Performance of the ALICE Zero Degree Calorimeters and upgrade strategy

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Abstract. The Zero Degree Calorimeters (ZDCs) of the ALICE experiment were designed with the twofold purpose of both estimating the centrality in heavy ion collisions by measuring the energy carried away by the spectator nucleons and of measuring the luminosity delivered to the experiment exploiting the high cross sections for neutron emission from electromagnetic dissociation processes. The measurement of centrality has been successfully extended to p–A collisions with the detection of nucleons ejected from the nucleus by the collisions with the projectile proton ("gray" nucleons) and those resulting from de-excitation processes ("black" nucleons). The applications of the detector in triggering and analysis have expanded during the years of operation in the LHC RUN1 and RUN2. These now include both the reaction plane and the longitudinal asymmetry measurements in heavy ion collisions. Moreover the ZDCs are used to reject the parasitic interactions of main bunches with satellite bunches in A–A and p–A collisions and to tag diffractive events in pp collisions. The foreseen operation in RUN3 with the tenfold increase in the luminosity delivered by LHC in heavy ion collisions, together with the continuous acquisition strategy that is being adopted by ALICE, will be challenging for the ZDC readout system. The readout upgrade will be based on FMC digitizers with trigger, timing and charge integration functionality performed through FPGA.

1. Introduction

ALICE [1] is the LHC experiment dedicated to the study of the properties of Quark-Gluon Plasma (QGP), a state of nuclear matter where quarks and gluons are deconfined, that can be created in relativistic heavy ion collisions. ALICE is composed of several detector systems providing excellent tracking and particle identification capabilities [2] to study the different signals emerging from the QGP: hadronic particles, photons, dielectrons and dimuons. It is complemented by several detectors (mainly at forward rapidities) that allow the characterization of the global properties of the heavy-ion collisions in terms of time, vertex position, impact parameter (centrality) and collision plane. Among these the Zero Degree Calorimeters (ZDCs) allow the measurement of the energy carried by the spectator nucleons, i.e. by those nucleons that, in case of non-zero impact parameter or because of finite interaction probability, do not directly participate to the hadronic collision and therefore move along the beam direction with approximately same momentum as before the collision.
2. The ALICE Zero Degree Calorimeter

The ZDC system [1] is composed of three sets of sampling calorimeters based on the detection of Cherenkov light produced in radiation-hard quartz fibers. The neutron calorimeters (ZN) are placed between the LHC beam pipes on opposite sides (ZNA on the “A side” of ALICE and ZNC on the “C side” in the naming scheme of the experiment) at about 112.5 m from the interaction point (IP). The LHC separation dipole “D1” removes the outgoing beam and the spectator protons from the ZN acceptance. Due to the severe space constraints the ZNs are made of a high density tungsten alloy as passive material with transverse dimensions of $7\cdot 7$ cm$^2$ and 100 cm length with 1936 quartz fibers embedded. The proton calorimeters are placed close to the external side of the outgoing beam pipe and detect spectator protons. Due to the less stringent space constraints they are made of brass with transverse dimensions of $22.4 \cdot 12$ cm$^2$ and length of 150 cm with 1680 quartz fibers embedded.

One out of two fibers is sent to a common photomultiplier (PM), while the remaining ones are grouped into bundles and connected to four different PMs forming four independent towers. The calorimeters therefore have a coarse segmentation. This allows the measurement of the average impact point of the spectator nucleons, some redundancy in case of PM failure and a suppression of the PM noise with the coincidence of the signal of the common PM with the sum of the signals of the towers.

Two small electromagnetic calorimeters (ZEM1, ZEM2) placed on the A side at $\sim 7.5$ m from the IP, at 8 cm from LHC axis covering the pseudorapidity region $4.8 < \eta < 5.7$, detect a small fraction of the energy released in the collisions and allow the separation of hadronic and electromagnetic interactions.

