the production of trigger request by combining the inputs from trigger detectors. The CTP plays a pivotal role in identifying physics events, which are recorded for later analysis. As was described in previous chapters, the ALICE upgrade strategy is therefore based on collecting $> 10n\,b^{-1}$ of Pb-Pb collisions at luminosities up to $\mathcal{L} = 6 \times 10^{27} \text{ cm}^{-2} \text{ s}^{-1}$ corresponding to collision rates of 50 kHz, instead of 8 kHz during Run 1.

The central trigger processor (CTP) will be upgraded to accommodate the higher interaction rate, providing trigger and timing distribution (TTS); for detectors upgrading the TTS will be using the new Timing Trigger Control based on Optical networks (TTC-PON) or via Giga Byte Transceiver protocol (GBT) and the old TTC for detectors not upgrading.

5.2 Introduction to TTC-PON

In the Large Hadron Collider (LHC) experiment at CERN, the Timing, Trigger and Control (TTC) system is a crucial system dedicated to synchronization of experiment electronics to the LHC beam. Currently it consists of a point to multipoint unidirectional optical communication system in which the master sends data at 80 Mbps to up to 32 slave node [30]; this system presents several limitations for the future needs of the LHC experiments operations. To cover these requirements a bidirectional link and higher bandwidth have been designed.

In the telecommunications industry, passive optical networks (PON) are a widely adopted solution in the Fiber To The Home (FTTH) deployments [31]. It consists of a point-to-multipoint bidirectional optical system in which a master node, called Optical Line Terminal (OLT), and several slave nodes, called Optical Network Unit (ONUs), are present. The TTC-PON system has two directions of the data transmission: in the *Downstream* directions (from OLT to ONUs) information is broadcast continuously at a given wavelength; in the *Upstream* direction (from ONUs to OLT), information is transmitted with another wavelength making use of a multiplexing access scheme (commonly time division multiplexing, in which data transmission occurs in burst) in order to allow the data transmission from several slaves [32]. The architecture of the old TTC system and the TTC-PON system are shown in figure 5.1

The current TTC-PON system is based on the XG-PON technology which allows a downstream transmission at 9.953 Gbps and an upstream transmission at 2.488 Gbps. Those values have to be slightly modified to 9.6 Gbps and 2.4 Gbps since the downstream data transmission rate has to be an even multiple of the LHC bunch clock frequency (40.078 MHz).

Downstream Path. In the downstream direction, OLT transmits continuously at 9.6 Gbps with a wavelength of 1577 nm. The frames are constructed on a LHC bunch clock period basis, appending an 8-bit header and using 24 bits for internal control communication between the OLT and ONUs.

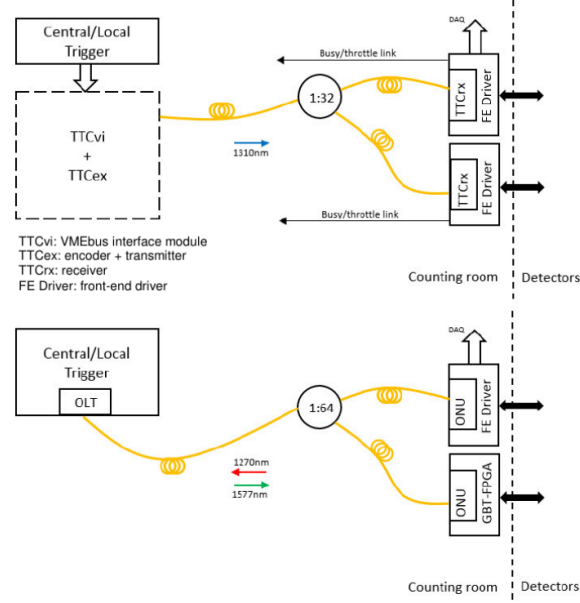


Figure 5.1: Top, Old TTC architecture; Bottom, TTC-PON architecture (from [32]).

Upstream Path. In the upstream direction, ONU transmit at 2.4 Gbps with a wavelength of 1270nm. The upstream data transmission scheme is based on Time Division Multiplexing Access (TDMA). Each ONU has a time slot allocated to transmit 8b10b encoded information. The ONU burst is composed of four fields: preamble, delimiter (comma), ONU address and payload, as is shown in figure 5.2.

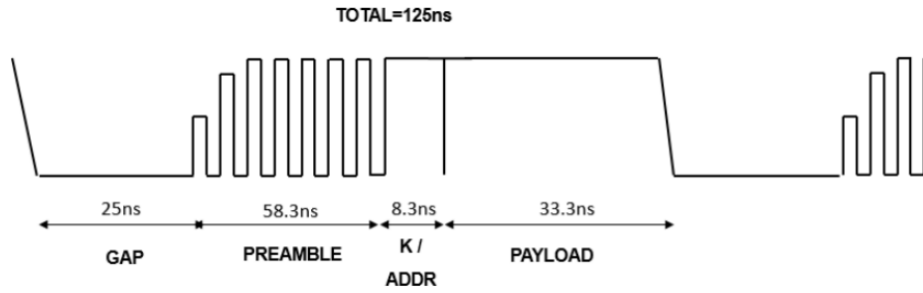


Figure 5.2: ONU burst (from [32]).

Time Division Multiplexing arbitration [32]. In TTC-PON the upstream bandwidth allocated to each ONU is fixed and the number of ONUs is known before run is initiated.

Those characteristics make it possible to have a fixed time slot for the transmission of each ONU during a run and therefore the OLT does not have to pass a token every time an ONU is allowed to transmit. Instead, a broadcast signal (TTC-PON heartbeat) is sent every $T_{HB} = Number_{ONUs} \times 125 \text{ ns}$; two headers are used in downstream transmission, the regular header sent every 25 ns, and the heartbeat header sent every T_{HB} . The heartbeat serves as a time reference signal to the ONUs, which reset an internal counter every time a heartbeat is received. The potential problems of the collision of different ONUs is overcome with a calibration procedure before a run is started. The calibration consists of performing a roundtrip latency measurement for each ONU and compensating the transmission offset depending on the roundtrip value; the procedure is arbitrated by the OLT, a given ONU is put in calibration mode (transmits continuously and sends back the received header, acting as a header mirror, other ONUs are turned-off) and the distance between the transmitted heartbeat header and the received heartbeat header is measured.

5.3 TTC-PON system in ALICE

The basis of the new TTS in ALICE is the new TTC-PON system. The architecture of the TTC-PON system in ALICE is shown in Figure 3.9. ALICE is the first experiment of the LHC to evaluate the TTC-PON system; since 2015 the ALICE-CTP has a close collaboration with the TTC-PON developers (EP-ESE department) at CERN. Starting the qualification with a single OLT connected to a single ONU implemented in two KC705 evaluation boards controlled via Microblaze using Software Development Kit (SDK) from Xilinx and just testing the downstream path, until the implementation of the 9 OLTs and 1 ONU in the LTU Logic Firmware controlled via IPbus, testing downstream and upstream paths. The evolution of the TTC-PON system in ALICE-CTP is shown in figure 5.3.

In the downstream direction from CTP to CRUs, the CTP will provide trigger information with a fixed and deterministic latency after resets and power ups. The downstream framing scheme is constructed on a LHC bunch clock period as is shown in figure 5.4. In the TTC-PON protocol each downstream frame is composed of four fields: 8 bit of header, 4 bits are for internal system control and monitoring, which are assembled in a 36 bits frame and further

5. ALICE Central Trigger System (Interfaces)

5.3 TTC-PON system in ALICE

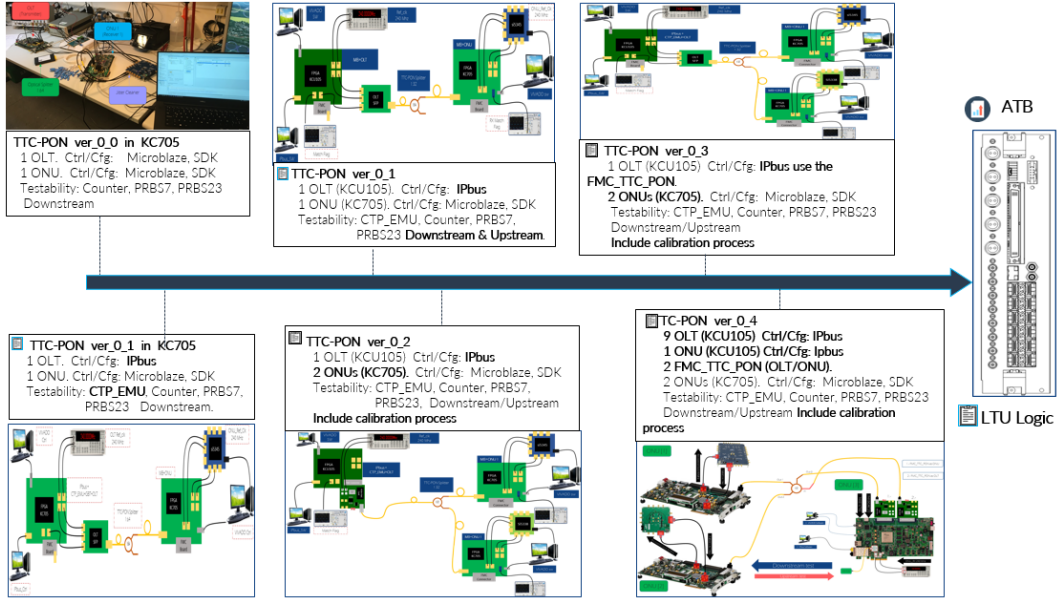


Figure 5.3: Evolution of the TTC-PON system in ALICE-CTP (2015-2018).

protected by an error-detecting code; 200 bits are available for user, (trigger message in our approach), and 28 bits are redundancy bits of a forward error correction (FEC) scheme.

