The Resistive Plate Chambers of the ATLAS experiment: performance studies

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ATLAS (A Toroidal LHC ApparatuS) is one of the four experiments ready for p-p collisions scheduled in autumn 2009 at the LHC at CERN. It is a general purpose experiment, with a physics program that spans from the search of the Higgs Boson to the evidence of physics Beyond the Standard Model (BSM). Events with final state muons are a signature of the most promising physics channels, e.g. the Standard Model Higgs Boson decaying into four muons ($H \rightarrow 4\mu$). For this reason a completely independent in-air Muon Spectrometer with a toroidal magnetic field for muon track measurement has been realized to trigger and measure the momentum of high energy muons. Resistive Plate Chambers (RPCs) provide the first-level muon trigger and the measurement of the coordinate in the non-bending direction in the barrel region of the Muon Spectrometer. The installation in the experimental hall of RPCs has been completed and extensive tests of their performance have been performed with cosmic-rays muons. An overview of the ATLAS experiment, focusing on the results of the studies on the RPCs performance will be presented.

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I. The Large Hadron Collider

The Large Hadron Collider (LHC) [1] is a two-ring-superconducting-hadron accelerator and collider installed in the existing 26.7 km tunnel that was constructed between 1984 and 1989 for the CERN LEP machine. It is designed to collide two proton beams with a centre-of-mass energy up to 14 TeV and an unprecedented luminosity of $10^{34} \text{cm}^{-2}\text{s}^{-1}$. It can also collide heavy ions (Pb) with an energy of 2.8 TeV per nucleon and a peak luminosity of $10^{27} \text{cm}^{-2}\text{s}^{-1}$.

Beams can cross in four points, each hosting a different experiment. At the crossing point the angle between the beams is 200 $\mu$rad.

The two high luminosity insertions in point 1 and point 5, diametrically opposed, host the general purpose experiments ATLAS and CMS respectively. Two more experiments, one aimed at the study of heavy ions collisions (ALICE) and one designed to perform accurate studies on B physics (LHCb) are located in point 2 and point 8 respectively.

Each LHC proton beam contains 2835 bunches of $10^{11}$ protons each. The existing CERN accelerator chain is used as injection system for the LHC. The bunches, with an energy of 26 GeV are formed in the PS, and are characterized by a 25 ns spacing. Three trains of 81 bunches, corresponding to a total charge of 2.43 $10^{13}$ protons, are then injected in the SPS on three consecutive PS cycles, thus filling 1/3 of the SPS circumference. The resulting beam is accelerated to 450 GeV before being transferred to the LHC. This cycle has to be repeated 12 times in order to fill both the LHC counter-rotating beams.

II. The ATLAS Muon Spectrometer

The Muon Spectrometer of the ATLAS [2] experiment has been designed to measure the momentum of particles in the pseudorapidity range $|\eta| < 2.7$ and to trigger on these particles in the region $|\eta| < 2.4$.

The target performance is a stand-alone transverse momentum resolution of approximately 10% for 1 TeV tracks (Figure 1), which translates into a sagitta along the z (beam) axis of about 500 $\mu$m, to be measured with a resolution of \( \lesssim 50 \mu\text{m} \).

Three air-core toroid magnets, one in the barrel (the central region of the detector, $|\eta| < 1.05$) and two in the end-caps (the regions at the edge of the experiment), host the particle detectors for the trigger and for precision tracking. The bending power, which ranges between 1 and 7.5 Tm (depending on the pseudorapidity) and the low amount of material crossed by the muons in the spectrometer, allow the precise determination of the transverse momentum.
Resistive Plate Chambers (RPCs) and Thin Gap Chambers (TGCs) provide the information to the muon trigger in the barrel and in the end-caps respectively, while Monitored Drift Tubes (MDTs) in the barrel and end-caps regions and Cathode Strip Chambers (CSCs) in the forward region ($|\eta| > 2$), precisely measure the position in the bending plane 1.

