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Commissioning and calibration of the Zero Degree Calorimeters for the ALICE experiment

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Abstract. The Zero Degree Calorimeters (ZDCs) for the ALICE experiment will measure the energy of the spectator nucleons in heavy ion collisions at the CERN LHC. Since all the spectator nucleons have the same energy, the calorimeter response is proportional to their number, providing a direct information on the centrality of the collision. Two sets of ZDCs are located at opposite sides with respect to the interaction point (IP), 116 m away from it. Each set consists of a neutron (ZN) calorimeter, placed between the two beam pipes, and a proton (ZP) calorimeter, positioned externally to the outgoing beam pipe. The ZDCs are spaghetti calorimeters, which detect the Cherenkov light produced by the shower particles in silica optical fibers embedded in a dense absorber. In summer 2007 the ZN and ZP calorimeters have been placed on a movable platform and then installed in the LHC tunnel. The results of the commissioning studies and in particular the solutions adopted to control the stability of the PMTs response will be shown: light injection with a laser diode and cosmic rays. The foreseen calibration with e.m. dissociation events in Pb-Pb collisions will also be discussed. Finally the first measurements carried out during the commissioning in the LHC tunnel will be presented.

1. Introduction

The ALICE experiment [1] at the LHC collider will study ultrarelativistic heavy ion collisions, where the formation of the Quark Gluon Plasma (QGP), a state of matter where quarks and gluons are deconfined, is expected. The Zero Degree Calorimeters (ZDC) will measure the energy carried by the non-interacting nucleons ("spectators") in order to select central nucleus-nucleus collisions, where the conditions for QGP formation are most favourable. Since the spectator nucleons will have approximately the same energy as the beam nucleons (2.7 TeV), the ALICE ZDCs will be used as multiplicity detectors. Two identical sets of calorimeters are located at opposite sides with respect to the beam interaction point (IP), 116 m away from it. Each set of detectors consists of a neutron (ZN) and a proton (ZP) Calorimeter. The ZN is placed at zero degrees with respect to the LHC axis, between the two beam pipes, while the ZP is positioned externally to the outgoing beam pipe. The spectator protons will be separated from the ion beams by means of the separator magnet of the LHC beam optics.

Table 1. *Synopsis of ZDCs parameters.*

Detector	ZN	ZP
Dimensions	$7.2 \cdot 7.2 \cdot 100$ cm^3	$22.8 \cdot 12 \cdot 150$ cm^3
Filling ratio	1/22	1/65
Absorber	W-alloy	brass
Density	17.6 g/cm^3	8.48 g/cm^3
Number of slabs	44	30
Slab thickness	1.6 mm	4 mm
Number of fibers	1936	1680
Fiber spacing	1.6 mm	4 mm
Fiber diameter (silica core)	365 μm	550 μm
Numerical aperture	0.22	0.22
Number of PMT	5	5
Type of PMT	Hamamatsu R329-02	Hamamatsu R329-02

2. ZDC description

The ZDCs are quartz-fiber spaghetti calorimeters [2, 3], with silica optical fibers as active material embedded in a dense absorber. Their principle of operation is based on the detection of Cherenkov light produced by the charged particles of the shower in the fibers. The response is very fast thanks to the intrinsic speed of the emission process, making such detectors suitable for triggering purposes. Moreover, the radiation tolerance of the quartz fibers ensures a high radiation resistance; in fact the ZDCs will operate in a highly radioactive environment, where the estimated dose is of the order of $\simeq 10^4$ Gy/day at a Pb–Pb luminosity of 10^{27} cm^{-2}s^{-1}. Finally, thanks to the dense passive material and to the detection of the Cherenkov light, a reduced transverse size of the detectable shower is achieved, allowing the construction of extremely compact devices. The technical specifications of the ZDCs are summarized in table 1. The

Figure 1. Photo of one set of ZDC calorimeters on the movable platform on the surface.

