Off-line time calibration of the ATLAS RPC system

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ABSTRACT: Resistive Plate Chambers (RPC’s), operated in saturated avalanche regime, are used in the Muon Spectrometer of the ATLAS experiment to produce the first level of the muon trigger in the central region, $|\eta| < 1.05$. The trigger logic, based on a coincidence of hits in three layers of detector doublets, takes advantage of the very good time resolution of these detectors which allows to easily identify the LHC bunch crossing.

The RPC readout electronics, based on a 320 MHz clock, allow to store a very granular time information, making the RPC system, potentially, the detector providing the most accurate time measurement in ATLAS. To fully exploit the intrinsic time resolution of detector and readout electronics, a careful calibration of the system is needed, involving about 330,000 channels. The ATLAS data recorded during 2011 in LHC p-p collisions at $\sqrt{s} = 7$ TeV have been used to show that, after applying an off-line calibration procedure, a time resolution uniform over the entire detector and stable in time, can be reached. A simulation of the various contributions to the observed time of flight per single channel, implemented in the software for the ATLAS simulation, allows to understand the resolution measured in data. The time resolution is understood in terms of the intrinsic detector resolution, the digitization error and the various components relevant at different levels of refinement of the time calibration procedure.

Achieving the ultimate timing resolution of the RPC system is a very powerful way of extending the physics potential of ATLAS experiment, for example, in searches for particles moving with low velocity from the interaction point. In addition, good time resolution may be a key ingredient for background rejection, which may become of overwhelming importance in future scenarios of increased LHC luminosity.

KEYWORDS: Timing detectors; Resistive-plate chambers; Trigger detectors; Particle tracking detectors (Gaseous detectors)

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1 ATLAS RPC trigger chambers

The ATLAS Resistive Plate Chambers (RPC’s) are planar large size gaseous detectors working in saturated avalanche regime with resistive electrodes and two orthogonal pick-up readout strip panels located outside a 2 mm-thick active gas volume. In the ATLAS experiment three layers of RPC detectors are used in the ATLAS Muon Spectrometer barrel (|η| < 1.05) to generate a hardware muon trigger signal.

In the ATLAS experiment [1] there are 1116 RPC units for 26 different topologies, a total active surface of about 4000 m², and about 330,000 electronic channels.

The muon candidates are identified by fast geometrical coincidence pattern (trigger roads) in the two measurement views (η-φ). This allows to provide a Region of Interest Δη × Δφ=0.1×0.1 for the muon candidates, the highest among one of the six programmable transverse momentum thresholds, and the coarse measurement of the bending (η) and non-bending (φ) coordinates, useful to seed the next on-line trigger level, in addition to the bunchcrossing identification number. The on-detector trigger-readout electronics, based on the Coincidence Matrix ASIC (CMA) [2], operates with a clock frequency of 320 MHz, corresponding to eight times the frequency of the bunch crossing clock, allowing a resolution for digitization of about $\frac{125\text{ns}}{\sqrt{12}} = 0.9\text{ ns}$. The on-line time alignment is done with tracks, both for trigger output signals and readout hits, in order to maximise trigger efficiency inside a 25 ns trigger window. After on-line calibration, and before off-line calibration, the fraction of events not associated to the correct bunch crossing was about 1% and mostly due to a badly calibrated trigger tower. See figure 17 of reference [3], corresponding to 2010 data, where this fraction was few times larger.

2 RPC time in data and simulation

RPC has excellent time resolution due to the planar geometry, in contrast to the traditional wire chamber cylindrical geometry. In fact, in any position inside the gas volume, the constant electric field can start a charge avalanche multiplication just after the elementary ionization process takes
place. The time fluctuations of the avalanche signal scale proportionally to the gas volume thickness and for ATLAS RPC this corresponds to a time resolution of about 1.2 ns [4].

In order to achieve the best possible time resolution in off-line analysis, it is important to establish a time calibration procedure based on algorithms that take correctly into account several factors. There are fixed delays (due to cables, optical links, configurations . . . ), that need to be measured once and thereafter absorbed in a calibration constant, and track dependent delays, such as: the particle time of flight, the spatial spread of the interaction point, the signal delay along the readout strips, which must be corrected knowing the kinematics and the geometry of the track. The signal delay along the readout strips is a relevant effect, and it is evaluated by multiplying the signal propagation speed, assumed to be 208 ns/mm, and the distance from the readout electronics, given by the associated orthogonal coordinate.