3. Detector performance

3.1. ZDC system as luminometer in Pb–Pb collisions

![Energy spectrum of ZNA for mutual electromagnetic dissociation of both Pb ions (continuous red line) and hadronic collisions (dashed blue line). The inset shows an expanded view of the low energy region. The two processes have the same signature of emission of neutrons in the acceptance of both calorimeters and can be distinguished by considering the particle production around mid-rapidity.](image)

At LHC energies, in the operation with heavy ions, the minimum bias rate on the ZDCs is dominated by electromagnetic dissociation processes [3]. These can occur even when the impact parameter of the two colliding ions is larger than the sum of the nuclear radii and therefore hadronic interactions are not possible. The cross section for electromagnetic processes
is dominated by nuclear excitation (giant resonances and intranuclear cascades) followed by de-excitation, mainly with the emission of one or more neutrons [4]. These are emitted at rapidities very close to the one of the beam (and of spectator nucleons) and therefore are detected by the neutron ZDCs. These reactions can also occur with a double photon exchange leading to neutron emission from both ions (mutual electromagnetic dissociation), a signature in common with hadronic interactions. In Fig. 1 the neutron spectra for electromagnetic dissociation cross sections at $\sqrt{s_{NN}} = 2.76$ TeV [3] that were found to be in good agreement with theoretical predictions [4]. The event rate on the neutron ZDCs is routinely used for the measurement of delivered luminosity, in van der Meer scans [2] and for cross section normalization in ALICE [5].

3.2. ZDCs in event selection

Thanks to the good time resolution the ZDCs are used to reject parasitic collisions. At the LHC collider the RF buckets are spaced about 2.5 ns apart and only 1 out of 10 are supposed to be filled with protons or ions (main bunches) giving a bunch spacing that is multiple of 25 ns. However some particles can drift in the adjacent buckets (satellite bunches) and, due to the small crossing angle, can give main-satellite or satellite-satellite collisions. For the parasitic collisions the signals in the neutron ZDCs are shifted by multiples of 2.5 ns at least in one of the two calorimeters. Parasitic interactions can therefore be identified by considering the difference of the arrival times of the particles in the ZDCs that is related to the vertex position and the sum of the arrival times that is related to the absolute time of the collision. An example is given in Fig. 2 from Ref. [6].

The ZDC system is also used to increase the selectivity of the cuts that select hadronic collisions rejecting the background from electromagnetic collisions since in this kind of background the typical neutron multiplicity is much lower than in hadronic collisions [6] as can be appreciated also from Fig. 1.

![Figure 2.](image)

**Figure 2.** Correlation between the sum and the difference of times recorded by the neutron ZDCs on either side of the interaction region. The large cluster in the middle corresponds to collisions between ions in the nominal RF buckets of each beam, while the small clusters along the diagonals (spaced by $\sim 2.5$ ns in the time difference) correspond to collisions in which one of the ions is displaced by one or more RF buckets.

3.3. Measurement of event centrality

The ZDC system has been designed to provide an estimate of the impact parameter of the collision (centrality) in nucleus-nucleus (A–A) and proton-nucleus collisions (p–A). In A–A collisions the ZDC, in principle, allows a direct estimate of the number of participant nucleons $N_{\text{part}} = A - N_{\text{spec}}$ through the detection of the energy carried away by the $N_{\text{spec}}$ non-interacting “spectator” nucleons. However, unlike the fixed target experiments, at colliders the monotonic correlation between impact parameter and ZDC response is partially destroyed. In peripheral
collisions many nucleons remain bound in nuclear fragments, that continue to travel in the beam pipe for a long path and are not detected by the ZDCs. Centrality classes can nevertheless be defined by selections on the two-dimensional distribution ZDC energy vs ZEM as it is shown in Fig. 3 since the energy measured in the ZEM calorimeter (albeit with poor resolution) is monotonic with centrality. The ZDC system therefore provides an independent centrality estimate, insensitive to vertex position, complementary to the ones performed using particle multiplicity.

