EPJ Web of Conferences **320**, 00014 (2025) https://doi.org/10.1051/epjconf/202532000014
CALOR 2024

Performance of the ALICE Zero Degree Calorimeters in LHC Run 3

Stefan Cristi Zugravel[1,2,⋆] on behalf of the ALICE Collaboration

[1] *INFN Torino*
[2] *DET POLITO Torino*

Abstract. The Zero Degree Calorimeters (ZDC) of the ALICE experiment at the LHC were designed to characterize the event and monitor the luminosity in heavy-ion collisions. In order to fully exploit the potential offered by the LHC increased luminosity in Run 3, while preserving the time and charge resolution performance, the ZDC readout system was upgraded to allow the acquisition of all collisions in self-triggered mode without dead time. The presence of electromagnetic dissociation (EMD) processes makes the ZDC operating conditions extremely challenging, raising the readout rate for the channels of the most exposed calorimeters up to ≈ 1.4 Mevents/s, compared to an hadronic rate of about 50 Kevents/s sustained by all other detectors. The new acquisition chain is based on a commercial 12 bit digitizer with a sampling rate of ≈ 1 GSps, assembled on an FPGA Mezzanine Card. The signals produced by the ZDC channels are digitized, the samples are processed through an FPGA that, thanks to a custom trigger algorithm, flags for readout the relevant portion of the waveform and extracts information such as timing, baseline average and event rate. The system is fully integrated with the ALICE data taking infrastructure and acquired physics data during the 2023 LHC heavy-ion data taking. The architecture of the new readout system, the auto trigger strategy, and the ZDC performance during the 2023 Pb–Pb collisions are presented.

1 Introduction

The Zero Degree Calorimeters (ZDCs) of the ALICE experiment at CERN consist of two identical sets of calorimeters located on both sides of the interaction point 2 (IP2) (namely side A and side C), 112.5 m away from it [1, 2]. At the IP2 the two LHC beams circulating in two different beam pipes are put into collision into a common beam pipe. Each set of detectors consists of a neutron (ZN) and a proton (ZP) calorimeter. The ZN is placed at zero degree with respect to the LHC axis, between the two beam pipes, while the ZP is positioned externally to the outgoing beam pipe. The ZDC detector is completed by 2 forward electromagnetic calorimeters (ZEM) placed at about 7.35 m from IP2, on side A. The ZDC calorimeters are based on the detection of Cherenkov light produced in radiation-hard quartz fibers. The ZDC was designed to characterize the events and monitor the luminosity during heavy-ion data taking [3–6].

2 The new readout system

During the LHC Long Shutdown 2 (2019–2022) the ALICE experiment upgraded its trigger and readout system in order to be able to acquire Pb–Pb collisions in continuous readout at an hadronic rate up to 50 kHz [7–10]. The ZN detector is mainly sensitive to neutron emission in hadronic and EMD interactions. The presence of EMD interactions raises the event rate of the most exposed channels by a factor ≈ 28 bringing the event rate up to 1.4 MHz [11–13]. The readout system used in Run 1 and Run 2, before the Long Shutdown 2, based on Charge-to-digital converters (QDCs), with a fixed dead time of ≈ 10 μs, could not cope with such high event rate [14]. In order to be compliant with the new acquisition mode foreseen in Run 3, a completely redesigned readout system was installed at IP2 [15]. The new hardware and firmware were studied in order to:

- preserve the time and charge resolution performance of Run 2 (≈ 20% energy resolution for the single neutron peak and ≈ 0.35 ns time resolution w.r.t. ALICE L0 trigger);
- allow data taking in self-triggered mode without dead time (namely "continuous readout") at an average event rate in Pb–Pb collisions of 2.5 MHz. This value was calculated by multiplying the expected event rate by a safety factor of ≈ 2;
- be capable of triggering efficiently in presence of a large signal dynamics (from a single neutron signal from EMD processes up to ≈ 60 neutrons for Pb–Pb central collisions);
- have a triggering algorithm capable of flagging physics events with a bunch spacing of 50 ns; this is lower than the length of the signal of 60 ns;
- evaluate for each orbit the average of the baseline in the bunches where no collisions take place;

[⋆] e-mail: stefan.zugravel@to.infn.it

- monitor and compute in real time the collision rate for each channel independently.