In the ATLAS simulation software [5], the time of the RPC hits is emulated in such a way to reproduce the expected measurement in a perfectly timed system. The components contributing to the spread of the bare time measurements are: the time of flight of the particle from the interaction point, evaluated by GEANT4 [6] in the particle propagation process, and the time of the signal propagation along the strip. In the simulation, a Gaussian smearing of 1.5 ns is applied to reproduce time jitter effects measured in RPC H8 test beam [2]. A nominal time of flight, as given by a relativistic track hitting the center of the strip, is then subtracted in order to mimic the on-line time alignment procedure which inside a trigger tower maximizes the trigger efficiency for compensating all relative delays.

A simple RPC standalone tracking is implemented off-line [7] and based on RPC space points, which are defined by adjacent hits (clusters) on both orthogonal views but on the same gas volume. The cluster time is defined as the minimum raw time of the adjacent hits belonging to the cluster. The tracks are straight lines defined by six space points per view with 1 cm space resolution. A cut on the global chi2 per degree of freedom of the straight line fit to the 6 space points is equivalent to selecting high transverse momentum tracks. To have a clean sample of muons we require that the hits contributing to the RPC track match, within 0.1 for both $\eta$ and $\phi$ coordinates, the extrapolation in the RPC plane of an off-line high quality muon.

We verify the RPC time simulation and reconstruction algorithms simulating Geantino tracks without interaction point spread. Geantino’s are non-interacting and neutral tracks, which leave hits in active volume but don’t create secondary interactions and don’t bend in magnetic fields. In the left plot of figure 1 several key distributions of RPC cluster time due to one million simulated Geantino tracks are shown. The root mean square values are reported and correspond to the values expected from a simple calculation assuming a time resolution of 1.75 ns (1.5 ns RPC time resolution added in quadrature to the 0.9 ns resolution for digitization) and no correlations in the time fluctuations between different gas volumes and views ($1.75\sqrt{2} = 2.47$ ns relative time spread). The right plot of figure 1 shows the distributions of RPC cluster time in fully simulated $Z \rightarrow \mu\mu$ events. In such realistic events the time distributions appear with non-Gaussian tails and the fit are made with a Gaussian function and asymmetric power law function. The time spread of the Gaussian core is about 2 ns and the ratio of background events inside a $\pm 3$sigma window to the signal events in the Gaussian core is about 1%.
Figure 1. Left: distribution of RPC cluster time with signal time propagation along strip subtracted (continuous line), distribution of RPC cluster time difference between two near-by gas volume for the same view (dotted line), distribution of RPC cluster time difference with signal time propagation along strip subtracted between orthogonal view belonging to the same gas volume (dashed line). The RPC hits are simulated with non-interacting neutral tracks (Geantino’s). Right: distribution of RPC cluster time with signal time propagation along strip subtracted in simulated $Z \rightarrow \mu \mu$ events for LowPt layers and both views. The superimposed fits are made with a Gaussian function (central core) and asymmetric power law function (non-Gaussian tails) [8].

3 RPC off-line time calibration

We assumed as off-line time calibration criteria that the arrival time of a relativistic track leaving the interaction point is on average equal to 100 ns; this is in the center of the CMA readout window. A simple calibration algorithm is employed strip by strip. The calibration constant per strip $\tau_{\text{cal}}$ is defined as:

$$\tau_{\text{cal}} = t_{c} - MP\left(t_{\text{raw}} - t_{\text{prop}}\right),$$  

(3.1)

where MP is the most probable value of the distribution of the strip time $t_{\text{raw}}$, minus the signal delay $t_{\text{prop}}$. $t_{c}$ is conventionally set to 100 ns, which corresponds to the readout window center.\(^1\) In order to have a clean sample of tracks for the calibrations only RPC hits matched with muon tracks are considered in the time distribution.

