Performance of the readout system of the ALICE Zero Degree Calorimeters in LHC Run 3

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Abstract. The ALICE Zero Degree Calorimeters (ZDC) provide information about event geometry in heavy-ion collisions through the detection of spectator nucleons and allow to estimate the delivered luminosity. They are also very useful in p–A collisions, allowing an unbiased estimation of collision centrality. The Run 3 operating conditions will involve a tenfold increase in instantaneous luminosity in heavy-ion collisions, with event rates that, taking into account the different processes, could reach 5 MHz in the ZDCs. The challenges posed by this demanding environment lead to a redesign of the readout system and to the transition to a continuous acquisition. The new system is based on 12 bit, 1 Gsps FMC digitizers that will continuously sample the 26 ZDC channels. Triggering, pedestal estimation and luminosity measurements will be performed on FPGA directly connected to the front-end. The new readout system and the performances foreseen in Run 3 are presented.

1. Introduction

ALICE is the LHC experiment that is dedicated to study the different signals of the formation of quark-gluon plasma in heavy-ion collisions [1]. It is composed of a central barrel in a solenoidal magnetic field with excellent tracking and PID capabilities, a forward muon spectrometer used to study quarkonia and heavy flavor decays, and several forward detectors used to characterize the collision [2]. Among those detectors is the Zero Degree Calorimeter (ZDC) system of four hadronic calorimeters that detect protons and neutrons emerging from the collisions at rapidities close to the one of the beam. The ZDCs are located in the LHC tunnel, 112.5 m from the interaction point (IP) (ZNA on the "A side" and ZNC on the "C side" in the naming scheme of the ALICE experiment). These are complemented by two small electromagnetic calorimeters (ZEM), at $\sim$ 7.5 m from the IP on the "A side" (opposite to the muon spectrometer), to tag hadronic collisions. The main purpose of these calorimeters is to provide an independent measurement of the time of the collision, vertex position, centrality, event plane, and to measure the luminosity in heavy-ion operation [3, 4, 5, 6].

During years 2019 and 2020 the LHC and its injection chain underwent an upgrade that will allow to reduce the bunch spacing in heavy-ion operation down to $\sim 50\,\text{ns}$ and increase the luminosity by about a factor 10, increasing the hadronic interaction rate in Pb–Pb collisions from 8 kHz to 50 kHz. In order to exploit the potential offered by the increased luminosity, the ALICE experiment upgraded several detectors [7] and its trigger and readout system [8] in order to be able to acquire all collisions in triggerless mode without dead time with a quasi-online reconstruction [9].

2. The upgrade strategy of the ZDC readout system

The operating conditions for the ZDC in LHC Run 3 will be very challenging, expecially concerning Pb–Pb collisions, due to the presence of a strong physical background from electromagnetic dissociation processes [10, 11] (EMD), in particular for the neutron calorimeters. These processes have large cross sections for neutron emission, $\sim 6.6\,\text{b}$ for correlated neutron emission that hit both ZNs and $\sim 110\,\text{b}$ for uncorrelated neutron emission that impact on each side. The resulting trigger rates will be of the order of $\sim 2.5\,\text{MHz}$, well beyond the possibilities of the VME based system [12] that was successfully operated during Run 1/2. The EMD background cannot be rejected in a triggerless acquisition since its signature in the ZDC cannot be distinguished from ultra peripheral hadronic collisions.

2.1. The architecture of the upgrade

Thanks to the low number of channels to be instrumented, a viable solution was found in FMC digitizers, that allow a continuous sampling of the input signal and a real-time signal processing on a FPGA. This allows data reduction with the implementation of autotrigger algorithms and, if necessary, an improvement of the same algorithms along the life of the experiment without changing the hardware. The architecture will therefore be modular. A scheme of one module of the readout system is shown in figure 1. Also implemented on FPGA is the pedestal evaluation by averaging the waveform during intervals where no collision can happen, depending on the LHC filling scheme. The number of autotriggers is also integrated over each LHC orbit in order to provide an online estimation of the luminosity delivered to the experiment.

