The Readout System for the ALICE Zero Degree Calorimeters

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***Abstract*—ALICE at the CERN LHC will investigate the physics of strongly interacting matter at extreme energy densities where the formation of the Quark Gluon Plasma is expected. Its properties can be studied from observations like the production of mesons with charm and beauty quarks. These signals have to be studied as a function of energy density, which is determined by the centrality of collisions. One of the physics observables that is closely related with the centrality of the collision is the number of spectator nucleons that can be measured by the Zero Degree Calorimeters (ZDC). Having a direct geometric interpretation allows to extract the impact parameter with minimal model assumptions. This paper describes the readout system of the ZDC. The ZDC readout consists of a VME system with a ZDC Readout Card, a VME Processor, Discriminators, a ZDC Trigger Card, scalers, QDCs and TDCs. The system was successfully tested during the 2009 ALICE data taking and is currently operational at the LHC.**

***Index Terms*—ALICE, calorimeters, centrality, FPGA, readout system, VME, ZDC, ZRC.**

I. INTRODUCTION

ALICE [1] is dedicated to the study of ultra relativistic heavy ion collisions at the CERN Large Hadron Collider, in Geneva, Switzerland. It will investigate the physics of strongly interacting matter at extreme energy densities, where the formation of a new phase of matter, the Quark Gluon Plasma (QGP), is expected [2], [3]. The properties of the QGP can be studied from different types of observables like, for example, the production of mesons with charm and beauty quarks, the production of direct photons, the change in the yield of strange quarks, etc. A key ingredient in the interpretation of the experimental results is the dependence of those observables on "centrality". In a heavy ion collision, only the nucleons in the overlapping area of the two nuclei take part in the collisions, and are hence called "participants". The non-interacting nucleons ("spectators") continue essetially unperturbed along the beam direction. The centrality of the collision is a measurement of the overlapping of the two nuclei, and it is frequently expressed in terms of fraction of cross section, impact parameter or number of participants. Experimentally, it can be estimated studying several observables which scale with centrality (e.g., particle density at midrapidity). The Zero Degree Calorimeters, measuring the energy of the spectator nucleons, provide the most direct measurement of centrality.

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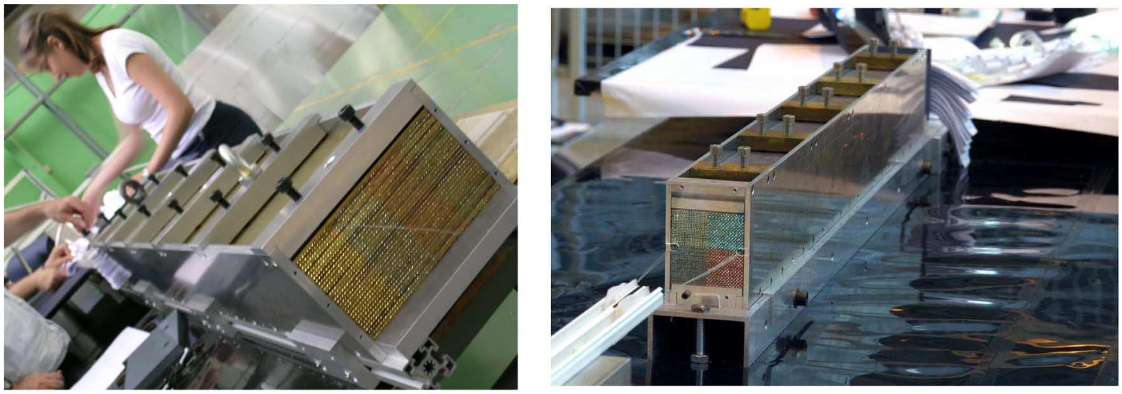
II. DETECTOR

The ZDC system [4] detects the spectator nucleons (protons and neutrons) that are separated by the LHC separator magnets [5]. The ZDC system is composed of four calorimeters: two proton calorimeters (ZP) to detect spectator protons and two neutron calorimeters (ZN) to detect spectator neutrons. ZP and ZN are shown in Fig. 1. They are located 116 m away from the interaction point on both sides, along the beam line (hence the name Zero Degree Calorimeters). The proton calorimeters are internal to the LHC ring and the neutron calorimeters are located between the two beam pipes. The location of the ZDC with respect to the beam line and the interaction point (IP2) is shown in Fig. 2. The different abbreviations marked in Fig. 2 are related to the LHC and their details can be found here [5]. The ZDCs are made of heavy metal plates grooved to allocate a matrix of quartz fibers. There are 1680 quartz fibers in ZP and 1936 quartz fibers in ZN. There are 30 brass plates in ZP and 44 tungsten-alloy plates in ZN. The grooved slabs are stacked to form a parallelepiped, with the quartz fibers aligned parallel to the beam axis.