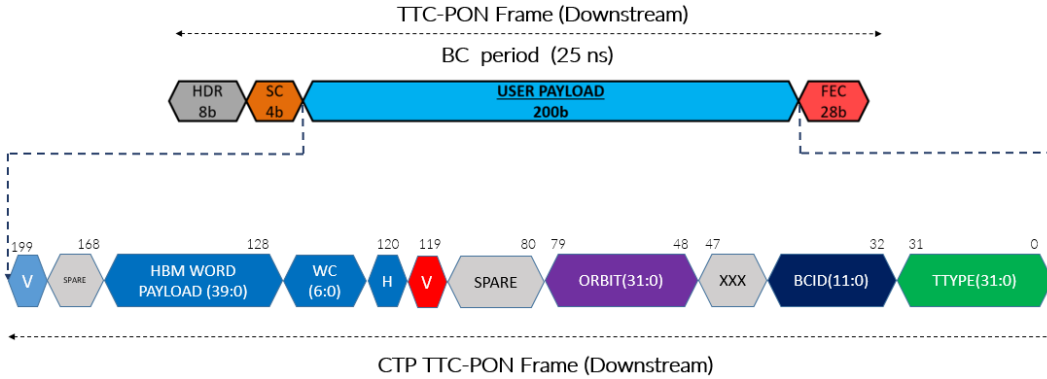


Figure 5.4: TTC-PON Downstream frame.

In the upstream direction from CRUs to CTP, the CTP will receive the status of the all CRUs participating in the run. In the upstream direction, transmission of ONUs has to be synchronous to the OLT clock, which requires a local synchronization procedure, that

is, downstream recovered clock is cleaned by means of an external PLL and used to drive the transmit PLL of the FPGA transceiver. The upstream path require a fine resolution calibration as was explained in the previous section. The upstream data transmission scheme consists of 125 ns time slots per ONU which are arbitrated in a round-robin manner by the OLT. The upstream frame is shown in figure 5.5. Each burst is divided into five fields: 140 bits preamble are used for receiver settling time adjustment; 8 bits of header are used for frame alignment: 8 bits of address are for ONU identification; 8 bits are used for slow control responses and 56 bits are available for the user (Heart beat acknowledge message in our approach).

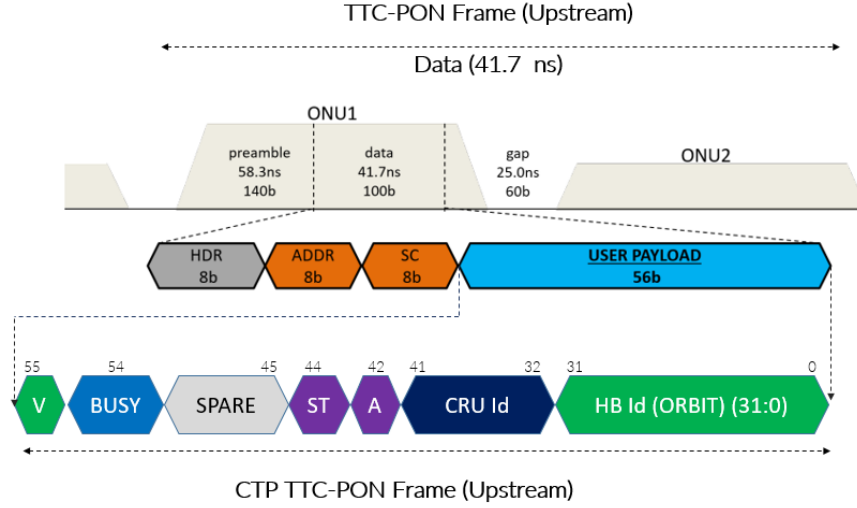


Figure 5.5: TTC-PON Upstream frame.

The TTC-PON firmware implemented in ATB include 9 OLTs, 1 ONU, 1 I^2C arbiter, all control is through the IPbus protocol. The block diagram of the TTC-PON firmware implemented is shown in figure 5.6. To avoid timing problems due to different clock domains in the design, the firmware was properly constrained.

TTC-PON I^2C Arbiter

Monitoring and control of the TTC-PON components is extremely important for the CTS during the Run 3. As previously described the CTS will be located in ALICE cavern, an

5. ALICE Central Trigger System (Interfaces)

5.3 TTC-PON system in ALICE

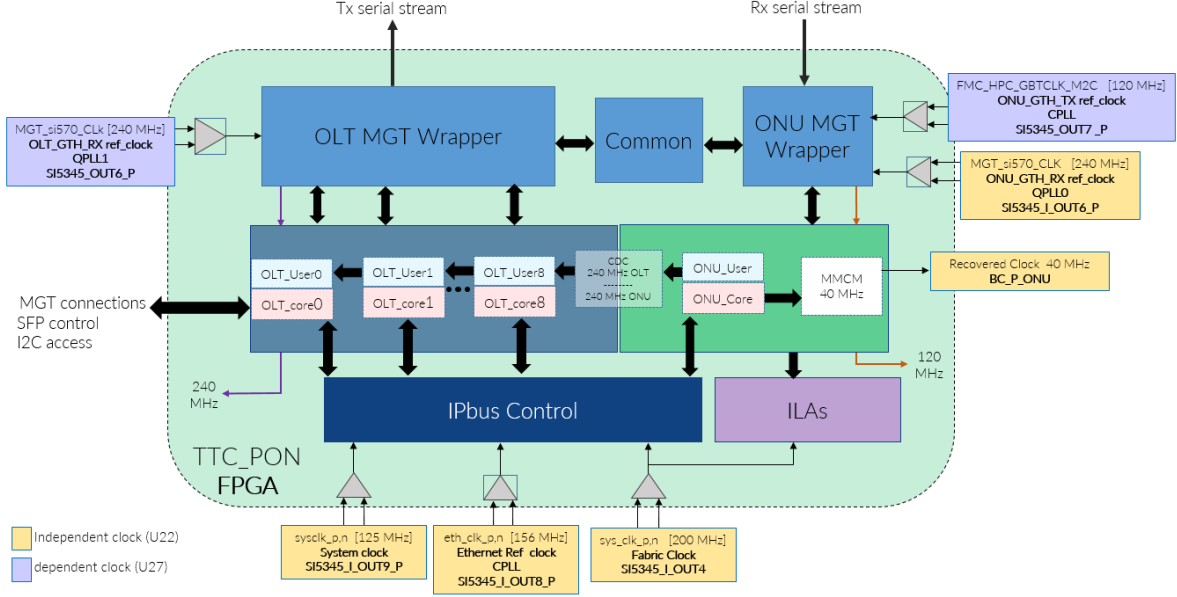


Figure 5.6: Simplified block diagram of the TTC-PON firmware implemented in ALICE Trigger Board.

access will be restricted. Access to TTC-PON components (e.g OLTs and ONUs) is possible in two ways, directly through to IPbus slave or via TTC-PON network. For this reason a I^2C arbiter was designed and implemented, where the user can decide the way to access the TTC-PON components. The design of the I^2C arbiter is depicted in figure 5.7. The core of I^2C arbiter is a multiplexer, where the user chooses the channel to be active, the channels available in the multiplexer are listed in table 5.1.

In order to test the I^2C arbiter, a systematic temperature reading of the TTC-PON components was performed. The access to TTC-PON components was in 3 different paths:

1. Access trough IPbus I^2C Slave.
2. Access trough IPbus TTC-PON core.
3. Access trough TTC-PON network.

5. ALICE Central Trigger System (Interfaces)

5.3 TTC-PON system in ALICE

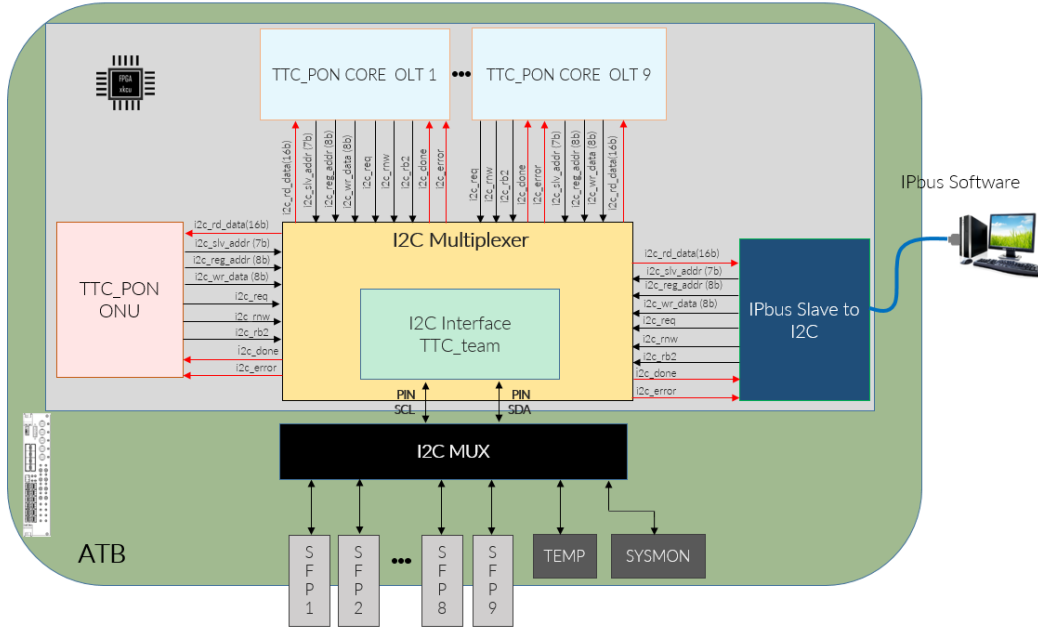


Figure 5.7: Simplified block diagram of the I^2C arbiter.