Figure 2. Photo of one set of ZDC calorimeters on the movable platform in the tunnel.

quartz fibers, hosted in the slab grooves, are placed at 0° with respect to the incident particle direction and come out from the rear face of the calorimeter, directly bringing the light to the photomultipliers. One out of two fibers is viewed by an individual photomultiplier (PMTc), while the remaining fibers are collected in bundles and sent to four different photomultipliers forming four independent towers [4]. The photomultiplier chosen is the Hamamatsu R329-02, with quantum efficiency of the order of 25% at a wavelength of 400 nm.

3. ZDC monitoring system and calibration

The ZN and ZP calorimeters have been tested in the H6 beam line of CERN SPS with hadron and electron/positron beams of various momenta (50–180 GeV/c). During the beam tests we inter–calibrated the individual PMTs and we verified the uniformity of the response as a function of the impact point of the particles on the front face of the calorimeters. For hadron beams we measured the light yield to be 0.9 and 1.1 photoelectrons per GeV and the energy resolution, $\sigma(E)/E = (257\pm3)\%\ GeV^{0.5}/\sqrt{E} \oplus (10.3\pm0.6)\%$ and $\sigma(E)/E = (237\pm2)\%\ GeV^{0.5}/\sqrt{E} \oplus (12.5\pm0.2)\%$, for ZN and ZP respectively. One of the two ZN has also been tested in the H8 beam line with an ^{115}In beam of 158 GeV/c per nucleon, in order to check the linearity of the response as a function of the number of the incoming nucleons. The performance of the detectors are summarized in [5, 6, 7, 8].

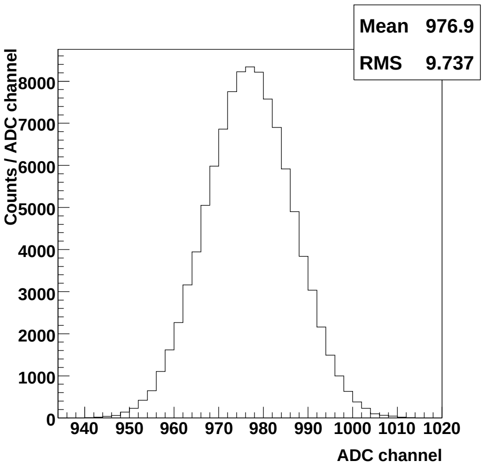

Figure 3. Typical PMT response to laser light.

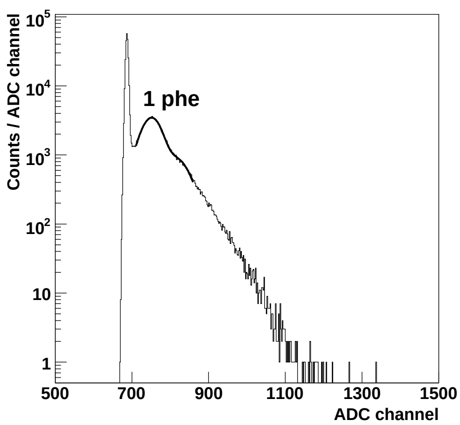

Figure 4. Single photoelectron signal obtained with a laser trigger.

3.1. ZDC monitoring system

The beam test phase is now finished. In summer 2007 two identical ZDC systems, each one composed of a ZN and a ZP calorimeters, have been assembled on the surface on a movable platform (Fig. 1) and then installed in the LHC tunnel (Fig. 2), at opposite sides with respect to the IP. The movable support structure will allow for lowering the detectors during injection to protect them from possible beam losses and to minimize the absorbed dose. The movement is controlled remotely from the ALICE DCS. Each ZDC system is equipped with a picosecond light pulser PLP-10 (405 nm, 70 ps) for the monitoring of the stability of the gain of the PMTs and the radiation damage of the fibers. The pulsed light source utilizes a laser diode head, which is positioned in a sealed box below the calorimeters. A few fibers in each calorimeter, longer than the normal ones, come out from the front face of the calorimeter, coupling the light source to the photomultipliers. A reference PMT, located in the sealed box, monitors the laser light stability. The laser is remotely controlled and a laser trigger will be used in order to monitor the PMT response variations with an accuracy at the level of 1%, as shown in Fig. 3. The PMT response depends on the PMT gain and on the light trasmission through the fibers, which both vary due to radiation damage.