The nucleons that enter the calorimeter initiate a hadronic shower on hitting the metal plates. When a particle of the shower crosses a fiber, it can produce Cherenkov light. This light propagates in the fiber by total internal reflection up to its end, where a photomultiplier converts the light into an electric signal. The fibers emerge on the rear side of the calorimeter and are read out by five Hamamatsu R329–02 photomultipliers [6]. Each ZDC calorimeter is segmented into four towers. One out of two fibers is sent to a single photomultiplier (PMTc), while the remaining ones are connected to four different photodetectors (PMT1 to PMT4), which collect the light from each tower (Fig. 3). This segmentation allows to check the relative behaviour of the different towers and to give a rough localization of the spectator nucleon spot on the front face of the calorimeter. In this way it is possible to continuously monitor the beam crossing angle at



(a) (b)

Fig. 1. The Zero Degree Calorimeters. There are two identical sets of calorimeters stationed at 116 m from the interaction point on both sides. Each set consists of a (a) proton calorimeter (ZP) and (b) neutron calorimeter (ZN).

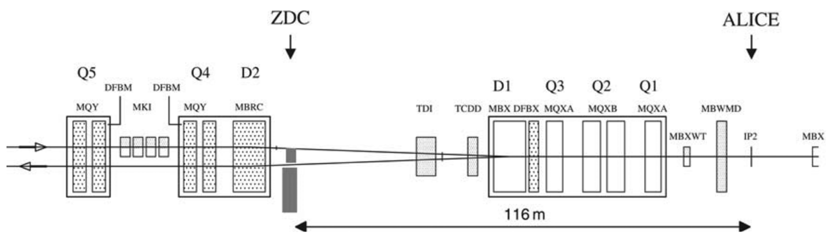


Fig. 2. Schematic view of the beam line and ZDC location. The ZDCs are located 116 m from the beam interaction point (IP2) on opposite sides.

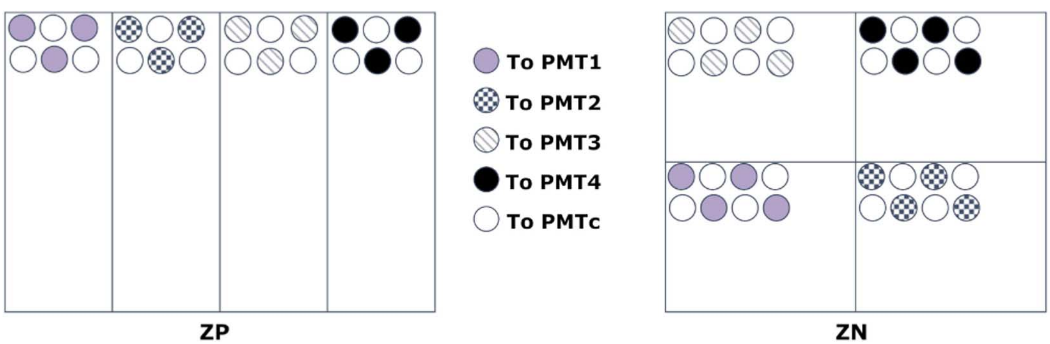


Fig. 3. Quartz fiber connections to the PMTs.

the interaction point. The information coming from the PMTc provides a complementary measurement of the shower's energy, useful for calibration purposes. The amplitude of the electric signal (converted from the light by the photomultiplier) is proportional to the energy of the incoming protons and neutrons, allowing a measurement of the energy carried away by the spectator nucleons, which in turn gives an estimate of the size of the overlap region of the two colliding nuclei.

ZP and ZN are complemented by an electromagnetic calorimeter (ZEM), located at 7.5 m from the interaction point, which measures the electromagnetic energy produced in the forward direction, which is anticorrelated with centrality.

The readout operation of the ZDC is performed depending on the state of ALICE triggers [7]. The ALICE trigger system decides whether a collision is worth processing and has two main parts—the Central Trigger Processor (CTP) and the Local Trigger Unit (LTU). The CTP generates three levels of hardware triggers: L0, L1 and L2, before an event is declared suitable for further processing and transmission to the ALICE DAQ. The LTU serves as an interface between the CTP and the front end electronics of each sub-detector. Its main roles are to guarantee the synchronization of the subdetectors by distributing the 40 MHz LHC clock, to issue the trigger signals and to examine the busy state of the detector. The signals are sent over LVDS cables (L0 and BUSY) or over an optical fibre (CLOCK, L1, L2 plus additional information encoded into the L1 and L2 messages) using a specific protocol named Trigger Timing and Control (TTC [8], [9]).