Table 5.1: Channels of the I^2C arbiter .

Channel No	Link Active	Code (32b)
1	OLT 1	h'1
2	OLT 2	h'2
3	OLT 3	h'3
4	OLT 4	h'4
5	OLT 5	h'5
6	OLT 6	h'6
7	OLT 7	h'7
8	OLT 8	h'8
9	OLT 9	h'9
10	ONU	h'A
11	IPbus	h'B

The evolution of temperature after system power up shows the correct access of the TTC-PON components, additionally this test indicated that the TTC-PON components on ATB are in a safe temperature range over the test. (see figure 5.8)

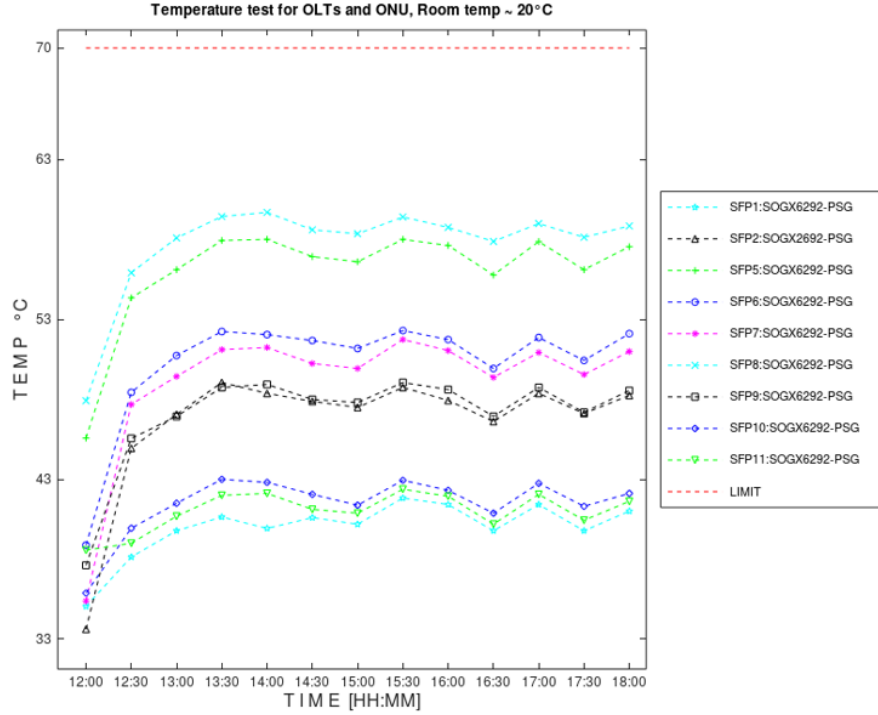


Figure 5.8: Temperature test with 9 OLTs (GOFOTON) connected, in FULL VME Crate with air cooling.

Data Generators. As was described in chapter 3 the LTU in standalone mode provide a fully emulation of the CTP, in addition to this CTP emulator data generator, the TTC-PON firmware offers five different data generators for debugging and to qualify the TTC-PON link:

1. LTU DATA: data from ONU receiver.
2. PRBS7: Pseudo Random Binary Sequence 7
3. PRBS23: Pseudo Random Binary Sequence 23
4. Constant: Fixed Pattern.

5. Counter: 8 bit counter

In order to choose the data to be transmitted a multiplexer (TTC-PON Data mux) was implemented, The data transmitted and received can be saved into a DDR4 memory, to crosscheck the information if it is required. These data generators are depicted in figure 5.9.

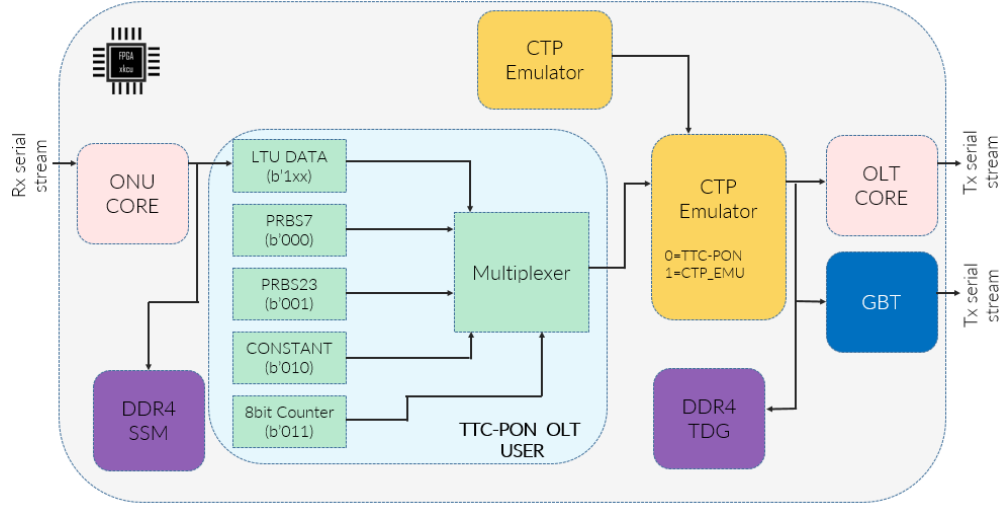


Figure 5.9: Data generators available in LTU firmware.

Downstream Latency

In global mode the CTP provide the trigger information to LTUs and then the LTUs forwarding the trigger information to CRUs trough TTC-PON network with fixed and deterministic latency after resets, power ups and even after FPGA reprogram process this latency should be as short as possible. An 8 bit counter is used to measure this latency. The counter goes to zero every time of counter reach the 237 value ($\sim 6\mu s$) and a flag at OLT (CTP) level is created to indicate the value is send. A match-flag is created when the ONU (LTU) received the special value. This latency between those two flags are then measured using oscilloscope. The CTS latency has been measured since the first version of the TTC-PON firmware. During the fist stage of the qualification of the TTC-PON system and with the purpose to chose the correct devices for the ATB (e.g FPGA, PLLs), the TTC-PON protocol was extensively evaluated using commercial boards (KC705 and KCU105). The experimental setup and results of the measurement of the downstream latency using commercial boards are

5. ALICE Central Trigger System (Interfaces)

5.3 TTC-PON system in ALICE

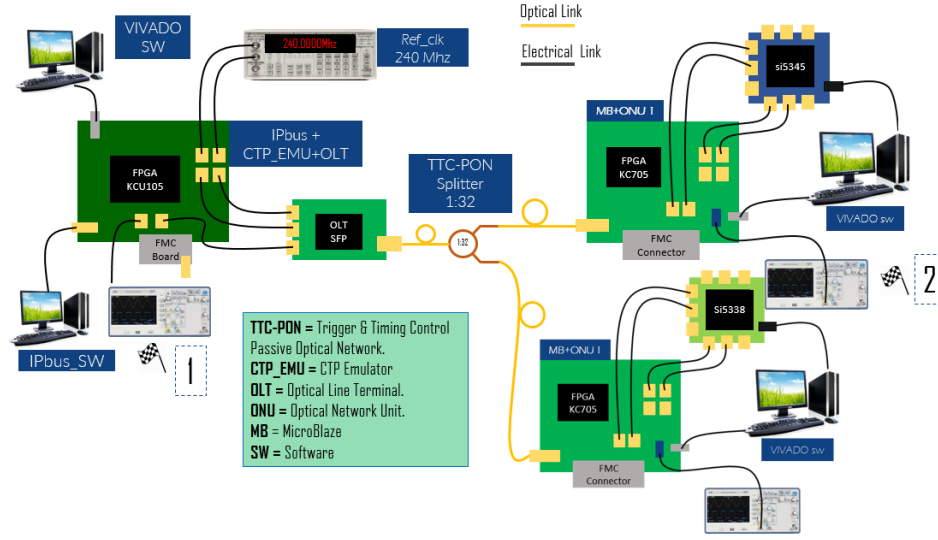


Figure 5.10: Downstream latency measurement experimental setup using commercial boards.

shown in figures 5.10, 5.11 . The results using commercial boards gave us the confidence to use the FPGA KintexUltraScale in ATB.

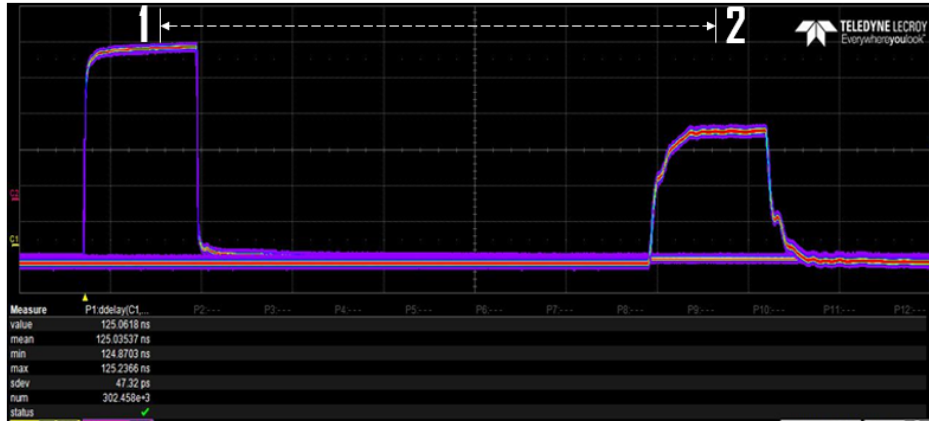


Figure 5.11: Downstream latency measurement using commercial boards .