Once the calibration constants are extracted from the data, the off-line calibrated time $t_{\text{cal}}$ must be defined consistently as (see plots of figure 2):

$$t_{\text{cal}} = t_{\text{raw}} - t_{\text{prop}} + \tau_{\text{cal}}.$$  

(3.2)

Analogously, the real time of flight $t_{\text{TOF}}$ is the calibrated time minus the 100 ns offset and plus the nominal time of flight given by the spatial hit position with respect to the interaction points $d$:

$$t_{\text{TOF}} = t_{\text{cal}} - t_{c} + c \cdot d,$$  

(3.3)

\(^{1}\)This time offset is not considered in simulated data and in figure 3.
where $c$ is the speed of light. In fact, a ultra-relativistic particle leaving the interaction point at $t=0$ will have in average a calibrated time equal to zero and a time-of-flight equal to the nominal ones. It is worth to notice that the signal delay must always be subtracted because it is a systematic time shift that adds to the real arrival time.

The 330,000 thousand calibration constants were measured adding together several runs of June 2011. The time measurement, as defined by equation (3.2), was stable for all channels and for all 2011 (corresponding to an integrated luminosity of about 4.8 fb$^{-1}$). Figure 3 on the left shows the achieved time resolution by the off-line calibration. The time distributions are obtained from a data run not used in the calibration constant extraction. The data selection is based on RPC clusters matched in both eta view and phi view with at least one extrapolated track reconstructed in the inner detector and in the muon spectrometer. It turns out that the time resolution obtained by on-line time alignment is of 4.7 ns, which corresponds to a resolution of 4.2 ns after signal time delay subtraction, and the time resolution obtained after off-line calibration is of 1.99 ns to be compared with the ideally expected 1.75 ns. The electronic noise and the time-walk introduced by analog and digital part coupling are expected to make-up the rest of the time resolution and explain the difference between 1.75 ns and the 1.99 ns.

This is a very significant result because it is obtained for the entire RPC system, using many months of data taking, using a small calibration sample also excluded from the plots. The RPC time resolution achieved by simple off-line calibration algorithms is very near to the single unit resolution and proves that RPC detector can easily operate in standalone mode thanks to its tracking and timing capability.

Figure 2. Left: RPC cluster time corrected with signal time propagation along strip subtracted vs strip number for one layer before off-line calibration. Right: The same as left plot but after off-line calibration [8].
4 Background suppression and velocity measurements

The achieved off-line time resolution is very effective in reducing correlated and un-correlated background such as: loopers, beam-gas, parasitic beam-beam, beam collimator interactions, cosmic rays, and cavern background (mainly neutrons and gammas). In figure 3 on the right, the time spread between views (2.5 ns) and gas volumes (2.6 ns) is plotted in log scale together with the arrival time. It is possible to notice a long non Gaussian tail in the arrival time also for hits matched with prompt tracks which can be identified by using RPC time information. The time spread of the Gaussian core is about 1.99 ns and the ratio of background events inside a ±3sigma window to the signal events in the Gaussian core is about 3%.

The velocity of particles was measured doing a linear fit between the incremental distance between spatially averaged space points and the average of the corresponding time-of-flight for each one of the 6 layers. In figure 4 the distribution of velocity measurements is shown with Geantino tracks (left plot) and for real data (right plot) after off-line calibration. The redundancy in the RPC trigger system and its good tracking capability allow particle velocity measurement with a precision of about 4% with interaction point constrain and of about 17% without it. The better velocity measurement precision reached with Geantino’s track are just due to the uncorrelated time measurements between different views of the same gas volume.
Figure 4. Left: distribution of velocity measured with RPC pointing track with interaction point constrain (circles) and without it (squares) using simulated non-interacting neutral tracks (Geantino’s). Right: distribution of velocity measured with RPC pointing track with interaction point constrain (circles) and without it (squares) using 7TeV pp collision data [8].

5 Conclusions

The ATLAS RPC detector reached a time resolution of about 2 ns for the entire RPC system and during all 2011 data taking where the number of interactions per crossing went from about five to about eighteen, making in-time and out-of-time pile-up challenging. The RPC time information, having a precision of an order of magnitude less than LHC bunch-crossing period, can be very useful in rejecting combinatorial and cavern background already for the standalone detector, and even more when combined with other detectors or full reconstruction algorithms.

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