In order to exploit the existing infrastructure, the VME format was chosen for the new readout; more specifically the IFC1211 carrier from IOxOS [15]. Each module has two FMC connectors, one hosts an ADC3112 from IOxOS (a 12 bit, with ENOB of 10 bits, ADC with ≈ 1 GSps sampling rate, 1 V amplitude, 4 channels, configurable with 50 Ω termination), while the other FMC connector sits 4 SFP+ connectors, of which only 2 are used to implement a CERN developed 4.8 Gbps bi-directional optical link (GBT) [16]. Each analogue signal from the ZDC is directly connected to one of the digitizer inputs which produces 12 digital samples per LHC bunch crossing (BC = 25 ns). The system performs the triggering evaluation on already digitized data using an INFN developed differential algorithm reported in Eq. (1), where y_i is the i^{th} sample and t is a configurable threshold [17].

$$T = (y_i - y_{i+k} > t) \;\; \& \;\; (y_{i+1} - y_{i+k+1} > t) \qquad (1)$$

Typical values for the algorithm parameters are $k = 4$ and $t = 10$. The slow control, the configuration of the parameters, and the handling of the reset procedures are all carried out using the Single Word Transfer (SWT) protocol implemented through the ALICE Common Readout Unit (CRU) [18, 19]. The complete readout system is composed of 8 IFC1211 modules, each one capable of managing 4 ZDC channels, thus 32 in total. The ZDC detector has 26 channels, the remaining 6 are used for redundancy purposes [15, 20]. The system was successfully commissioned at low rate with a Pb–Pb low intensity test run in November 2022.

2.1 The auto-calibration procedure

The ADC sampling clock and the ZDC logic clock are generated by two different PLLs. The first one internal to the digitizer itself; the second one recovered from the GBT link. Each time the link is established, thus at each LHC fill, the phase between the two clocks changes. For proper time measurements the peak of the nominal signal must be centered relative to the bunch crossing. This is done through a set of two delay parameters (sample and coarse) for each channel. The delay sample shifts the waveform inside the BC with a granularity of 1 sample, meanwhile the delay coarse moves the signal with 1 BC granularity and is used to compensate for the delay of the analog signal coming from the LHC tunnel. An in-firmware procedure was implemented to automatically calculate and set the appropriate delay parameters at each start of fill. All ZDC channels are in-time with each other thanks to a fine tuned delay line which takes into account the different timing response of each PMT. This means that the delay parameters are used to compensate only the phase shift between the reference GBT clock and the sampling clock of each ADC module. During the calibration procedure the Central Trigger Processor (CTP) [19] sends a special 30 mV amplitude, 2 ns width reference signal, always in sync with the LHC beams, to each ZDC channel. When the rate of the reference signal is higher than a configurable threshold (usually 5 kHz) the ZDC logic begins the calibration procedure following these steps:

- all the delays are set to 0 in order to start from a known value;
- the logic does a scan of all possible delay sample values (from 0 to 11) and each time fills an histogram where each bin represents the sample where the auto-trigger algorithm fired. The number of entries to be reached can be configured from 256 to 4096 in steps of powers of 2;
- once the delay value that leads to the highest number of entries in bin (sample) number 6 is found, the logic raises a flag and waits for the other channels to finish;
- when all the channels are ready a fine tuning procedure begins. If the previous operation does not converge in a configurable timeout number of tries the calibration gets aborted;
- a second step is done focusing on the value of the digitized signal in samples 5, 6 and 7. Since the ZDC signal has negative polarity, if the value of sample number 6, on average, is the lowest, it means that the peak of the waveform is centered with respect to the BC, and thus the delay sample parameter gets frozen, otherwise it can be tuned by ±1;
- a similar approach is used for the delay coarse setting. During the calibration phase the reference signal is always sent to the same known BC which is saved as a configurable parameter. The logic records a configurable number of LHC orbits focusing on the BC where the calibration signal is expected and the two coming before and after that. A 3 bin histogram is generated where the bins are BC-1, BC, and BC +1 and the entries are the number of auto-trigger events in each BC;
- if the center bin has the highest number of entries then the delay coarse value remains unchanged, otherwise it gets corrected by ±1 BC depending on the case. It is worth noting that this delay coarse procedure is not iterative, the measurement is done just once since the expected variation from fill to fill is at maximum ±1 BC.

3 Performance during the 2023 Run 3 Pb–Pb data taking

From September 26^{th} to October 29^{th} 2023 the first Pb–Pb data taking campaign of Run 3 was carried out. During this five week period the number of collisions recorded by ALICE is 40 times greater than the total recorded by the experiment in its previous periods of heavy-ion data taking, from 2010 to 2018 [21]. Thanks to the upgrades to the LHC machine and the new readout capabilities of the ALICE experiment, a center-of-mass energy of 5.36 TeV per pair of nucleons and a collision rate six times higher with respect to Run 1 and Run 2 were achieved. The ZDC detector acquired physics data during all of the runs working also as luminomiter of the experiment.

3.1 Waveform signal

The continuous sampling of the signal provided by the ADC & FPGA system allows the recording of the complete raw ADC samples of the waveform. In Fig. 1, the signal from the neutron calorimeter on side A is shown, with the sample numbers from 0 to 11 (1 BC) on the X-axis and the waveform amplitude in ADC counts on the Y-axis. The EMD interaction in which a single neutron is emitted is the most likely event. In this case the typical amplitude is ≈ 27 ADC counts (measured from the baseline of the signal at 1100 ADC counts down to the first peak at 1073 ADC counts) which corresponds to a measured electric signal of 8 mV amplitude. The hadronic collisions are much less frequent, and provide a much larger signal, peaking at ≈ 2100 ADC counts (620 mV). The system was able to handle the self triggering in presence of this large signal dynamics.

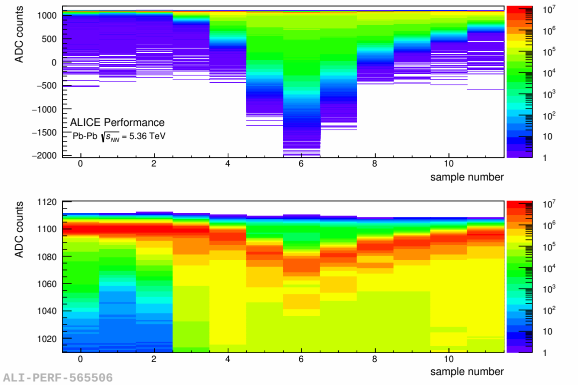

Figure 1. TOP: neutron calorimeter side A signal waveform. BOTTOM: zoom on 1 and 2 neutrons signals.

3.2 Energy resolution

As mentioned in section 2.1, the ZDC signal is timed in such a way that the peak of the waveform is in sample n°6, thus, by summing the values from sample n°4 to sample n°8 the integral of the waveform is obtained. This value can be plotted on a histogram and the energy spectra of the calorimeter is obtained as shown in Fig. 2. The readout system used during Run 1 and Run 2 had a resolution for the 1 neutron peak of ≈ 20%, while the new system reached a resolution of ≈ 15%.

3.3 Time resolution

The correlation between the sum and the difference of the times recorded by the 2 ZNs on either side of IP2 allows to discriminate the nominal interactions from all the parasitic collisions. An example is shown in Fig. 3; the nominal interactions being in the central red spot, while on the diagonals the parasitic interactions are displayed. The LHC RF work at 400 MHz and nominally only one out of 10 buckets can contain a packet [22]. The parasitic interactions are caused by some ions falling in the adjacent RF buckets with respect to the nominal ones.