In p–A collisions the ZDCs in the Pb remnant direction detect the so called “slow nucleons” emitted by the excited nucleus: “black nucleons" that are equilibrated particles, from evaporation, disintegration, or fragmentation of the remnants of the original nucleus and “gray nucleons”, prompt, pre-equilibrium particles, knocked out of the nucleus during the collisions. The ZDC response in p–A is monotonic with impact parameter. The experimental spectra are modeled by the Slow Nucleon Model (SNM): a Glauber model complemented with a parameterization of experimental results on slow nucleon production in hadron-nucleus interactions at lower energies [7]. An example of the centrality selection based on the ZN information is shown in Fig. 4. It has been observed that the ZN information, thanks to different underlying physics process, is free from biases due to multiplicity fluctuations that affect centrality estimators based on particle production around mid-rapidity in p–A.

![Figure 3. Spectator energy deposited in the ZDC calorimeters in Pb–Pb collisions as a function of ZEM signal amplitude. The correlation is used to define centrality classes.](image1)

![Figure 4. Energy spectrum in p–A collisions for the neutron calorimeter in the Pb remnant direction. On the left side of the plot the peaks of single and multiple neutron emission are visible. The distribution is classified in centrality bins.](image2)

### 3.4. Measurement of longitudinal asymmetry

A recent analysis development is the estimation of longitudinal asymmetry in Pb–Pb collisions (see Ref. [8] and references therein). Due to the event-by-event fluctuations in the number of participant nucleons in each of the two colliding nuclei, the center of mass of the Pb–Pb is usually not at rest in the laboratory frame. The asymmetry in the number of participants can be defined as: $\alpha_{\text{part}} = \frac{A - B}{A + B}$ where $A$ and $B$ are the number of participant nucleons and can be related to the rapidity shift of the interaction region $y_0 \simeq \frac{1}{2} \ln \frac{A}{B}$. The asymmetry in the participants is in turn anticorrelated to the asymmetry in the number of spectator nucleons that can be estimated by the ZDCs. In Fig. 5 the distribution of asymmetry parameter $\alpha_{\text{ZN}}$ is shown...
for the 15–20% centrality interval. A Gaussian fit to the distribution yields a width 0.13, while
intrinsic resolution on \( \alpha_{ZN} \) varies from 0.023 to 0.050 depending on centrality.

\[ \text{Figure 5.} \] The distribution of the asymmetry parameter \( \alpha_{ZN} \) for
the 15–20% centrality interval. The distribution is divided into three
regions by a selection on \( \alpha_{ZN} \).

\[ \text{Figure 6.} \] The ratio of \( dN/d\eta \) distribution for events
from the different regions of \( \alpha_{ZN} \). (a) The square
(star) symbols corresponding to \( R13 \) (\( R23 \)) are obtained
by taking the ratio of \( dN/d\eta \) of events from Region
1 (Region 2) to Region 3. (b) The data points are
obtained after reflection across \( \eta = 0 \).

Models predict that the rapidity shift of the interaction region is translated into a longitudinal
boost in particle production. Hence the \( dN/d\eta \) distributions in Pb–Pb were analyzed in detail
to search for an the effect. These are obtained by considering the information from different
detectors depending on the \( \eta \) region of interest: V0 detector, Time Projection Chamber and
Internal Tracking System in order to cover the widest accessible \( \eta \) range. In the analysis, the
ratio of asymmetric (Region 1 and 2 of Fig. 5) vs. symmetric events (Region 3 of Fig. 5)
was considered, in order to reduce possible systematic errors connected with acceptance and
reconstruction efficiency. The results are show in Fig. 6. A deformation of the \( dN/d\eta \)
distributions of about \( \sim 4\% \) is observed over the investigated pseudorapidity range. The ratio
can be fitted with a polynomial function to quantify the effect. The change induced in the
\( dN/d\eta \) distributions by the longitudinal asymmetry is dominated by the linear term.