Chambers in the barrel region are located between and on the eight coils of the superconducting barrel toroid magnet, while the end-cap chambers are in front and behind the two end-cap toroid magnets. The $\phi$ symmetry of the toroids is reflected in the symmetric structure of the muon chamber system, consisting of eight octants. Each octant is subdivided in the azimuthal direction in two sectors with slightly different lateral extensions, a large (L) and a small (S) sector, leading to a region of overlap in $\phi$ (Figure 2). The chambers in the barrel are arranged in three concentric cylindrical shells around the beam axis at radii of approximately 5 m, 7.5 m and 10 m. In the two end-cap regions, muon chambers form large wheels, perpendicular to the z-axis and located at distances of $|z| \sim 7.4$ m, 10.8 m, 14 m and 21.5 m from the interaction point.

FIG. 1: Contributions to the momentum resolution for muons reconstructed in the Muon Spectrometer as a function of transverse momentum for $|\eta| < 1.5$. The alignment curve is for an uncertainty of 30 $\mu$m in the chamber positions.

RPCs are assembled together with a MDT of equal dimensions in a common mechanical support structure. RPCs provide the first-level muon trigger: two RPC chambers are installed together in the barrel middle station (BM) which provide the low-$p_T$ trigger information. The high-$p_T$ trigger makes use of the RPC modules installed on the outer barrel chambers (BO) combined with the trigger result from the low-$p_T$ system. Each chamber consists of two independent detector layers, each measuring $\eta$ and $\phi$ coordinates via two orthogonal sets of read-out strips. A muon track that crosses three stations delivers six measurements in each view. This redundancy in the track measurement allows the use of a 3-out-of-4 coincidences in both projections for the low-$p_T$ trigger and a 1-out-of-2 OR for the high-$p_T$ trigger. This coincidence schema increases the trigger robustness, rejecting fake tracks from noise and cavern background and ensuring good trigger efficiency with different detector performance. A system of programmable coincidence logic allows concurrent operation with a total of six thresholds, three associated with the low-$p_T$ trigger (threshold range approximately 6-9 GeV) and three associated with the high-$p_T$ trigger (threshold range

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1 The bending plane is parallel to the beam axis and is called the $\eta$ view. The plane perpendicular to the beam axis is the non-bending plane and is called $\phi$ view.
approximately 9-35 GeV). The RPCs are also used to provide the coordinate along the MDT tubes in the non-bending plane.

Similarly, in the end-cap two TGC doublets and one triplet are installed close to the middle station and provide the low-$p_T$ and high-$p_T$ trigger signals. The TGCs measure the coordinate of the muons in the direction parallel to the MDT wires. In addition some TGC chambers are installed close to the inner MDTs to improve the position measurement accuracy along this coordinate.

III. The Resistive Plate Chambers of the ATLAS experiment

The first published work on Resistive Plate Chambers (RPCs) was in 1981 [3]. Since then they had great development and they are now widely used in both high-energy and astroparticle physics experiments.

RPCs are gaseous detectors and their operation is based on the detection of the gas ionization produced by charged particles when traversing the active area of the detector, under a strong uniform electric field applied by resistive electrodes. The electrodes are made of a mixture of phenolic resins (usually called bakelite), which has a volume resistivity $\rho_V$ between $10^9$ and $10^{12}$ $\Omega$cm. The plates are kept spaced by insulating spacers. The thickness of the plates and the distance at which they are kept (the gas gap) are different for different experiments. If RPC chambers are used as trigger detectors the gas gap is of the order of 2 mm while in the case they are used as time of flight detectors the gas gap reduces to 200 - 300 $\mu$m. In the following we refer to the characteristics of RPCs for the ATLAS experiment (Figure 3). RPCs used in the ATLAS experiment have 2 mm thick plates, kept at 2 mm one from each other. The spacers are cylindrical with 12 mm diameter and are placed every ~ 10 cm in both directions. The plate external surfaces are coated by thin layers of graphite painting. The graphite has a surface resistivity of ~ 100 kΩ, thus allowing uniform distribution of the high voltage along the plates without creating any Faraday cage that would prevent signal induction outside the plates (as would happen using, for example, metallic electrodes). Between the two graphite coatings is applied a high voltage of about 9.8 kV (at room temperature and standard atmospheric pressure), resulting in a very strong electric field which provides avalanche multiplication of the primary ionization created by the incident particle. The presence of such high electric field calls for extreme smoothness of the inner surfaces of the bakelite plates, which is obtained covering the surfaces with a thin layer of linseed oil. The discharge electrons drift in the gas and the signal induced on pick-up copper strips is read out via capacitive coupling, and detected by the front-end electronics. Read-out strips have a typical width of ~ 30 mm and are grouped in two ($\eta$ and $\phi$) read-out panels orthogonal to each other.