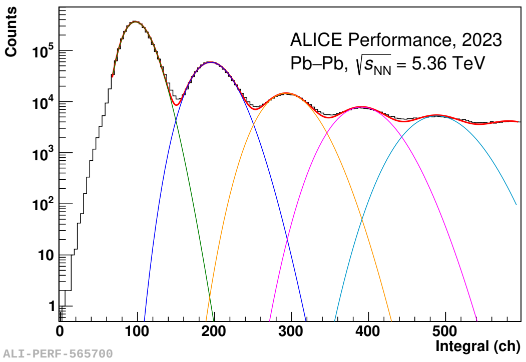

Figure 2. Neutron calorimeter, side C, energy spectrum with fit up to the 5 neutron peak.

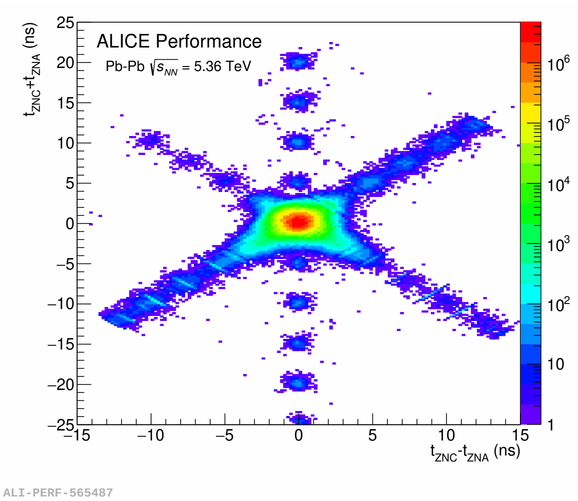

Figure 3. Timing plot: ZNC+ZNA vs. ZNC-ZNA.

3.4 PMT Ageing

During the October 2023 Pb–Pb data taking the single neutron and proton peaks were monitored in order to keep the radiation damage under control. Especially during the data taking at full intensity, the most exposed calorimeters reached an event rate up to 1200 kHz; this caused a current in the photo-multipliers higher than what was seen during Run 1 and Run 2 that led to a progressive ageing of the light detectors. A trending plot of single neutron and single proton peak position is shown in Fig. 4. It can be noted that the signal loss is more important for neutron calorimeters than for proton calorimeters; this is due to the higher rate sustained by the first ones. In order to maintain the amplitude of the single neutron peak in the range where the signal/noise discrimination is fully efficient, the voltages of the ZN photo-multipliers were increased in the last part of the data taking period to recover the signal loss.

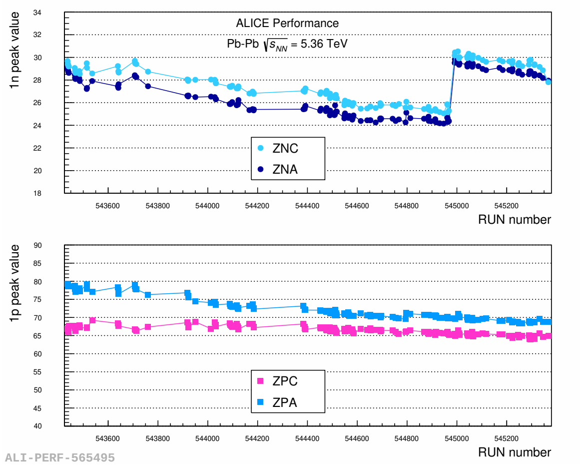

Figure 4. Trending plot for single neutron and single proton peaks.