In order to disentangle the PMT and fiber radiation damage two different systems are foreseen, which measure the absolute gain of the PMTs by means of the single photoelectron signal (Fig. 4). A cosmic ray trigger and a laser trigger, with an appropriate filter in front of the laser diode head, have been implemented. In fact the energy loss of cosmic rays (muons) in the calorimeters is negligible, producing in a small fraction of events only a few photoelectrons. For this purpose two scintillators are positioned respectively above and below each calorimeter. The cosmic ray trigger requires a coincidence between the signals coming from the two scintillators.

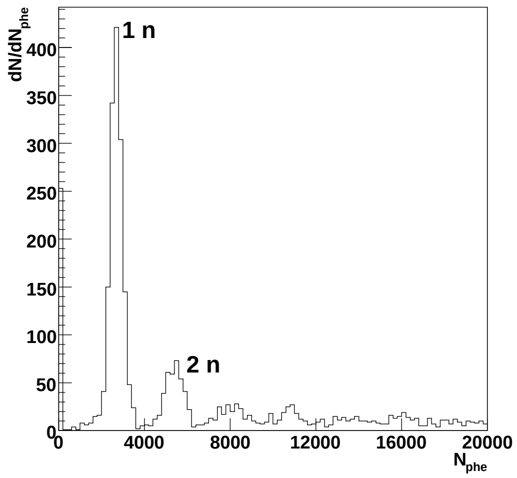

Figure 5. In-situ physical calibration. The expected light distribution in ZN in Pb-Pb e.m. dissociation events is shown. A clean separation of 1n-2n contribution is visible.

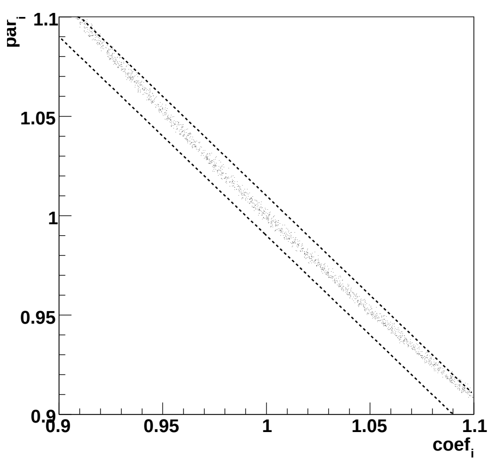

Figure 6. In situ tower inter-calibration. Parameters par_i obtained from the minimization vs input parameter $coef_i$ are shown. The dotted lines show the limits of $\pm 1\%$.

3.2. ZDC in-situ physical calibration

During operation with ion beams it is foreseen that the ZN calorimeters will provide an estimate of the LHC luminosity, by measuring the rate of mutual electromagnetic dissociation of the colliding nuclei in the neutron channel. A prediction for neutron emission in Pb-Pb e.m. dissociation events at 2.76 ATeV is shown in Fig. 5. All emitted neutrons fall in the neutron calorimeter acceptance. Thanks to the good energy resolution ($\sim$ 11% at 2.76 TeV), a clean separation of the single neutron contribution is achieved providing both physical calibration and stability monitoring.