III. Design Constraints

The ALICE experiment has been designed to cope with the high track multiplicities expected in Pb-Pb collisions at the LHC (about 4000 tracks per unit of rapidity). Therefore, high granularity detectors were developed. The readout speed is less critical given the expected rates of 8 KHz for minimum-bias Pb-Pb interactions at the maximum instantaneous luminosity forseen of 1027 $\mathrm{cm}^{-2}\mathrm{s}^{-1}$. The trigger is structured in 3 levels: L0, L1 and L2. The L0 level is issued around 1.2 μs after the event. The L1 trigger is issued 6.2 μs after the event and allows to select events for a particular physics case (for example,

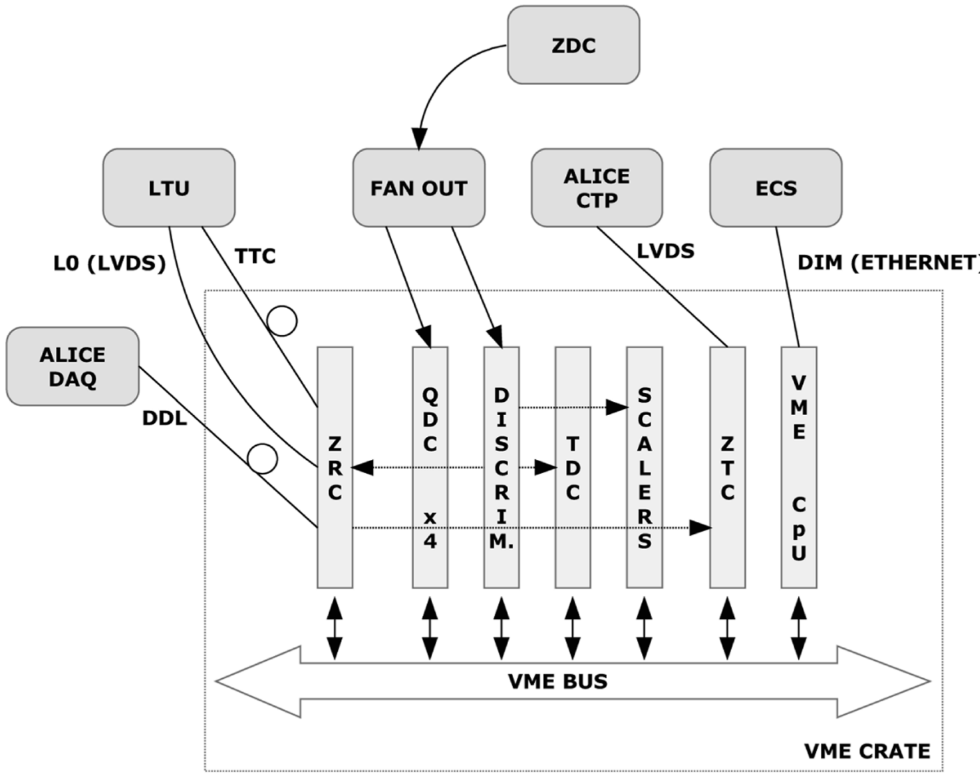


Fig. 4. The ZDC Readout Scheme. It consists of a VME system with a custom board(ZRC) as the master, a VME processor, QDCs, TDCs, Discriminators, ZTC and scalers.

thanks to the ZDC information—it will allow to increase the sample of the more interesting central events). The absence of a L1 trigger in correspondence with a L0 trigger is considered a reject trigger. The L2 trigger allows to reject pile-up and its timing is determined by the slowest detector present. Given these constraints, an efficient readout system should be able to stop the readout process as soon as possible if a L1 signal is not received and to sustain a trigger rate that is comparable with the minimum-bias interaction rate. For what concerns the ZDC these conditions can be satisfied using a VME-based [10] readout system with commercial Analog to Digital Converters and Time to Digital Converters (TDC). However the integration with the ALICE trigger and DAQ systems required the design of a custom readout board—the ZDC Readout Card (ZRC).

Other design constraints are the interaction with the ALICE Experimental Control System (ECS [11]) and the publication of the event rate in the calorimeters for the monitoring of the luminosity. Both of these functionalities have to be based on ethernet services.