4 Conclusions

The new ZDC readout system development was finalized and commissioned al low intensity during 2022. In October 2023 the system acquired data at full intensity during the Pb–Pb campaign. The detector operation at 50 kHz hadronic interaction was validated. In particular, it was verified that the energy resolution is better with respect to the previous readout. The new auto-trigger algorithm works efficiently as studied in simulation, and the ALICE computing farm handled without issues the data from the ZDC. Finally the ZDC operated as the ALICE luminometer, sending the ZN side C rate, i.e. the rate of neutron emission in EMD + hadronic interactions, to the LHC control center.

References

[1] ALICE Collaboration, Journal of Instrumentation **3**, S08002 (2008)
[2] ALICE Collaboration, International Journal of Modern Physics A **29**, 1430044 (2014)
[3] ALICE Collaboration, Phys. Rev. C **88**, 044909 (2013)
[4] ALICE Collaboration, Phys. Rev. C **91**, 064905 (2015)
[5] K. Oyama (2013), `arXiv:1305.7044`
[6] P. Cortese, for the ALICE Collaboration, Journal of Physics: Conference Series **1162**, 012006 (2019)
[7] ALICE Collaboration, Journal of Physics G: Nuclear and Particle Physics **41**, 087001 (2014)
[8] P. Antonioli, A. Kluge, W. Riegler (ALICE), Tech. rep., CERN (2013), `https://cds.cern.ch/record/1603472`
[9] P. Buncic, M. Krzewicki, P. Vande Vyvre, Tech. rep., CERN (2015), `https://cds.cern.ch/record/2011297`
[10] ALICE Collaboration, Journal of Instrumentation **19**, P05062 (2024)
[11] ALICE Collaboration, Phys. Rev. Lett. **109**, 252302 (2012)
[12] I.A. Pshenichnov, J.P. Bondorf, I.N. Mishustin, A. Ventura, S. Masetti, Phys. Rev. C **64**, 024903 (2001)
[13] I.A. Pshenichnov, Physics of Particles and Nuclei **42**, 215 (2011)
[14] S. Siddhanta, C. Cicalo, A. De Falco, M. Floris, A. Masoni, G. Puddu, S. Serci, A. Uras, G. Usai, R. Arnaldi et al., IEEE Transactions on Nuclear Science **58**, 1759 (2011)
[15] S. Zugravel, P. Cortese, G. Cotto, N.D. Marco, P.D. Remigis, L. Lombardo, G. Mazza, C. Puggioni, E. Puleo, L. Quaglia et al., Journal of Instrumentation **18**, C02009 (2023)
[16] M.B. Marin, S. Baron, S. Feger, P. Leitao, E. Lupu, C. Soos, P. Vichoudis, K. Wyllie, Journal of Instrumentation **10**, C03021 (2015)
[17] P. Cortese, M. Arba, G. Cotto, G. Dellacasa, N.D. Marco, P.D. Remigis, D. Falchieri, A. Ferretti, L. Lombardo, P. Mereu et al., Journal of Physics: Conference Series **2374**, 012091 (2022)
[18] O. Bourrion, J. Bouvier, F. Costa, E. Dávid, J. Imrek, T. Nguyen, S. Mukherjee, Journal of Instrumentation **16**, P05019 (2021)
[19] J. Kvapil, A. Bhasin, M. Bombara, D. Evans, A. Jusko, A. Kluge, M. Krivda, I. Kralik, R. Lietava, S.K. Nayak et al., EPJ Web of Conferences **251**, 04022 (2021)
[20] R. Arnaldi, E. Chiavassa, C. Cicalò, P. Cortese, A. De Falco, G. Dellacasa, N. De Marco, A. Ferretti, M. Gallio, R. Gemme et al., Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment **564**, 235 (2006)
[21] *alice-bags-about-twelve-billion-heavy-ion-collisions*, `https://home.web.cern.ch/news/news/experiments/`
[22] E. Ciapala et al., *Commissioning of the 400-MHz LHC RF System*, in *11th European Particle Accelerator Conference* (2008)