3.3. ZDC in-situ tower inter–calibration

The information coming from the PMTc provides a complementary measurement of the shower energy, particularly useful for in–situ inter-calibration purposes. In order to verify this assumption 5000 Pb-Pb minimum bias events at 2.76 ATeV were generated with a fast simulation based on Hijing generator [9]. The light produced in each tower is multiplied by a factor $coef_i$ randomly chosen in the range from 0.9 to 1.1, in order to simulate a de–calibration of the four towers (10% at most). A minimization of the sum of the squares of the deviations of the light measured in PMTc (E_c) from the sum of the light in the four towers is performed with respect to a multiplicative parameter par_i:

$$\sum_{i=1}^{n}(E_c - \sum_{i=1}^{4} par_i coef_i E_i)^2 \tag{1}$$

where E_i is the light in the i-th tower PMT_i. The result of the minimization procedure, which is repeated 200 times, each time varying the four input factors $coef_i$, is shown in Fig. 6. The resulting values for par_i, which re-equalize the response of the four towers, are obtained with an accuracy of 1%, as shown by the dotted lines.

4. ZDC commissioning on the surface: gain measurements

During summer 2007 the gain of the PMTs of the four calorimeters have been checked at different supply voltages. The single photoelectron signal (Fig. 4), already measured in the laboratory, has been obtained triggering on cosmic rays and laser events. The position μ of the ADC peak corresponding to the single photoelectron signal is evaluated performing a fit to the sum of two gaussian functions:

$$f(x) = C_1 e^{\frac{-(x-\mu)^2}{2\sigma^2}} + C_2 e^{\frac{-(x-(ped+2(\mu-ped))^2}{2(2\sigma^2)}}. \tag{2}$$

where *ped* is the position of peak corresponding to the ADC pedestal, seen to the left of the spectrum. The two terms correspond to the detection of 1 and 2 photoelectrons respectively.

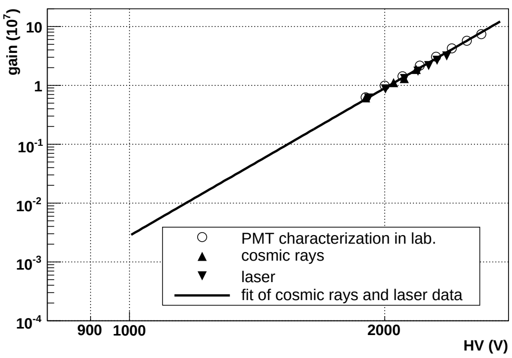

Figure 7. PMT gain as a function of the supply voltage; Cosmic rays (full triangle), laser (full triangle down) and previous PMT characterization (open circle) data are shown.

The gain is evaluated with the formula:

$$G = \frac{(\mu - ped) \cdot ADCgain}{At \cdot e}. \tag{3}$$

where At is the cable attenuation and e is the electron charge.

The gains, measured with the two methods, are plotted in Fig. 7 as a function of the PMT HV; the measurements have been fitted with a straight line on a log-log scale. A good agreement is achieved between this new set of measurements and the previous PMT characterization performed in laboratory.

In Pb-Pb collisions the PMTs will have to work at lower HV of the order of 1200–1300 V. Therefore in order to extend the gain measurements at low voltage we acquired laser events from HV ≈ 1200 V to HV ≈ 2300 V, using different filters, as shown in Fig. 8. Each time we changed the filter, we performed a junction measurement at the same HV, in order to be able to align the

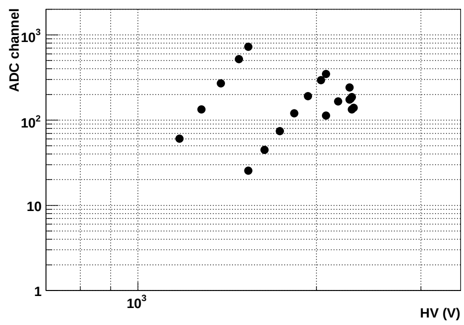

Figure 8. PMT response to laser light: ADC channel vs HV.