An important feature of the design is that the run configuration and run control functions are done by a VME processor, which also interacts with the ALICE Experiment Control System over the ethernet. These could have been considered to be implemented on a NIOS II [12] soft processor on the FPGA of the ZRC. This would have eliminated the VME processor and enabled the ZRC to evolve into a standalone readout system. However, these operations are quite complex, subject to a long prototyping phase and to changes according the run conditions and to the evolution of the ALICE control systems. Moreover the configuration tasks are concentrated in the start of run phase, while the communication needs between the processor and the ZRC during the data taking is minimal (one access every 10 s). For these reasons, it was appropriate to separate the readout and the control functions between the ZRC and the VME processor. Nevertheless, in future, a soft processor implementation can be evaluated and compared against the present system. The ZRC also includes the VME bus arbiter, which is independent of the readout logic and the ZRC configuration.

IV. Readout Components

The ZDC readout consists of a VME system [10] with a ZDC Readout Card (ZRC), a VME Processor, Discriminators, a ZDC Trigger Card (ZTC), scalers, Charge to Digital Converters (QDC) and Time to Digital Converters. The ZDC photomultiplier signals are split by an analog fan out and then sent to the QDCs for readout and to the discriminators, which produce ECL (Emitter-Coupled Logic [13]) signals to be sent to the ZRC where they are combined to form different centrality triggers that are then sent to the CTP via the ZTC. The overall scheme is shown in Fig. 4.

A. *ZDC Readout Card*

The ZDC Readout Card (ZRC), shown in Fig. 5, is a custom board that controls the overall readout operation. It consists of an Altera Stratix III FPGA (EP3SL50F780C4) [14], which hosts the readout logic. This FPGA has 480 user I/O pins, which is suited to our design. The logic resources present in this FPGA are sufficient for both the present readout logic and for possible future additions and modifications, if any, of the readout logic.

The ZRC receives the ECL signals from the discriminators and combines them to produce different triggers (Minimum

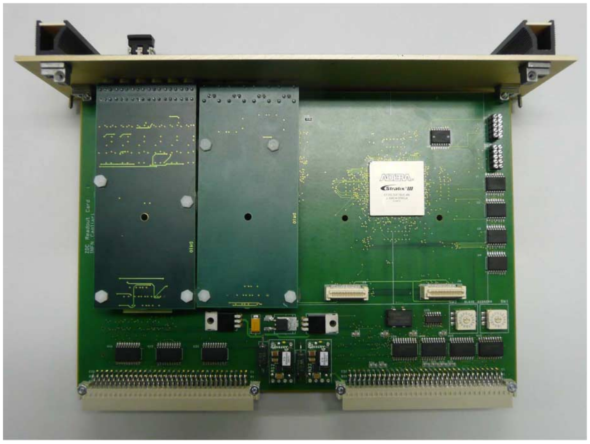


Fig. 5. The ZDC Readout Card (ZRC). It is a custom board with an Altera Stratix III FPGA.

Bias, Central, Semi Central, Electromagnetic dissociation) and sends them to the ZTC. The ZTC counts the number of triggers it receives, synchronizes them with the LHC clock and sends them to the Central Trigger Processor (CTP) of ALICE [7]. The ZRC processes the ALICE triggers from the LTU over an LVDS and an optical fiber link (TTC) [7]. It checks for any errors in the trigger timings. During the readout phase it is the master module. It also acts as the VME bus arbiter, yielding the bus to the VME processor when some control commands have to be sent to the ZRC. The ZRC reads the event data from the QDCs, TDCs and the ZTC over the VME bus. It also reads the scalers in response to requests by the CTP (calibration triggers) or following a user request via DIM (Distributed Information Management System [15]). The ZRC does the event building and sends the event data over the Detector Data Link (DDL [7]) to the ALICE DAQ. The event data format is shown in Fig. 6 and is explained in Section V.

B. VME Processor and the State Machine Interface

The VME processor interfaces the readout system with the Experiment Control System of ALICE using a state machine based on the package SMI (State Machine Interface [16]) that in turn is based on the DIM protocol over ethernet. Software based on these packages is implemented on the VME processor. This defines an SMI object (identified as ZDCPROXY) that provides the ECS an interface to control the configuration of the ZDC readout and trigger modules by sending specific messages over ethernet. The same software allows also to notify the ECS of eventual error conditions and to publish some information (like, for example, the ZDC scaler counts) when required. The processor also configures the ZRC over the VME bus before the start of a run. The configuration registers of the ZRC are shown in Fig. 7. The configuration procedure comprises the following:

- enabling the ZRC,
- programming the delay and width of the QDC gate,
- providing the ZRC with the trigger information (time intervals between different trigger levels arriving from the LTU),
- providing information to the ZRC to reset the link with the LTU if required, over the I2C bus [17],

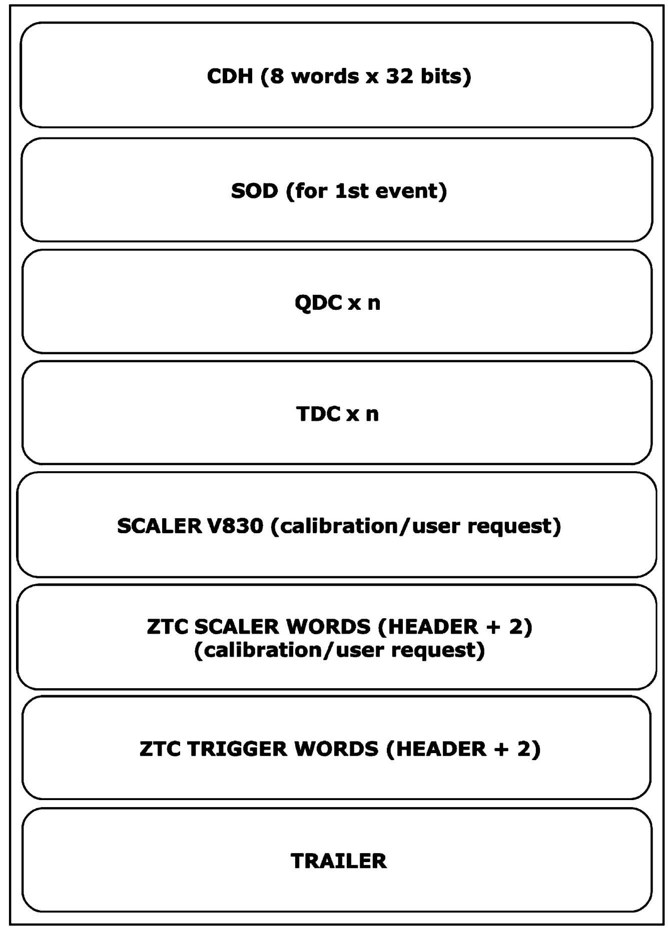


Fig. 6. The ZDC data format. The event data consists of a common data header (CDH), followed by the readout data. Scalers are included in case of a calibration run and an user request. The readout data is followed by a trailer.

- providing the base addresses of the VME modules present which are to be read by the ZRC,
- providing additional data (Start Of Data—SOD) containing the configuration information that are to be sent over the DDL during the first event together with the standard payload,
- defining the type of run,
- informing the ZRC that the run is going to finish.

C. ZDC Trigger Card

The ZRC receives the ECL signals from the discriminators and combines them to produce different triggers (Minimum Bias, Central, Semi Central, Electromagnetic dissociation) and sends them to the ZDC Trigger Card (ZTC). The ZTC counts the number of triggers it receives, synchronizes them with the LHC clock and sends them to the Central Trigger Processor (CTP) of ALICE [7].

D. Other Components

The QDCs and TDCs used are CAEN v965 [18] and CAEN v1290 [19] modules, respectively. The scalers used are CAEN v830 [20] modules. The QDCs and TDCs are configured to be read over the VME bus in a chained block transfer (CBLT [18]) mode. They are given local addresses to be identified in

Address	Description
0x00000000	BEEFDEAD (test for ZRC)
0x00080000	Status Register
0x00100000	Gate delay
0x00180000	L1 time register
0x00200000	L2 time register
0x00280000	I2C register
0x00300000	QDC base address
0x00380000	V830 base address
0x00400000	TDC base address
0x00480000	ZTC base address
0x00580000	First Event Data (write only - SOD)
0x00680000	User request to publish thescalars

Status register bits	Function
bit0	ZRC enable
bit3-10	CDH block attributes
bit11	Mask busy
bit12-14	L0 phase
bit20-25	Scaler read period (x100ms)
bit26-27	# of adc
bit28-31	VME modules present

Fig. 7. The ZRC configuration registers. The VME processor writes into these registers over the VME bus to configure the ZRC at the start of a run.

the chain. The chained block transfer over the VME bus is terminated by the BERR* signal (bus error signal [10]), which is monitored by the ZRC during the readout phase. The v830 scaler module is read by the ZRC in block transfer mode over the VME bus. The ZRC reads the scalers and the trigger words of the ZTC by VME read cycles.