In order to know the real value of the total downstream latency and verify the stability of the fixed latency in the complete chain of the systems in ALICE a systematic test was performed. The experimental setup is shown in figure 5.12. The measure of the downstream

5. ALICE Central Trigger System (Interfaces)

5.3 TTC-PON system in ALICE

latency over CTP - LTU - CRU - FEE is shown in figure 5.13. The results of the downstream latency in both scenarios are summarized in table 5.2.

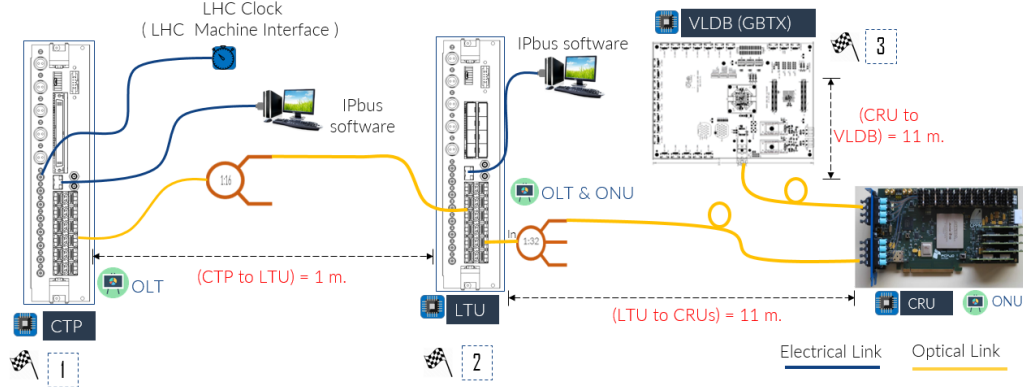


Figure 5.12: Downstream latency measurement experimental setup.

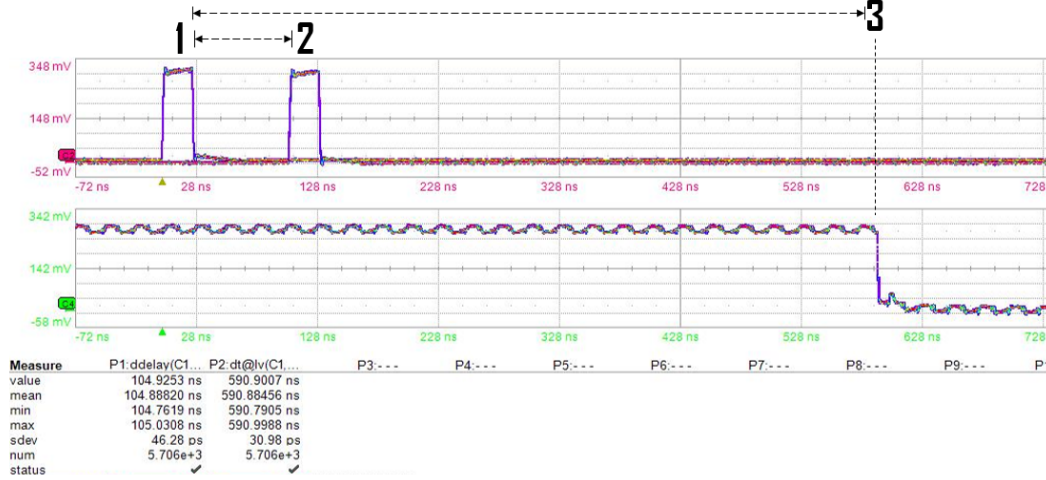


Figure 5.13: Downstream latency measurement.

BER Measurement

In order to evaluate the maximum number of the TTC-PON components at the same time, a special experimental setup was built (see figure (5.14), connecting 1 OLTs to 23 ONUs.

Table 5.2: Summary of the downstream latency measurements.

	Value	Value without cables contribution
Using commercial boards		
Data generator	Counter	
Latency CTP to LTU	~ 125 ns	~ 123 ns
Numbers of resets	500	
Numbers of power ups	50	
Using ATB		
Data generator	Counter	
Latency CTP to LTU	~ 105 ns	~ 102 ns
Latency CTP to FEE	~ 590 ns	~ 365 ns
Numbers of resets	300	
Numbers of power ups	30	

This experimental setup was very useful for testing the TTC-PON calibration procedure with a high number of ONUs connected. For the BER measurement in downstream direction a PRBS7 sequence is transmitted from OLT; at ONU level a PRBS7 checker should be activated. For upstream the settings are configured to operate in opposite in direction. The BER test configuration is uploaded via IPbus. BER was evaluated from the ratio of the number of errors recorded to the total number of bits transmitted.

The BER were measured during 75 hours and no errors were recorded, and a limit of $\text{BER} < 10^{-15}$ in downstream direction while a $\text{BER} < 10^{-14}$ were achieved. The different limits simply reflect the different transmission rates.

5.4 Introduction to GBT

The GBT chip [33] is a radiation tolerant ASIC (A Specific Integrated Circuit) that can be used to implement bidirectional multipurpose 4.8 Gbps optical links for high-energy experiments. Logically the link provides three "distinct" data paths for Timing and Trigger

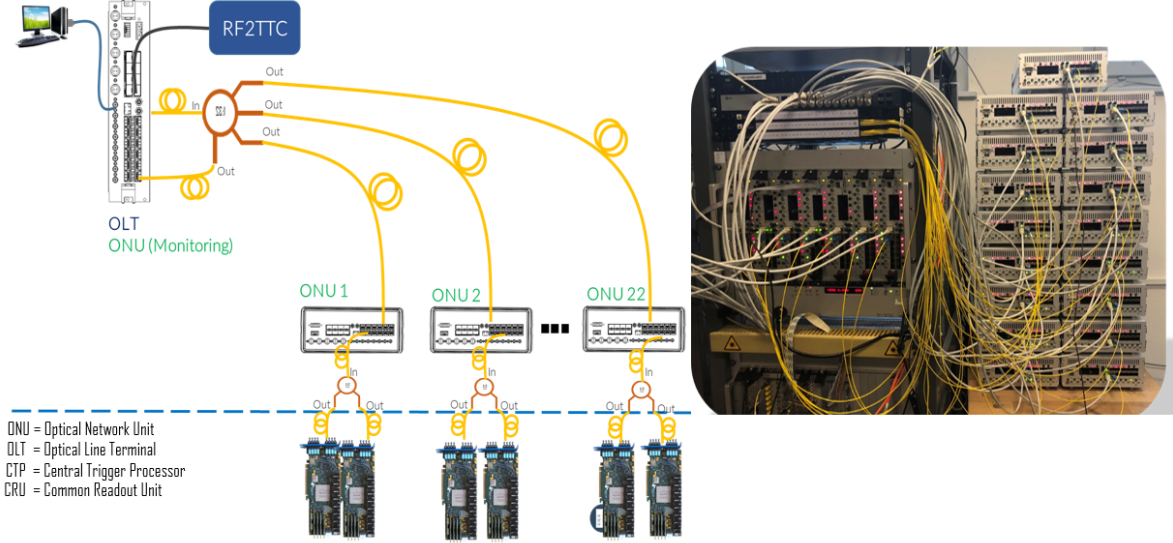


Figure 5.14: Experimental setup for BER measurements (1 OLT, 23 ONUs).

Control (TTC), Data Acquisition (DAQ) and Slow Control (SC) information. Although radiation hardness is required on detectors, it is not necessary for the electronics located in the counting rooms, where the GBT functionality can be realized using Commercial Off-The-Shelf (COTS) components and FPGAs [34]. The GBT link implementation scheme is shown in figure 5.15

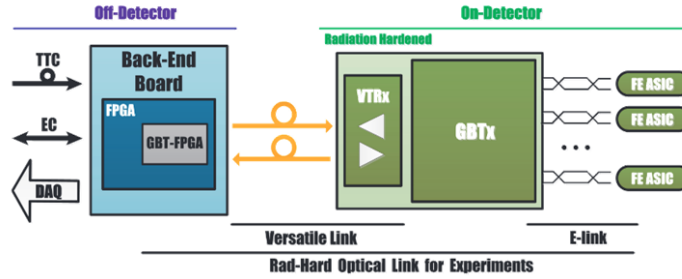


Figure 5.15: GBT Link implementation for experiments (from [33]).

In order to facilitate the implementation of the GBT-FPGA, the different components of the core are integrated in a single module called “*GBT Bank*”. The GBT Bank may include several “*GBT Links*” (the maximum number is vendor dependent). Each GBT Link is composed by a GBT Transmitter (GBT Tx), a GBT Receiver (GBT Rx) and a Multi-Gigabit

Transceiver (MGT) (see figure 5.16). The GBT-FPGA support two encoding schemes “GBT-Frame” (Reed-Solomon) and ”Wide Bus”).