4. Upgrade strategy

4.1. The ALICE upgrade

The LHC heavy ion program will extend to RUN3 and RUN4 with upgrades in the accelerator
injection chain that will allow to reach the design energy of \( 7Z/A \cdot \text{TeV} \) and increase
the instantaneous luminosity in Pb–Pb from the original design value of \( 10^{27}\text{Hz}/\text{cm}^2 \) to
\( \geq 6 \times 10^{27}\text{Hz}/\text{cm}^2 \). This will bring a corresponding increase of the hadronic interaction rate
in Pb–Pb from 8kHz to \( \geq 50\text{kHz} \). The ALICE upgrade program [9] has been designed to
take full advantage of this luminosity increase in order to achieve better significance for rare
signals. Most of the detectors will upgrade their readout system [10] to take data in triggerless
mode. The acquired data will then be processed with an online data filtering and reconstruction
[11] that will enable to develop sophisticated trigger algorithms for rare signals. Moreover the
experiment will improve the low transverse momentum coverage for heavy-flavor probes with
the installation of a new Beryllium beam pipe with smaller radius and the installation of a new,
pixel-based, Internal Tracking System [12], and will enable the detection of thermal dileptons at forward rapidity with the installation of the Muon Forward Tracker [13].

4.2. The ZDC upgrade strategy
The purpose of the ZDC upgrade [10] is to enable the detector to cope with the increased event rate while preserving its performances. The same calorimeters will be used while the voltage dividers of the PMs have already been upgraded with additional power supplies in order to stabilize the gain of the PM at high rate. The readout system will be upgraded with faster electronics. While in the first design the ZDC system was supposed to work in triggered mode, in order to increase the physics coverage on Ultra Peripheral collisions, it has been later decided to work in triggerless mode.

When running in triggerless mode the ZDC system will need to sustain a readout rate dominated by the high-cross-section electromagnetic dissociation processes [3] of $\sim 2.5 \text{ MHz}$ for the channels of the most exposed calorimeters (by taking into account a safety factor of 2) w.r.t. the foreseen hadronic rate of 50 kHz. This is difficult to cope with present electronics that is based on charge to digital converters (QDCs) that have a fixed dead time of $\sim 10 \mu s$ and on readout based on VME bus [14].

Thanks to the low number of channels to be instrumented, the investigated solution will be based on commercial FMC digitizers that allow a continuous sampling of the signal waveform followed by a real time analysis on a FPGA. A scheme of the readout system is shown in Fig. 7. Thanks to the adequate bandwidth available through the FMC connection from the digitizer to the FPGA the full waveform can be analyzed. Fast trigger and reconstruction algorithms are executed on the FPGA and the interesting portions of waveform are transferred to the acquisition and reconstruction system through an optical link (GBT).

To preserve the time and charge resolution of the present system and to match the bandwidth of the ZDC signals, the digitizers should have about 12 bit resolution (with an ENOB of $\sim 10$) with a sampling frequency of about 1 Gsps.

![Figure 7. Scheme of the readout system proposed for the ZDC upgrade. A fast digitizer (ADC) 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).](image)

4.3. Tests of digitizers and evaluation of analysis algorithms
Among the several digitizers available on the market, two were studied in detail. The FMC228 from Vadatech ($\sim 2 \text{ Vpp}$) and the ADC 3112 from IOxOS ($\sim 1 \text{ Vpp}$). The readout of the first digitizer is performed through 8 JESD204b serial lines at $\sim 10 \text{ Gbit/s}$ while the second uses parallel LV bus. In the FMC228 the coupling of the (single ended) signal from the photomultipliers with the (differential) ADC is performed using balun transformers with decoupling capacities while the second uses preamplifiers and has full DC coupling. For the AC coupled digitizer the baseline is not restored immediately after the signal as can be seen in Fig. 8. The decay constant of the positive signal is about $3 \mu s$. This has to be compared with the bunch spacing that could be decreased down to $50 \text{ ns}$ in heavy ion operation from the present value $\geq 100 \text{ ns}$. On the contrary this is the case for the DC coupled digitizer as can be
seen in Fig. 9. The use of a DC coupled digitizer would therefore simplify the development of the analysis firmware. Moreover the DC coupling would allow to exploit the full dynamic range of the digitizer by inserting a voltage shifter to match the $-0.5 \, \text{V} \div 0.5 \, \text{V}$ input dynamics.