The gas together with the operating voltage determine the detector working mode: avalanche or streamer. Avalanche mode is the typical Townsend mechanism. According to this mechanism the avalanche multiplication is due to the drifting electrons which collide with the gas molecule and produce further ionization. For extremely high values of the electronic charge (established by Meek in ~ $10^8$ electrons for noble gases) the avalanche becomes the precursor of a new process, called streamer. In this phase, the electrons have low kinetic energy and electron-ion recombination can occur with photon emission. Then the resulting photons can further ionize the gas molecules, restarting one more avalanche multiplication, delayed with respect to the first one. When the number of photons is large and the electric field strong enough there are several secondary avalanches, until the local density and electrons and ions distribution are such to connect the two electrodes: a plasma column between the electrodes has been formed. An extremely high current flows in the gas (~ 100 times larger than the typical avalanche), until all the electrons and ions are collected.

In the ATLAS experiment RPCs operate in avalanche mode and this is achieved choosing an appropriate high voltage and gas mixture:

![FIG. 3: Structure of a Resistive Plate Chamber of the ATLAS experiment.](image)
C₂H₂F₄ 94.7 % - C₄H₁₀ 5% - SF₆ 0.3 %.

Indeed, to work in avalanche mode the main component should be an electronegative gas, with high enough primary ionization production, but with low free path for electron capture. The high electronegative attachment coefficient limits the avalanche electrons number below the Meek limit. A gas showing these characteristics is the Tetrafluorethane (C₂H₂F₄).

Another component is a polyatomic gas, usually a hydrocarbon (C₄H₁₀), which has a high absorption probability for ultra violet photons, produced in electron-ion recombinations. This component allows to dissipate the photon energy by rotational-vibrational energy levels. Then the introduction of a quencher (as SF₆) furtherly suppresses streamer formation allowing to work in a pure avalanche mode, avoiding photoionization with related multiplication and limiting the lateral charge spread.

RPCs spatial resolution depends both on the read-out geometry an electronics. Using an analog readout it is possible to obtain resolution of ~ 1 cm, but with a digital read-out the resolution is limited by the strip width, typically of the order of a few centimeters.

Concerning time resolution, the high and uniform electric field applied to the gas gap by the electrodes is the same for all primary clusters, producing at fixed time the same avalanche growth, limited by the distance of the primary clusters from the anode. The signal at any time is the sum of simultaneous contributions from all primary clusters multiplications. The resulting time jitter for detectable signals is always < 2 ns.

The excellent time resolution makes the RPCs a very good candidate for trigger detector.

IV. RPCs performance

After the installation of the ATLAS detector in its experimental cavern, the main focus of activity is presently to study in situ its performance. Using the reconstructed tracks of cosmic muons, the performance of the detectors have been verified as by design, after the integration of the chambers in the full apparatus. Results shown in the following sections are from data recorded over the full Muon Spectrometer (~ 8000 RPC panels).

A. Efficiency

In order to determine the RPC efficiency, it has to be taken into account that RPCs provide the muon trigger thus introducing a bias on the efficiency measurements.

Since the trigger majority doesn’t include all the layers in the trigger decision, an unbiased sample of data can be used to calculate the efficiency for a given detector layer, excluding that layer from the trigger decision. For example if the trigger is requiring a coincidence of at least 3 RPC layers out of the 4 in the low-p_T (BM) station one can have an unbiased efficiency measurement for layer 1, by using only events where layers 2, 3 and 4 had a hit. This method has been applied in the analysis and in Figure 4 the RPC efficiency is estimated extrapolating muon tracks reconstructed from MDT hits and requiring the presence of an RPC hit within ± 70 mm. Corrections of the high voltage for temperature and pressure variations are not applied.