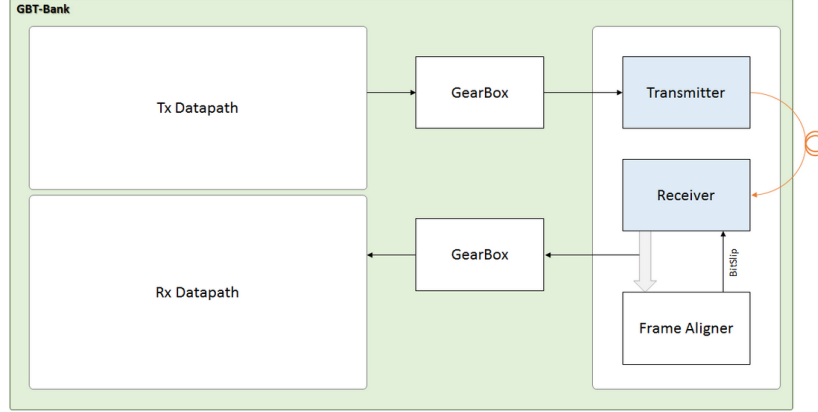


Figure 5.16: GBT Bank structure (from [33]).

The GBT-FPGA project provides two types of implementation for the transmitter and the receiver: the “Standard” version, for non-time critical applications and the “Latency-Optimized” version, ensuring a fixed, low and deterministic latency of the clock and data.

5.5 GBT in ALICE

As was described in the previous chapter, for detectors where latency is important (e.g ITS and MFT detectors), the CTS has the option to provide trigger messages directly to FEEs. In this particular case the interface LTU to FEEs will be through GBT links, on the other hand the readout of the CTP will be using GBT links as well. In the same case of the TTC-PON links, in the CTS, the GBT links require a fixed, low and deterministic latency in the transmission of the clock and triggers messages.

A short summary of the GBT-FPGA protocol evaluated is tabulated in Table. 5.3 and figure 5.17 gives the details of the GBT frame and how is used in the CTP.

Table 5.3: Settings of the GBT-FPGA protocol evaluated.

Parameters	GBT Protocol
Bandwidth (Channel)	4.8 Gbps
Bandwidth (User bits)	3.2 Gbps
Encoder	GBT Frame (Reed-Solomon)
Tx mode	Latency Optimized
Rx Mode	Latency Optimized
MGT ref clock	240 MHz and 120 MHz
GBT Model	GBT Clock Unified
Control	IPbus

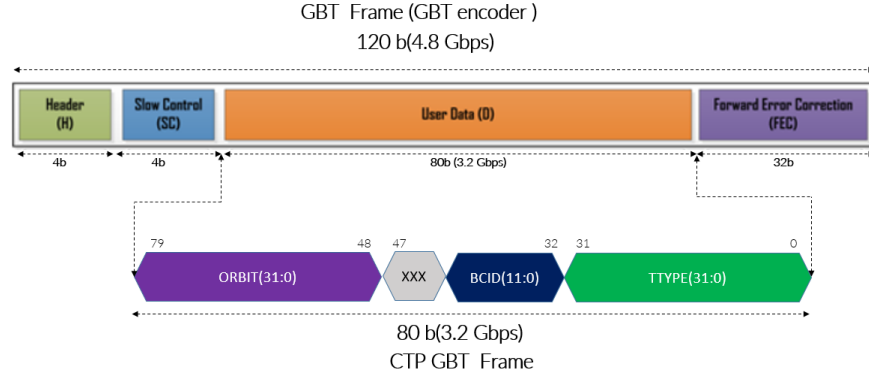


Figure 5.17: CTP GBT Frame

At the beginning, the evaluation of the GBT protocol was using commercial cards (KC705 and KCU105), and with only one GBT link implemented. The evaluation include a Versatile Link Evaluation Board (VLDB) [35], which is equipped with hard radiation components (e.g GBTx GBT-SCA VTRx and VTTx). When the ATB was ready the GBT-FPGA was implemented directly on the board. For example the two experimental setups presented in figure 5.18 were used. Currently the LTU firmware include 9 OLTs, 1 ONU and 2 GBT links, to avoid as much as possible the clock domain crossing and save FPGA resources, the FPGA-GBT firmware share clock resources with TTC-PON firmware, leaving a very complex firmware design with hard timing requests. The distribution of the links in ATB is shown in figure 5.19.

5. ALICE Central Trigger System (Interfaces)

5.5 GBT in ALICE

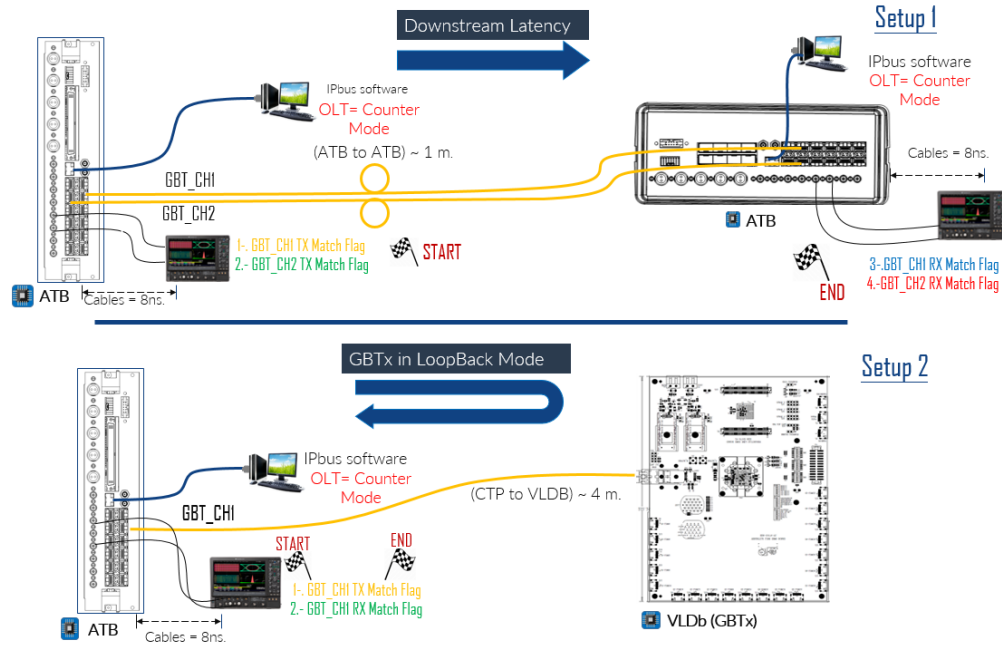


Figure 5.18: (Top) 2 GBT-FPGA Links tested in ATBs. (Bottom) 1 GBT-FPGA connected to VLDB in optical loopback mode.

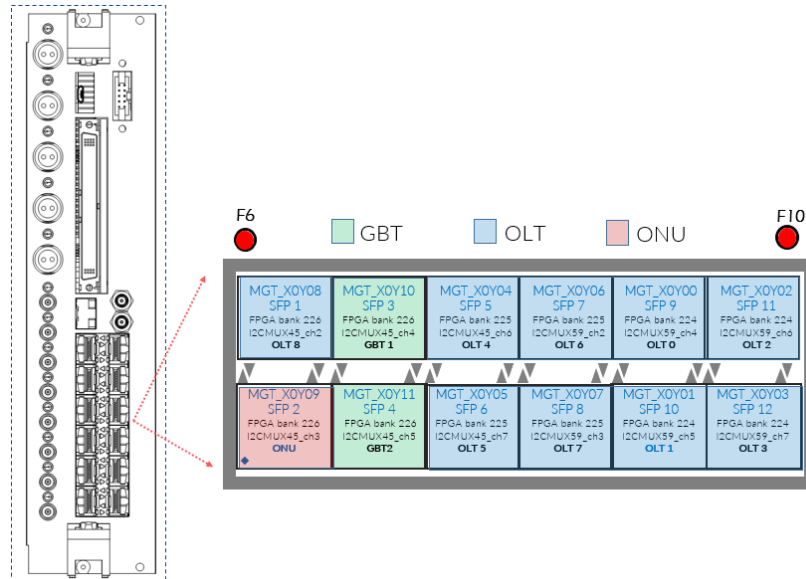


Figure 5.19: Distribution of the link in ATB, (9 OLTs, 1 ONU, 2 GBT).

5. ALICE Central Trigger System (Interfaces)

5.6 Phase stability and Jitter measurements

The latency in GBT link is a critical parameter for GBT in Latency Optimized mode. Optical loopback connection (round trip) was used for GBT latency measurement. The loopback delay corresponds to the length of time it takes for a signal to be sent plus the length of time it takes for an acknowledge of that signal to be received. It includes serialization, deserialization time along with propagation delay. The method for measuring the latency is described in figure 5.20, the same method was used for measurements with commercial boards.