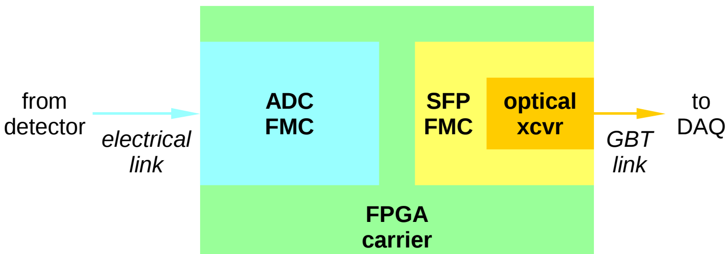

Figure 1. Scheme of the readout system for the ZDC upgrade. A fast digitizer in FMC format is read out by a FPGA and the portions of waveform where a signal is present are transferred to the acquisition through an optical link (GBT).

The identified solution for continuous readout is based on FMC digitizer ADC_3112 from IOXOS, mounting a TI ADS5409 digitizer. The mezzanine is hosted on a carrier of the same company. The carrier is in VME format to exploit existing infrastructure, the readout however will not be done on VME but on GBT-FPGA links. The most relevant specifications of the digitizer are: maximum sampling frequency of 1 Gs/s, 1 Vpp dynamics, 12 bit resolution with ENOB of 10 bit, and 4 channel per module. The ADC_3112 has DC coupling, a feature not very common among digitizers, that is nevertheless quite important for unipolar photomultiplier signals [6].

2.2. Operation of the digitizer

The 100 MHz crystal oscillator of the digitizer has been replaced with one with a slightly higher central frequency, in order to allow it to lock to the LHC bunch crossing (b.c.) frequency of ~ 40.079 MHz. In this way the sampling frequency will be a multiple of the LHC frequency and the clock phase with respect to the arrival of the signal will be constant, making easier to identify each collision. The sampling rate has been reduced from 1 GSps to 962 MSps to acquire 24 samples per bunch crossing.

The digitizer is readout with oversampling and decimation. In order to exploit the full input dynamics, the input signals will be shifted by ~ 450 mV and consequently the automatic baseline correction and inter-calibration of interleaved samples must be disabled. In principle one would therefore need to introduce an interleaving calibration algorithm in the FPGA firmware. Fortunately this is not necessary because the bandwidth of the signal is lower than ~ 240 MHz and therefore we can exploit the digital low pass filter and decimation feature of the digitizer. This oversampling-decimation technique effectively smooths the different offsets of even and odd samples and reduces electronic noise. This also has the advantage of reducing the data payload to 12 samples per bunch crossing.

2.3. Autotrigger strategy and cabling

A critical aspect of the ZDC operation in Run 3 will be triggering in the presence of a large signal dynamics (from a single neutron signal to ~ 60 neutrons for Pb–Pb collisions). The interval between consecutive interactions will be reduced to 50 ns, which is lower than the length of the signal. The autotrigger algorithm will therefore need to deal with a baseline that might not be fully restored when the next collision occurs. This will be accomplished by a differential trigger algorithm in which samples at different times are compared (sample y_{i} with sample $y_{\mathrm{i+shift}}$). If three successive pairs are above a configurable threshold th the firmware will trigger the acquisition of the event. The repetition of the trigger conditions for three successive samples improves the resilience to the electronic noise.