In Figure 5 the dependency of the efficiency on the applied high voltage for a given read-out panel is shown. Analogous plots are produced for each read-out panel. The study of efficiency dependence on the high voltage is fundamental to determine the working point of the detector. Indeed to operate in stable detector conditions the operating high voltage is choosen at the plateau value extracted from this kind of plots.

![FIG. 4: Distribution of average efficiency for RPC BM panels at working point (high voltage 9.6 kV). The two histograms are referred to two different trigger sources: RPC trigger and calorimeter-based trigger (L1Calo). The effectiveness of the algorithm to remove offline the trigger bias is clearly visible. The histograms are normalized to unity.](image-url)
FIG. 5: Dependence of the efficiency on the high voltage applied to the resistive plates for a given read-out panel.

Figure 6 shows the difference in the RPCs efficiency measurement distribution at different high voltage values. The efficiency plateau is already reached for 9.6 kV.

FIG. 6: Distribution of efficiency gradients between different high voltage values. Each panel gives an entry in each one of the distributions. The red plot for example shows that panels do not change significantly their efficiency between 9.8 kV and 9.6 kV. Brown and green curves show instead the effect of the rise of the efficiency plateaus.

B. Cluster Size

The signal induced on a strip and read out by the front-end electronics is defined as a hit. To study the RPC performance and to check the RPC efficiency a clustering algorithm has been implemented. The algorithm is based on the following rules:

- for each event a cluster is defined as a group of adjacent strips hit at the same time or within 15 ns. This time range is estimated as the maximum time for the signal induction/cross talk;
- in order not to count hits due to after pulses, only the first hit of each strip is considered by the cluster algorithm;
- the first hit in time defines the cluster time;
- the number of strips forming the cluster is the cluster size;
- the cluster centre is given by the geometrical centre of all the strips belonging to the same cluster.
- in a read-out panel more than one cluster can occur.

FIG. 7: Distribution of cluster size for $\eta$ and $\phi$ panels

Figure 7 shows the distribution of cluster size for $\eta$ and $\phi$ panels. $\eta$ view cluster size is a little bit lower with respect to $\phi$ view. This is as expected due to the chamber construction geometry. Indeed only $\eta$ read-out panels are separated from the gas volume by a PET foil.

In Figure 8 the distribution of cluster size for BM and BO panels is shown. No relevant difference between the two distribution is visible, as expected.
FIG. 8: Distribution of cluster size for BM and BO panels

FIG. 9: Distribution of spatial resolution divided by the strip pitch for clusters of size 1 (blue line) and size 2 (red line). Only $\eta$ RPC panels of BM chambers are shown.

C. Spatial Resolution

Figure 9 shows the spatial resolutions as measured on $\eta$ panels, for clusters of size 1 and 2. The residual $^2$ distributions are fitted with a Gaussian, and the resulting standard deviation is divided by the strip pitch, to allow comparison between different panels. As expected, clusters of size 2 give an improved spatial resolution due to the fact that the particle has crossed a very narrow region near the border of two adjacent strips.

Figure 10 (Figure 11) shows the comparison of spatial resolution with magnetic field on and off for clusters of size 1 (2). No relevant difference between the two distributions is visible as expected.

FIG. 10: Distribution of spatial resolution divided by the strip pitch for clusters of size 1 in the case with magnetic field on and off. Only $\eta$ RPC panels of BM chambers are shown.

FIG. 11: Distribution of spatial resolution divided by the strip pitch for clusters of size 2 in the case with magnetic field on and off. Only $\eta$ RPC panels of BM chambers are shown.

V. CONCLUSIONS

The ATLAS detector is completely installed in the cavern and is ready for the beams. Resistive Plate Chambers undergone extensive tests to verify their performance and the results shown here represent a part of the effort to bring the ATLAS Muon Spectrometer to life with cosmics.
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