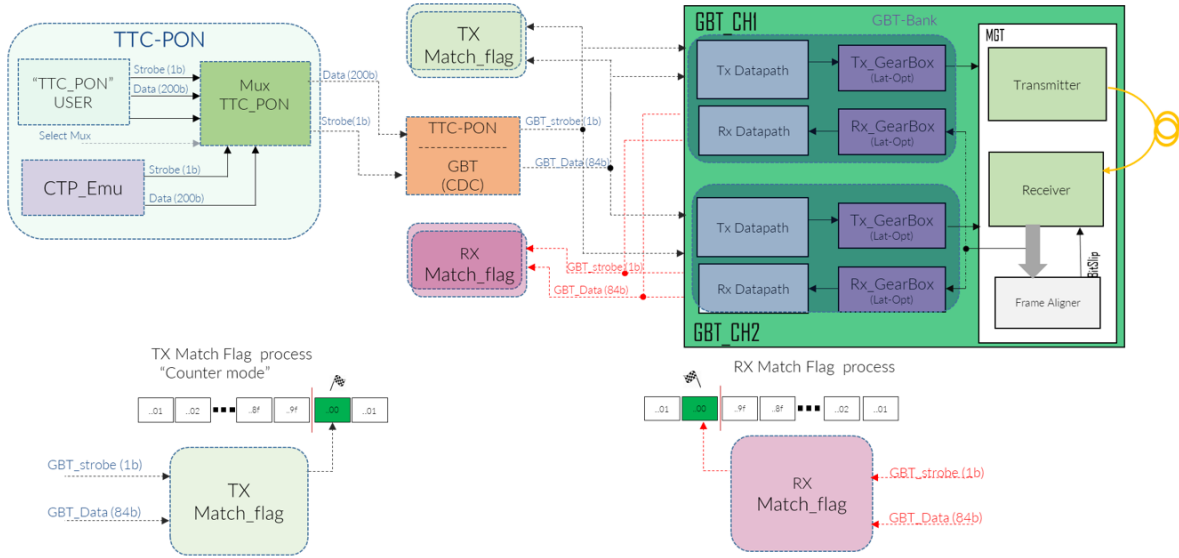


Figure 5.20: Block diagram of the method to measure the GBT Latency.

The results of the GBT latency measurements using different topologies are presented in table 5.4.

5.6 Phase stability and Jitter measurements

As described in chapter 3, the CTS will provide the trigger information (e.g trigger message, clock signal) in three different modes: (a) Detectors with non-critical latency critical system use the CRU connectivity, as the TPC and MCH detectors. (b) Detectors with latency critical CTS information connects directly to the CTP, such as ITS and MFT detectors, and

Table 5.4: Summary of the GBT latency measurements.

	Value
Using commercial boards, 120 MHz	
Data generator	Counter
Latency GBT-FPGA (Optical Loopback)	~ 210ns
Latency GBT-FPGA to VLDB (Optical Loopback)	~ 322ns
Downstream Latency GBT-FPGA to VLDB (E-link)	~ 152ns
Numbers of resets	100
Numbers of power ups	30
Using commercial boards, 240 MHz	
Data generator	Counter
Latency GBT-FPGA (Optical Loopback)	~ 145ns
Latency GBT-FPGA to VLDB (Optical Loopback)	~ 140ns
Downstream Latency GBT-FPGA to VLDB (E-link)	~ 243ns
Numbers of resets	100
Numbers of power ups	30
Using ATB 240 Mhz, Unified clock	
Data generator	Counter
Latency GBT-FPGA (Optical Loopback)	~ 110ns
Latency GBT-FPGA to VLDB (Optical Loopback)	~ 222ns
Latency OLT - ONU - GBT-FPGA (Optical Loopback)	~ 302ns
Numbers of resets	500
Numbers of power ups	40

(c) Detectors that would not being upgraded will receive the trigger information via old TTC system.

The LHC Clock is one of the most important accelerator signals delivered to the experiments. In the ALICE architecture this signal is received directly from the Radio Frequency to CTS machine interface, then is forward it to CTP, the CTP cleans it and forward it to the detectors. This signal represent the frequency at which the bunches are crossing each other and it is thus used to synchronize all the electronics system in charge of event detection and is distributed to each single part of the detectors. Its frequency is around 40.079 Mhz but varies with beam parameters (e.g. energy, particle type, etc.) by a few hundred of Hz. The quality of this

signal is therefore crucial for ALICE to ensure an accurate and reliable event reconstruction. The clock scheme of the CTS (*a* and *b* modes) for LHC Run 3 is shown in figure 5.21.

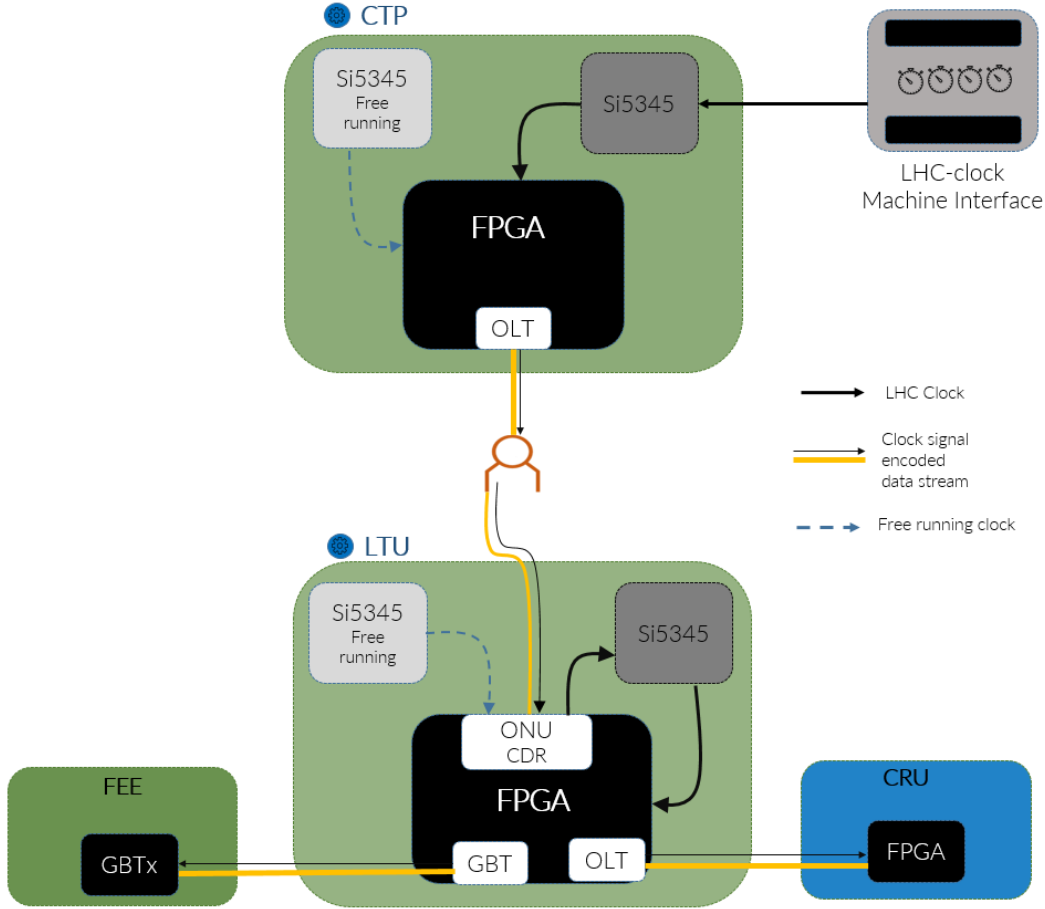


Figure 5.21: Central Trigger System clock scheme for LHC-Run 3

Jitter can be defined as “*the deviation of the significant instances of a signal from their ideal location time*” [36]. Jitter measurements were performed in different parts of the CTS. The experimental setup presented in figure 5.22 was built to measure the jitter skew at different temperatures. Jitter skew is the deviation from a reference signal. It is often used in LHC experiments, as the phase between the LHC clock and the beam itself has to be fixed and remain as steady as possible. For this type of jitter, the reference signal is usually the LHC Clock at the top of the distribution network. In our setup the clock reference is provided for CG635 clock generator.