V. Readout Procedure

At the start of a run, the ZDCPROXY is configured by the ECS via DIM. The VME processor requests the VME bus from the VME bus arbiter (implemented in the ZRC). After obtaining bus access, the processor configures the ZRC, resets all the buffers of the ZRC and configures the other VME modules. After this operation, the ZDC front end electronics are ready to process events.

The readout procedure depends on the type of run for ALICE. Apart from the global physics run there are different standalone runs, which include:

- the standalone bunch crossing run, which is a test for the data aquisition chain of ALICE,
- calibration runs like the pedestal, laser and the cosmic run,
- physics standalone runs like the minimum bias, semicentral, central and electromagnetic dissociation run. These runs are a test of the different triggers sent to ALICE.

A. Global Physics and Standalone Bunch Crossing (BC) Run

The trigger and readout sequences for global physics and standalone BC runs are shown in Figs. 8 and 9, respectively. The L0 signal arrives to the ZRC on the LVDS cable 1.2 μs after an event. The L0 signal is also broadcast over channel A of the TTC (within ALICE), but this is only useful for those detectors that do not need a critical timing of the L0 signal, as it may have a one clock cycle jitter. This option is excluded for the ZDC. On receiving the L0, the ZRC produces a NIM [21] gate with a programmable delay and width, which is sent to the QDCs and the TDCs. The ZRC asserts an LVDS signal called ZDC-BUSY, which is sent to the LTU to prevent any further arrival of triggers for new events. The QDCs and TDCs, on receiving the gate, initiate data conversion.

The L1 signal arrives over channel A of the TTC 6.2 μs after the corresponding L0 signal. This is followed by the L1 message (5 words) over channel B of the TTC, which is received at most 500 μs after the corresponding L0 signal. As soon as the ZRC receives the L1 trigger and the QDCs and TDCs have finished data conversion (7.2 μs), the ZRC reads the QDCs and TDCs over the VME bus using the Chained Block Transfer mode and stores the data in a FIFO for event building. In case of a L1 absence, the QDCs and TDCs are cleared by a hardware reset (a NIM signal from the ZRC).

The trigger words are then read from the ZDC Trigger Card over the VME bus and stored. For these words, a header is inserted during the event building stage. During calibration runs and upon a user request (via DIM), the ZRC reads and stores the scalers from the v830 module and the scalers from the ZTC, prior to reading the ZTC trigger words. Upon a user request, the scalers are also sent to the VME processor for publishing. The frequency with which the scalers are read can be programmed (in multiples of 100 ms) in the status register of the ZRC. A header is inserted for these scalers during event building. Finally, a trailer is inserted in the event data.

The L2 messages (8 words) are received over channel B of the TTCrx at most 500 μs after the corresponding L0 signal.

The ZRC forms a common data header (CDH [22]) using the words from the L1 and L2 message words. The header also contains error bits that indicate any errors during the readout phase or any trigger errors (for example, the timing difference violation between the L0 and L1 signals) detected by the ZRC. The different types of trigger errors and the ways of handling those errors is done according to the algorithms described in [23] and [24]. The event building is done according to Fig. 6, with the CDH followed by the readout data and finally the trailer.

When a L2 accept trigger arrives, and if the DDL is ready for data transfer, the ZRC transmits the event data to the ALICE DAQ. After successful data transmission over the DDL, the ZRC releases the ZDC-BUSY signal and is ready for processing a new event. If a L2 reject signal arrives, the FIFO storing the event data is cleared and the ZDC-BUSY signal is released.

In future, with the FPGA resources available on the ZRC, the system can be modified to accommodate a multi event buffer, if required. It is possible that the L0 and L1 signals for a certain event is followed by the L0 and L1 signals for the next event before the arrival of the L2 signal corresponding to the previous

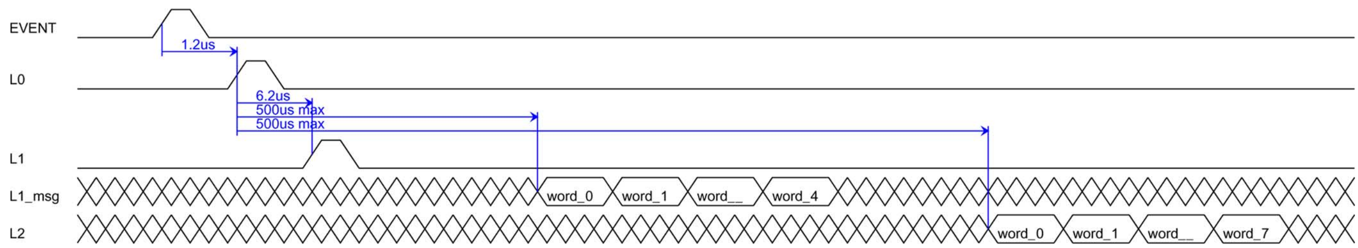


Fig. 8. A L2 accept sequence. The L0 trigger arrives 1.2 μs after an event. The L1 trigger arrives 6.2 μs after L0. This is followed by L1 trigger messages (5 words) which arrive at most 500 μs after L0. Finally, the L2 trigger messages (8 words) arrive at most 500 μs after L0.