![Figure 8. Detail of pulses from the ZDC photomultipliers of $\sim 450 \, \text{mV}$ obtained with a fast laser (pulse height of about 550 channels) acquired by the FMC228 digitizer with AC coupling.]

![Figure 9. Detail of pulses from the ZDC photomultipliers of $\sim 450 \, \text{mV}$ obtained with a fast laser (pulse height of about 1500 channels) acquired by the ADC3112 digitizer with DC coupling.]

A second comparison of the two digitizers was performed by analyzing the resolution on the charge measurement for a typical signal from ZDC photomultiplier. For these tests a fast blue diode has been employed. The reconstructed waveform of the digitizers was integrated over the time of a bunch crossing (25 ns) after an optimization of the integration range w.r.t. to the time of maximum amplitude of the signal. The results are compared with the performance of the present electronics that is based on CAEN V965 QDCs where all the signal ($\sim 60 \, \text{ns}$) is integrated. The results are shown in Fig. 10. The new digitizers give a resolution comparable or better than the present system. The ADC3112 has slightly lower resolution for high signal amplitudes while it is comparable with the FMC228 in the lower part of the pulse dynamic range.

![Figure 10. Comparison of the resolution on the charge of typical signals from ZDC photomultipliers. The performance of the present electronics based on charge to digital converters V965 by CAEN (stars) is compared with the two digitizers under test: FMC228 (open circles) and ADC3112 (closed circles).]

The digitizer clock will need to be synchronized with the LHC clock in order to ease the assignment of the digitized samples to the correct bunch crossing and orbit. This is likely to
require an hardware modification to the digitizers since these have built-in reference oscillators at 100 MHz that can lock to external reference frequencies differing by ratio of integers and cannot be tuned to the LHC bunch crossing frequency (∼40.079 MHz).

A critical aspect of the ZDC operation in RUN3 will be triggering the events with reduced bunch spacing (pile-up) in presence of a large signal dynamics (from a single neutron signal to ∼60 neutrons). In order to identify the presence of a signal, two techniques are under investigation: the integral of the pulse over one bunch crossing can be compared with the pedestal or a differential trigger algorithm could be used. Given the bunch structure of LHC that alternates “trains” of colliding bunches to “gaps” where no collisions can occur, it is possible to measure the pedestal of the signals during data taking. This allows taking into account a possible drift of the baseline and obtaining an accurate reference that can be used to identify the collisions in bunch crossings where it can take place. The algorithm will need to take into account the eventual presence of a collision in the preceding bunch crossing and update the pedestal reference accordingly. Alternatively it has been considered a differential trigger algorithm where samples at different times are compared (sample \( y_i \) with sample \( y_{i+\text{shift}} \)). If three successive pairs are above threshold \( th \)

\[(y_i - y_{i+\text{shift}}) > th \&\& (y_{i+1} - y_{i+\text{shift}+1}) > th \&\& (y_{i+2} - y_{i+\text{shift}+2}) > th \]

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 measurement of the arrival time of the signal will be performed with a constant fraction algorithm implemented on FPGA firmware or in the reconstruction software.

5. Conclusions

The importance of the ZDCs in analysis and normalization of ALICE data has grown over the years with applications that go beyond what was originally foreseen. The purpose of the ZDC upgrade is to preserve these performances in the challenging environment of Pb–Pb collisions at \( L = 6 \times 10^{27} \text{ Hz/cm}^2 \) allowing the ALICE experiment to fully exploit its physics potential. To this end the ZDC will need to upgrade its readout system. The foreseen solution involves the replacement of the current QDCs with fast digitizers that will allow a continuous sampling of the signal waveform followed by a real-time zero suppression and data reduction in a FPGA. In this way the ZDC system will be able to participate to the ALICE strategy of continuous readout with online reconstruction that is needed to fully exploit the physics reach given by LHC upgrade.

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