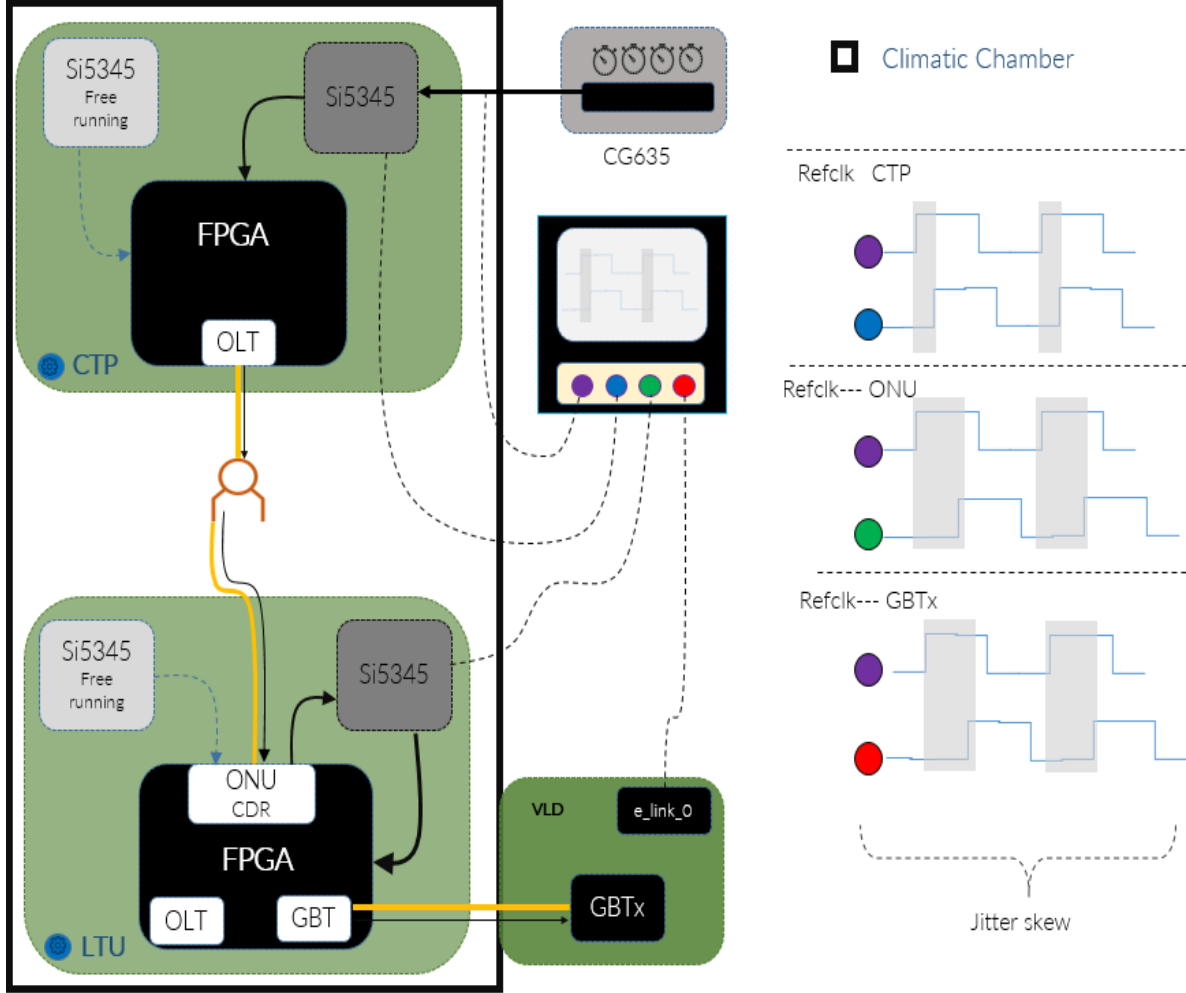


Figure 5.22: Central Trigger System clock scheme, experimental setup to perform the jitter skew measurements.

The jitter skew measurement also includes a test of the reset procedure, where different conditions after power-up or after the reset of the full chain were simulated. As an example, the results for one of these measurements are shown in figure 5.23 for one temperature, showing values with and without resets. The wider range of clock skew with resets is mainly due to specific functionality in the high-speed transceiver of Xilinx Ultrascale FPGA.

In order to complete the phase stability measurement with the experimental setup, and

5. ALICE Central Trigger System (Interfaces)

5.6 Phase stability and Jitter measurements

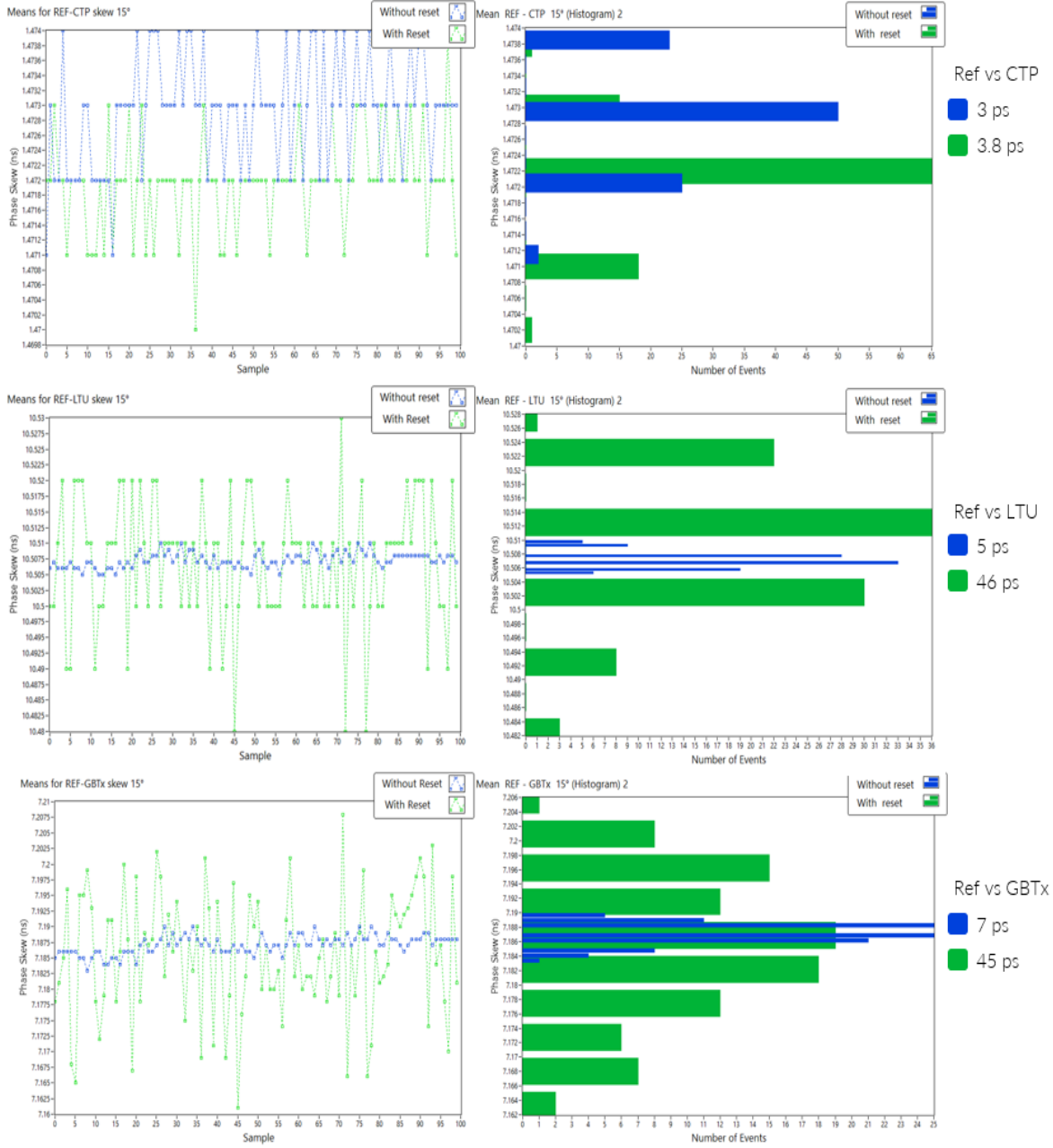


Figure 5.23: Clock phase stability at 15° , for the setup presented in 5.22. The blue color represents the clock skew without resets and green color skew with resets.

using a phase noise analyser, the phase noise analysis at different different temperatures were performed. The figure 5.24 shows the phase nose study done using the experimental setup showed in figure 5.22 The phase noise study (see figure 5.23 and 5.24) shows the small phase variation with respect the temperature, hence it can be concluded that the CTS clock distribution using TTC-PON system have a good performance under temperature variations.

5. ALICE Central Trigger System (Interfaces)
5.6 Phase stability and Jitter measurements

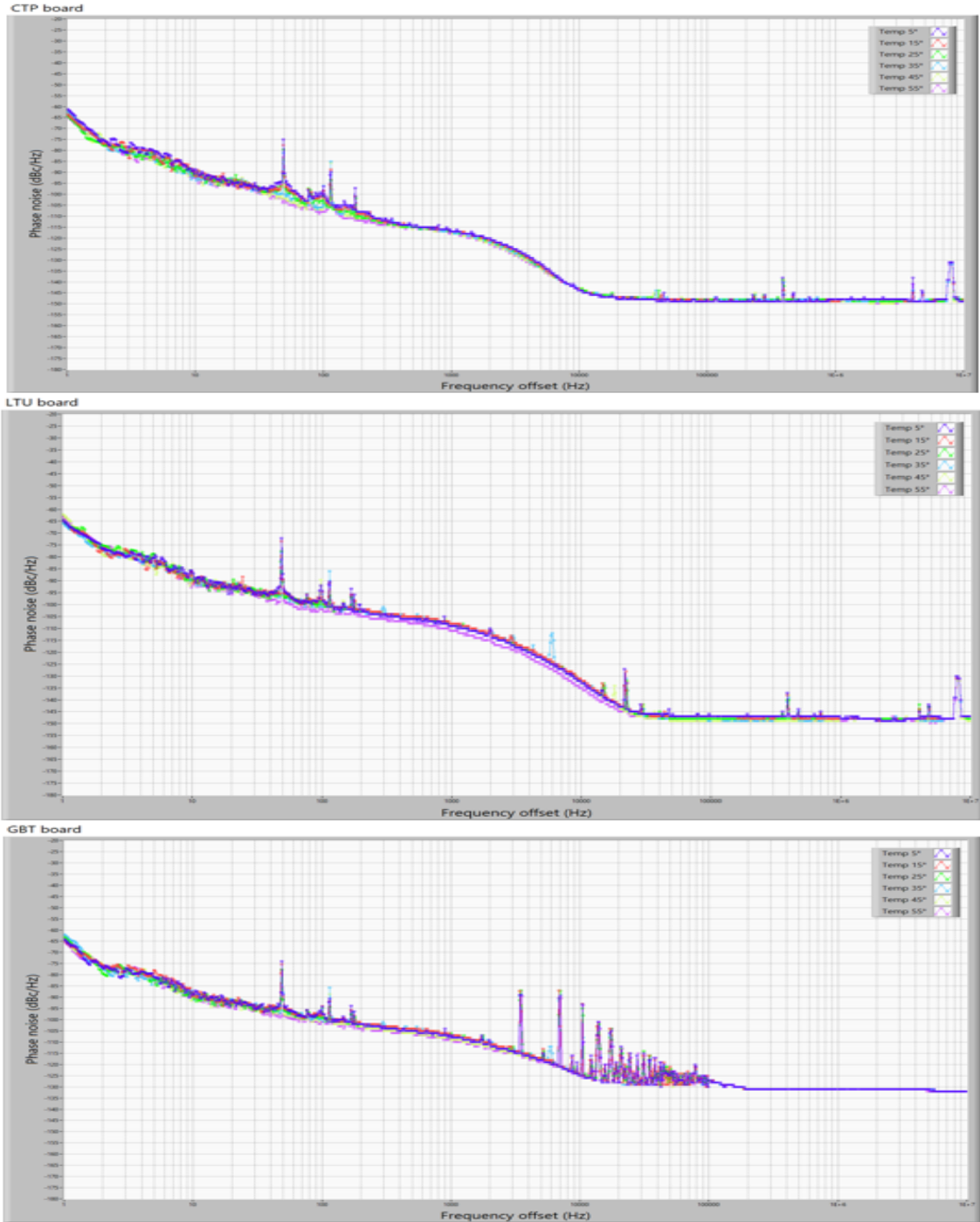


Figure 5.24: Phase noise for (top) CTP, (middle) LTU, (bottom) GBTx. At different temperatures.