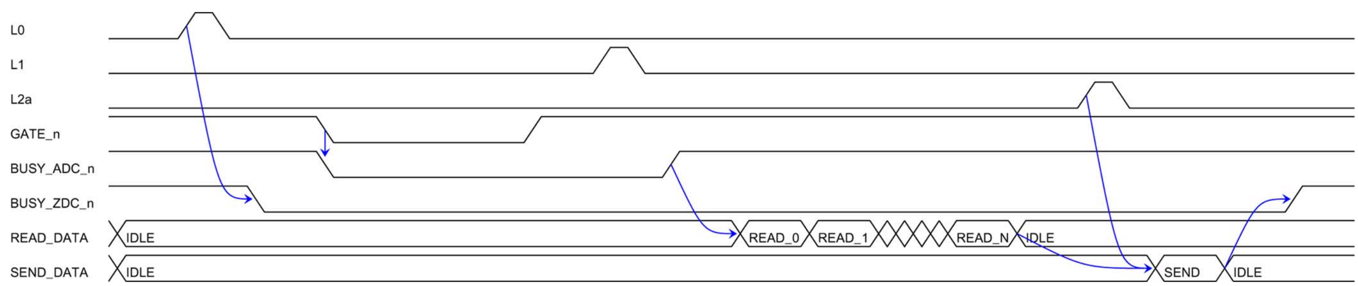


Fig. 9. A sample timing diagram for readout in a Physics run in ALICE. The readout is performed according to the state of the ALICE triggers. The system is busy during a readout and becomes ready to process a new event after successful transfer of the readout data.

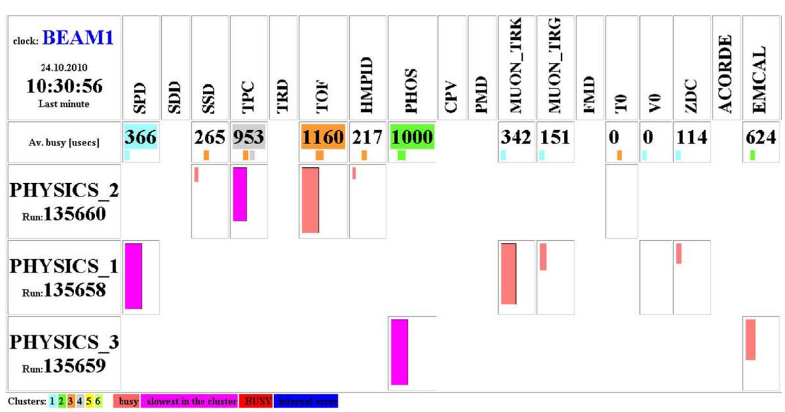


Fig. 10. A global physics run in ALICE showing the dead times of the participating detectors.

event. With a multi event buffer, the ZRC can start processing the L0 and L1 signals of the next event and start reading out the next event data while the previous event data is awaiting the corresponding L2 signal and hence its transmission to the ALICE DAQ. This would enable processing and storage of more events.

B. Standalone Laser, Physics, Cosmic and Pedestal Run

For what concerns other types of standalone runs, the triggering has to be different due to specific timing constraints. In fact, in this case, the trigger sequence is not started by the ALICE Central Trigger Processor but by the ZDC readout electronics, which take control of the LTU using its PULSER input.

A laser run is controlled by an internal timing unit. A pulse is sent to the lasers after specific intervals. Along with the laser pulses, the ZRC generates the gate for the QDCs. An internal trigger request is also generated and sent to the LTU. On receiving the request, the LTU sends trigger sequences to the ZRC. Thus, the gate for the QDCs is generated prior to the arrival of the L0 signal; the gate delay is programmed accordingly.

For a standalone physics run, the sequence is started by an external signal rather than from the internal timing unit signal. On receiving the external signal (NIM), the ZRC sends the trigger request to the LTU and the gate signal to the QDCs.