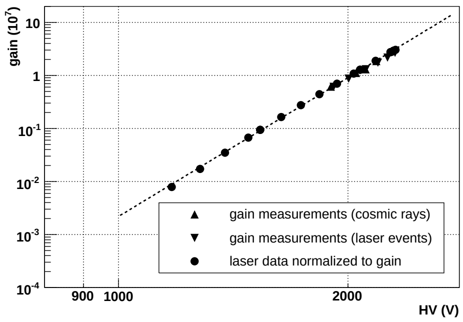

Figure 9. PMT response to laser light: gain vs HV.

points on a unique line on a log-log scale. In Fig. 9 the measurements performed with different filters have been rescaled and normalized to the gain previously measured at 2000 V. The PMT response to laser light, normalized to the gain at HV $\simeq$ 2000 V, is in reasonable agreement with the gain measurement extrapolation to low voltage.

5. ZDC commissioning in the tunnel: linearity measurements

The two ZDC systems, placed on their movable platform, are now installed in the LHC tunnel. Standalone runs in the framework of the general ALICE data acquisition system have been performed, flashing all the PMTs with the laser light. A preliminary check of the linearity of the entire system (PMT, bleeder and electronics in control room) has been done. The measurements have been carried out at two different laser light intensities in order to generate higher and lower PMT charge alternately, fixed at a ratio approximately 4:1. Different measurements of the ratio

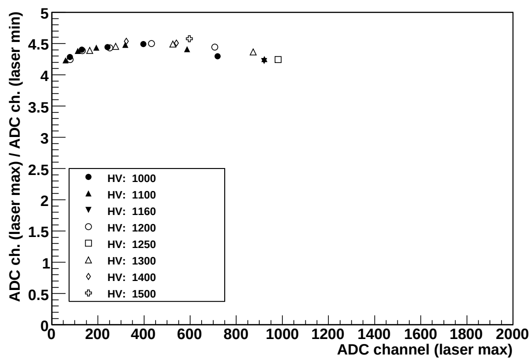

Figure 10. Linearity measurements for one of the ZN PMT: the ratio between higher and lower PMT charges is plotted as a function of the higher PMT charges for different HV of the PMT.

have been performed by inserting filters in front of the laser diode head, therefore varying the absolute intensity of the laser light. Preliminary results are shown in Fig. 10 for one of the ZN PMT, where the ratio between higher and lower PMT charges, measured by means of a QDC Caen V965, is plotted as a function of the higher PMT charges. Data have been collected at different HV of the PMTs, around the Pb-Pb working values. The data show a good linearity (within 6%) up to channel 1000 (200 pC). It was not possible to extend the measurements to higher charges due to the limitation of the input amplitude of the Linear Fan–In Fan–Out temporarily used ($\approx$1.4 V) in the ZDC electronic chain. We plan to replace these commercial modules with a custom Linear Fan–In Fan–Out with a higher maximum input amplitude, in order to extend the linearity measurements up to 800 pC, which corresponds to the full range of the QDC.

6. Conclusion

Two identical ZDC sets, each one composed of a ZN and a ZP calorimeters, are now installed at IP2 in the LHC tunnel. Each set is equipped with a laser light source for radiation damage monitoring of PMTs and fibers. A cosmic ray and a laser trigger will be used in order to measure the absolute gain of the PMTs, by means of the single photoelectron signal, in order to disentangle the PMT and fiber radiation damage.

Concerning the physical calibration, the single neutron signal from neutron emission in ion–ion e.m. dissociation events in the ZN calorimeter will provide a clean energy calibration. Moreover an inter–calibration method of the different towers, which use the complementary information coming from the PMTc, is discussed. The parameters which re–equalize the response of the towers are obtained with an accuracy of 1%.

Finally the results of the commissioning on the surface and in the tunnel, in particular the absolute gain of the PMTs and the linearity measurements, are presented. The absolute gain of the PMTs have been measured from HV $\approx$ 1200 V, the expected Pb–Pb working point, up to HV $\approx$ 2300 V. A good agreement is achieved between the cosmic rays, laser light measurements and the previous PMT characterization performed in laboratory. Linearity measurements of the entire system (detectors and electronics) have been performed. The data are consistent with linearity at the level of 6%.

7. Acknowledgment

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