The autotrigger strategy takes advantage of the segmentation of the detectors. The light produced by the hadronic showers is collected in such a way that half of the light is readout by a "common" photomultiplier (PM) and the other half by fibers that are bundled to divide the detector into four towers [13], providing some sensitivity to the impact position of protons and neutrons on the front face of the detectors. In normal operation the autotrigger of each neutron calorimeter is based on the common PM that has best energy resolution. The signals are therefore fanned-out to two modules but readout only once. The analog signals of the four towers are summed to provide an alternative autotrigger in case of failure of the common PM and therefore are readout on two modules. The remaining four free channels in the pair of modules are dedicated to the readout of the four towers. The coincidence of the common PM with the sum of towers is enforced during offline reconstruction to suppress fake hits due to the electronic noise of the PMs. For the proton calorimeters (ZP) the redundancy requirement is less stringent since, for hadronic collisions in the centrality ranges that are useful for analysis, the ZEM calorimeters also have signal. A cabling scheme that implements these ideas is shown in table 1.

2.4. Firmware architecture

The data flow of each digitizer in the FPGA is pipelined and the main blocks are summarized in figure 2. The logic is working at about ~ 240 MHz, i.e. six clock cycles are available to process the information produced in a bunch crossing.

The acquisition is controlled through a GBT link from the Common Readout Unit (CRU) that provides: commands to configure the electronics and the readout mode (continuous or triggered), start and stop acquisition commands, synchronization signals at the beginning of

Table 1. Cabling of the upgraded ZDC readout system with channel roles in normal operation. Vertical lines indicate the eight modules. The trigger channels are identified in bold (common photomultipliers and ZEM), the channels that are not readout in normal operation are in italics (sum of towers of neutron calorimeters that is readout only in the second module of each pair).

ZNA TC	***ZNA TC***	**ZNC TC**	***ZNC TC***	**ZPA TC**	***ZPA TC***	**ZPC TC**	***ZPC TC***
ZNA sum	ZNA sum	*ZNC sum*	ZNC sum	**ZEM1**	ZPA sum	**ZEM2**	ZPC sum
ZNA T1	ZNA T3	ZNC T1	ZNC T3	ZPA T1	ZPA T3	ZPC T3	ZPC T1
ZNA T2	ZNA T4	ZNC T2	ZNC T4	ZPA T2	ZPA T4	ZPC T4	ZPC T2

each orbit, orbit counter and bunch crossing counter, and eventual trigger information. The payload of the upstream link is 80 b for each bunch crossing and is fanned-out to the processing pipelines of each channel. The clock recovered from the GBT link is used to synchronize the clock of the digitizer. Digitizer data after decimation result in 12 words of 12 b for each channel and for each bunch crossing and are aligned with the bunch crossing with a resolution of 1 sample. After synchronization, 12 triple-trigger conditions are evaluated in a window of 12+2 samples related to each bunch crossing. If any of those are satisfied, the bunch is flagged for acquisition. Information from a local orbit counter, bunch crossing counter, and number of hits along the orbit are also inserted in the data stream for each channel.

Collisions at the IP can occur only in well defined bunch crossings, depending on the active LHC filling scheme. This feature is exploited to identify bunch crossings that are free from any signal and can be used to evaluate the average baseline for each orbit.

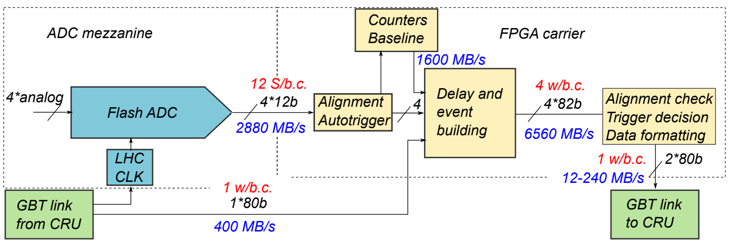

Figure 2. Scheme of the data flow in the FPGA firmware for a readout module. The rate of information for each link is shown as red text, in black the number of lanes * the bus width, and in blue the data bandwidth.