6

SUMMARY AND OUTLOOK

This chapter gives a short summary of the work covered by this thesis, finally an outlook of the work is then given.

In High Energy Physics experiments with high interaction rate (e.g ALICE experiment), the trigger system plays a very important role, because this system is required to select physics events and suppress background for the entire experiment. In run 3 of the LHC, it is envisaged that the luminosity for Pb-Pb collisions will increase significantly, leading to a 50 kHz interaction rate for Pb-Pb, while in pp and pA mode the interaction rate can be kept to 200 kHz. In these conditions the readout system the central trigger processor requires a major upgrade. From the Trigger system point of view the ALICE upgrade will require a very different triggering strategy from the current one and hence a new Central Trigger System (CTS) is needed. The new ALICE central trigger system has been planned by the ALICE collaboration, to prepare for the next LHC-Run3 starting from 2021. The work has concentrated on the design and construction of the new CTS of the ALICE-LHC experiment.

The architecture of the new CTS for the ALICE experiment has been presented. For LHC-Run3 we will keep the concept of a Central Trigger Processor (CTP) and Local Trigger Unit (LTUs) as detector interface. It is important to know that the CTS will manage a system of detectors with markedly different properties. The majority of detectors, which will read out at the nominal interaction rate, are dead-time free. However in order to provide backwards compatibility to detectors not being upgraded, the trigger system must cope with detectors which will have dead-time during the readout process.

The basis of the new CTS is a universal trigger board called (ALICE Trigger board) based on the Kintex UltraScale FPGA, able to support up to 20 High-speed links; the new trigger

distribution will be able to run with a 9.6 GHz. Special effort has been given in the design and test of the ATB.

The ATBs produced in the first phase of production of the ALICE-CTP have been extensively tested. Special firmwares have been developed for the tests, these firmwares cover from the IBERT test, IBERT+, the evaluation of the IPbus system including several interfaces like IPbus- I^2C , IPbus-SPI, IPbus-ICAP (it is very important for the FPGA reconfiguration) to the DDR4 memories controller which is a time constraint firmware. The test results of all ATBs have been published on a Wiki Webpage.

The principal features of the new system, comprising a CTP, a LTU and a novel Timing Trigger Control system based on Passive Optical Network (TTC-PON) have been presented. The TTC-PON qualification on ALICE CTS has been presented. The qualification results shows that the system fulfils the required specifications.

Additionally tests of a laboratory system analogous to the full ALICE system were presented. The temperature dependence of timing parameters of the system was measured. The results of the test indicates that the system fulfils required specifications.

Finally, it is worth mentioning that the first phase of the ALICE central trigger system was designed, implemented and tested. The ALICE Trigger boards were delivered to the detector laboratories with appropriate firmware and software and the detectors will use them and integrate these into their systems.

The second phase will be initiated in April 2019.

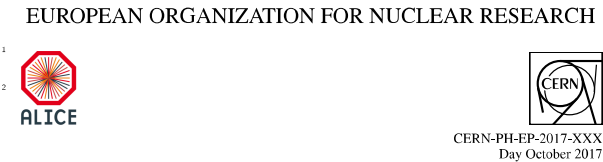
6.1 Publications

The ALICE Central Trigger Processor

Authors: L.A. Perez Moreno, A. Fernandez Tellez, G Tejada Munoz, M. Krivda, D.Evans

Status: Revision.

Target: Nuclear Instruments and Methods in Physics Research.



The ALICE Central Trigger Processor
L.A.Perez Moreno for ALICE Collaboration*

Abstract
The ALICE Central Trigger Processor used for LHC Run 1 (2009-2013), Run 2 (2015-2018) and Run 3 (2020-2024) is described. The Physics requirements for ALICE are markedly different from those of the other detectors, leading to a different design for the trigger system, for example utilizing different detector subsets for different physics on an event-by-event basis. The system configuration for Runs 1 and 2 are fairly similar, while for Run 3 a significantly different system is being prepared, albeit one allowing many legacy features to take into account the fact that some ALICE detectors are not planning a major electronics upgrade. The software model for the control of the trigger system is described, and for Run 1 and Run 2 operation, some performance figures will be given.

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*See Appendix A for the list of collaboration members

Trigger System Design Review

Authors: L.A. Perez Moreno, A. Fernandez Tellez, G Tejada Munoz, M. Krivda, D.Evans, O.Villalobos. R.Lietava.

Status: Published

Target: ALICE Experiment Internal Note.



Trigger System

Design Review

July 2017

D. Evans¹, A. Jusko¹, M. Krivda¹, L. Lietava¹, L. A. Pérez Moreno ²
O. Villalobos Baillie¹

1. University of Birmingham

2. Autonomous University of Puebla

Version 2.0

Study of cosmic ray events with high muon multiplicity using the ALICE detector at the CERN Large Hadron Collider

Authors: L.A. Perez Moreno, A. Fernandez Tellez, G Tejeda , M.Rodriguez for ALICE Collaboration

Status: Published

EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH



CERN-PH-EP-2015-196
23 July 2015

Study of cosmic ray events with high muon multiplicity using the ALICE detector at the CERN Large Hadron Collider

ALICE Collaboration*

Abstract

ALICE is one of four large experiments at the CERN Large Hadron Collider near Geneva, specially designed to study particle production in ultra-relativistic heavy-ion collisions. Located 52 meters underground with 28 meters of overburden rock, it has also been used to detect muons produced by cosmic ray interactions in the upper atmosphere. In this paper, we present the multiplicity distribution of these atmospheric muons and its comparison with Monte Carlo simulations. This analysis exploits the large size and excellent tracking capability of the ALICE Time Projection Chamber. A special emphasis is given to the study of high multiplicity events containing more than 100 reconstructed muons and corresponding to a muon areal density $\rho_\mu > 5.9 \text{ m}^{-2}$. Similar events have been studied in previous underground experiments such as ALEPH and DELPHI at LEP. While these experiments were able to reproduce the measured muon multiplicity distribution with Monte Carlo simulations at low and intermediate multiplicities, their simulations failed to describe the frequency of the highest multiplicity events. In this work we show that the high multiplicity events observed in ALICE stem from primary cosmic rays with energies above 10^{16} eV and that the frequency of these events can be successfully described by assuming a heavy mass composition of primary cosmic rays in this energy range. The development of the resulting air showers was simulated using the latest version of QGSJET to model hadronic interactions. This observation places significant constraints on alternative, more exotic, production mechanisms for these events.

arXiv:1507.07577v3 [astro-ph.HE] 1 Sep 2016

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*See Appendix A for the list of collaboration members

The ALICE Trigger system for LHC Run 3

Authors: L.A. Perez Moreno, M Krivda, D.Evans, A Jusko, R.Lietava

Status: Published (Proceedings of Science)



The ALICE trigger system for LHC Run 3

M. Krivda^{*}, D. Evans, K.L. Graham, A. Jusko, R. Lietava, O. Villalobos Baillie and N. Zardoshti

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for the ALICE Collaboration.

The ALICE Central Trigger Processor (CTP) is going to be upgraded for LHC Run 3 with completely new hardware and a new Trigger and Timing Control (TTC-PON) system based on a Passive Optical Network (PON) system. The new trigger system has been designed as dead time free and able to transmit trigger data at 9.6 Gbps. A new universal trigger board has been designed, where by changing the FMC card, it can function as a CTP or as a LTU. It is based on the Xilinx Kintex Ultrascale FPGA and upgraded TTC-PON. The new trigger system and the prototype of the trigger board will be presented.

*Topical Workshop on Electronics for Particle Physics
11 - 14 September 2017
Santa Cruz, California, U.S.A.*

^{*}Speaker.

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<https://pos.s1000.it/>

arXiv:1711.01200v1 [physics.ins-det] 3 Nov 2017

General characteristics of the AD detector

Authors: L.A. Perez Moreno, A. Fernandez Tellez, M. Rodriguez for ALICE Collaboration

Status: Published (ALICE Technical Note)

General characteristics of the AD detector

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April 9, 2016

1 Introduction

The AD detector (ALICE Diffractive) [1] consists of two assemblies, ADA and
ADC, each made of two layers of scintillators. Each layer has four scintillator
modules (see fig. 1). The two assemblies are installed around the beam pipe
in the forward region, ADC is located inside the LHC tunnel (fig. 2), ADA
is situated behind the compensator magnet on the A-Side. The parameters

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