The readout procedure for the standalone cosmic run is similar to that of the standalone physics run.

The standalone pedestal run is similar to the laser run except the fact that no laser pulse is sent.

The external pulsing signals and the trigger request signals are masked for the readout sequence of the first and last events since these special events are always triggered by the request of the DAQ control system. The logic also takes into account the LHC long gap, during which the LTU does not entertain trigger requests.

VI. Conclusion

The readout system was successfully tested during the 2009 data taking for ALICE at the CERN LHC. According to the ALICE DAQ and Trigger requirements, the system can accept a new trigger 25 ns after releasing the ZDC-BUSY signal. The

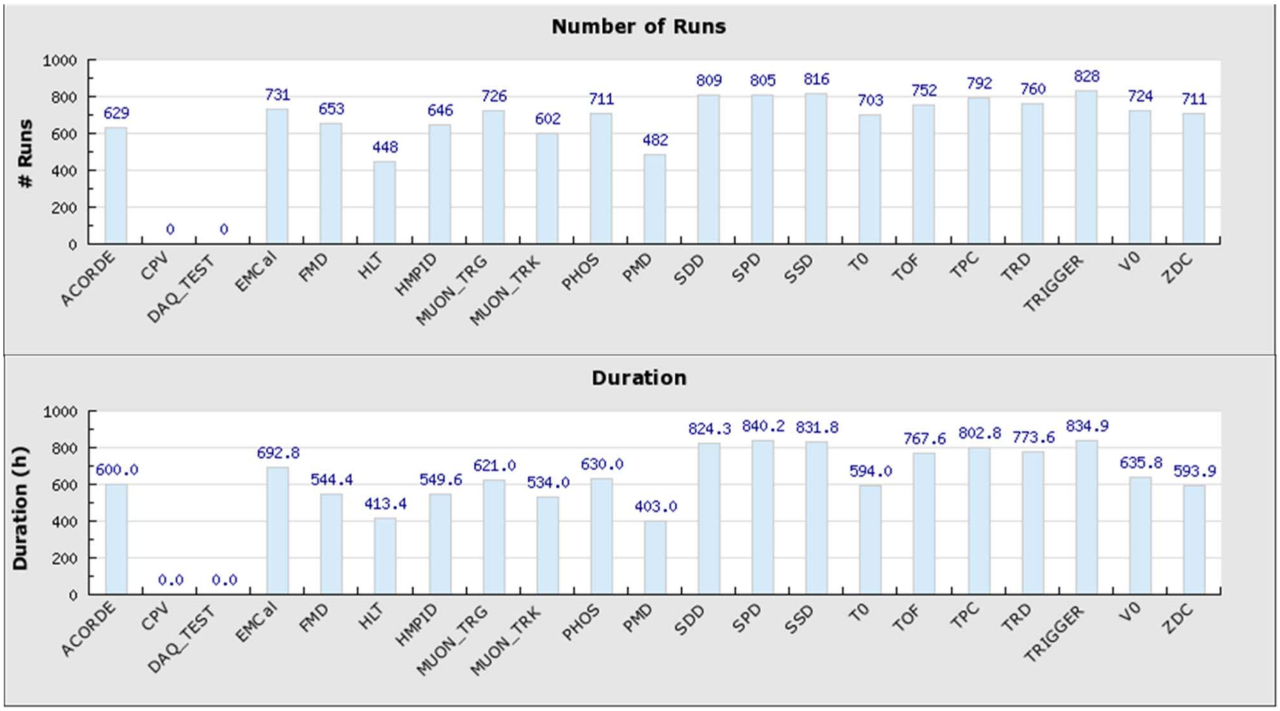


Fig. 11. During the period 01.01.2010 to 18.10.2010, ZDC participated in 711 global physics 'good' runs for 593.9 hours involving the PHYSICS-1 partition of ALICE.

maximum sustainable data rate in this condition is 9 KHz corresponding to a readout time of 114 μs. This is comparable with the expected interaction rate and is much lower than the readout time of the tracking detectors. Therefore the ZDC readout in this new configuration is not a limiting factor for data taking speed. A global physics run during proton-proton collisions showing the dead time of the participating detectors is shown in Fig. 10.

The system is currently operational at the CERN LHC. According to the statistics recorded by the ALICE electronic logbook [25], during the period 01.01.2010 to 18.10.2010, there were 876 global physics runs (run quality marked as 'good') for 886.5 hours in ALICE involving the PHYSICS-1 partition. ZDC participated in 711 of those runs for 593.9 hours (Fig. 11).

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