The first stage of the event building combines the different pieces of information for each channel by means of a ring buffer delay that synchronizes the output of the digitizer with the ALICE trigger information and with locally computed quantities. Processing is synchronous up to this stage. The full information on each bunch crossing is then passed to the second stage of event building using a FIFO. The final selection algorithm performs an alignment check of the four data streams, verifies the autotrigger condition or the presence of the ALICE trigger, verifies the presence of interactions in the three preceding bunch crossings (pile-up) and formats the output data for transmission to the CRU. In the present implementation a hit on a triggering channel enables the acquisition of all the active channels connected to the module. If no autotrigger or trigger condition is present the event is discarded from the FIFO.

In autotrigger mode, each active channel produces a payload of 60 B of which 30 B are for the signal and the other 30 B are the samples of the previous bunch crossing (with respect to the triggered bunch crossing), that are used to perform a more accurate baseline subtraction during reconstruction and to detect the presence of pile-up. Each module is readout by two GBT links. The payload bandwidth ranges from 12 MB/s for the modules with lower occupancy (connected to the detectors sensitive mainly to hadronic collisions) to about 240 MB/s for the four modules dedicated to the readout of the neutron calorimeters.

3. Expected performances and conclusions

During 2018 Pb–Pb LHC run an ADC_3112 digitizer was operated in parallel to the ALICE system using a prototype acquisition system, allowing to test the performances of the new electronics, to determine the optimal operating conditions, and to develop reconstruction algorithms. In figure 3 a typical minimum bias Pb–Pb ZDC spectrum at $\sqrt{s} = 2.76$ TeV is shown. Neutron multiplicities up to three neutrons are separated. The resolution on the 2.76 TeV single neutron emission detected by ZNC is $\sim 17\%$, with an improvement with respect to the previous used electronics ($\sim 20\%$ resolution on single neutron energy). In figure 4 the reconstructed arrival time of the signals is shown. The time resolution with respect to the ALICE L0 trigger is ~ 0.35 ns, a value that is comparable with the performance of the previous system.

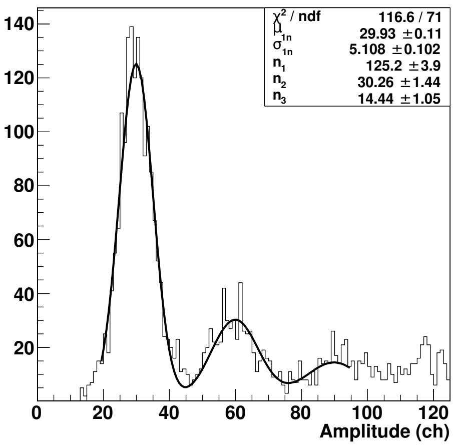

Figure 3. The reconstructed signal amplitude spectrum in minimum bias Pb–Pb collisions, obtained with a prototype readout.

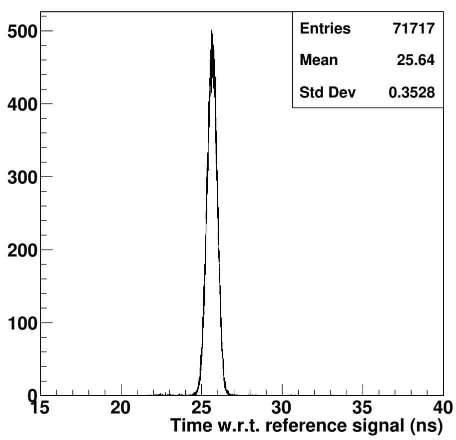

Figure 4. Reconstructed signal arrival time for minimum bias Pb–Pb collisions with respect to a reference signal (ALICE L0 trigger).

In conclusion, FMC digitizers with online signal processing and auto-triggering performed on FPGA are a viable solution for the digitization of fast detectors with few readout channels like ALICE ZDC calorimeters, expecially in the harsh environment of Pb–Pb collisions at LHC where these detectors will be exposed to a strong physical background from Electromagnetic Dissociation of Pb ions. For unipolar signals a DC coupled digitizer is essential and the operating parameters need to be carefully tuned. In particular oversampling followed by digital low pass filtering and decimation by two is quite effective in reducing digitization noise.

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