Performance of the ATLAS RPC detector and Level-1 muon barrel trigger at $\sqrt{s} = 13$ TeV

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Abstract. The Level-1 muon trigger system of the ATLAS experiment at the Large Hadron Collider selects muon candidates with six transverse momentum thresholds and associates them with the correct LHC bunch crossing. The barrel region of the ATLAS Muon Spectrometer is instrumented with Resistive Plate Chambers (RPCs), covering the pseudo-rapidity range $|\eta| < 1.05$. The RPC detectors are arranged in three concentric double layers and consist of 3600 gas volumes, with a total surface of more than 4000 m^2 . This contribution will discuss the performance of the RPC detector and Level-1 Muon Barrel trigger system, using the data from proton-proton collisions recorded during the 2018 data-taking period at a centre-of-mass energy of 13 TeV.

1. The ATLAS RPC Muon Barrel System

The barrel region of the Muon Spectrometer (MS) of the ATLAS experiment [1] at the Large Hadron Collider (LHC) covers a pseudo-rapidity $\dagger$ range up to $|\eta| < 1.05$ and it employs Resistive Plate Chambers (RPCs) [2] for the muon trigger. RPCs cover a surface area of about 4000 m^2 ; they are arranged in three concentric layers and are divided in 16 sectors (organized in 8 small and 8 large sectors) along the azimuthal coordinate. The innermost stations, RPC1 and RPC2, are located in the Medium Layer (BML/BMS for large/small sectors) of the MS, while the third station, RPC3, is in the Outer Layer (BOL/BOS for large/small sectors). Each RPC detector consists of two gas gaps (2 mm width), read out by two orthogonal planes of strips, called panels, in η and ϕ views, with a pitch of 23 – 35 mm.

In the MS, the Barrel Toroid magnet, consisting of eight super-conducting coils, generates a magnetic field of about 0.5 T which bends muons in the $\eta - z$ plane, allowing the muon transverse momentum (p_T) measurement. RPCs provide up to 6 position measurements (both in η and ϕ directions) along the muon trajectory, with a space-time resolution of about 1 cm x 1 ns. They are assembled together with Monitored Drift Tube (MDT) chambers [3], which are used for precise muon tracking in the bending

$\dagger$ ATLAS experiment uses a right-handed coordinate system. The origin of the system is in the nominal proton-proton interaction point, set in the center of the ATLAS detector. The z-axis is along the beam line, while the xy plane is the plane perpendicular with respect to the beam line. The positive x-axis is defined as pointing from the interaction point to the centre of the LHC ring and the positive y-axis is defined as pointing upwards.

direction only. Hence, besides providing the trigger signal, RPC detectors are also used to measure the muon ϕ coordinate in the barrel region of the MS.

According to the High Luminosity LHC (HL-LHC) program, the ATLAS experiment will have to cope a foreseen instantaneous luminosity of $7.5 \cdot 10^{34} \text{ cm}^{-2} \text{ s}^{-1}$ with an average number of interactions per bunch crossing ($\langle \mu \rangle$) of ~ 200 . In order to guarantee suitable performances, several updates are foreseen in the MS Phase-II upgrade [4]. To increase the current detector coverage and the robustness of the trigger, a new type of RPCs, with 1 mm gas-gap width and thinner electrodes, will be installed in the inner layer (BI) of the barrel MS, not currently instrumented with RPC detectors. This will allow a higher muon trigger efficiency and a reduction of the muon fake trigger rate. Moreover, the MDT chambers in the BI layer will be replaced with new small-MDT, with half of the tube diameter with respect to the current detectors, to make space for the new RPCs.

2. The Level-1 muon barrel trigger logic

The Level-1 (L1) muon barrel trigger algorithm is based on the coincidence of hits from three concentric RPC stations (both in η and ϕ projections) [2]. Two different regimes, based on the muon transverse momentum, exist:

- the **low- p_T trigger** requires a coincidence between the innermost two RPC stations (RPC1 and RPC2). It is used to select muons with p_T above the three thresholds of 4 GeV/c, 6 GeV/c and 10 GeV/c (called MU4, MU6 and MU10 respectively);
- the **high- p_T trigger** requires an additional confirmation on the third external station (RPC3) and selects muons with p_T above the thresholds of 10 GeV/c (called MU11, to be distinguished from MU10) and 20 GeV/c (MU20). A third high- p_T threshold, MU21, is defined in such a way the muon transverse momentum requirement is the same of MU20 but the trigger signals from some RPC chambers, located in the ATLAS sectors 12 and 14 (the two small sectors located in the bottom region of the detector), are not taken into account [5].

Only the high- p_T triggers are used for single-muon signatures, while the low- p_T triggers are used in coincidence with other triggers which exploit the signals from the ATLAS calorimeter [6].

3. Detector response and detector efficiency

The detector response of ATLAS RPCs is studied using offline muon tracks, reconstructed by the ATLAS software [7], extrapolated to the surface of each RPC detector with the goal to compute the expected muon position on the read-out strip panels, both in η and ϕ views. For this purpose, an extrapolator tool [8], which takes into account the magnetic field, the detector geometry and the material distribution, has been used.

The association of a L1 muon trigger candidate to the correct collision bunch crossing (BC) is one of the main task of the Level-1 muon barrel trigger and it requires

a precise time calibration of the RPC read-out electronics. Hits from various RPC detectors are calibrated using programmable delays in steps of $1/8$ BC (3.125 ns), in order to provide the correct timing [9]. The hit time distributions, after the calibration procedure, are shown in Figure 1 for two representative read-out strip panels in η and ϕ views for a run recorded in 2018. The small fraction of hits outside the ± 12.5 ns time window demonstrates the low noise rate and the good performance of these two read-out strip panels.

In this study, three set of RPC hits are defined. Hits within a time window of ± 12.5 ns with respect to the triggered bunch crossing (BC0) are called *inTime hits*. If, on top of the timing requirement, hits are also within ± 30 mm far from the extrapolated muon track position (*on track hits*), they are called *signal hits*. If no selections are applied, they are simply referred as *all hits*. The hit multiplicity distribution for the same RPC read-out strip panels as well as their detector efficiencies are shown in Figure 2 for one representative run recorded in 2018. The RPC detector efficiency is defined for each read-out strip panel as the ratio between the number of hits associated to a muon track and all the reconstructed muon tracks passing through that panel. It is used as one of the main indicators of the RPC performance. The difference among the efficiencies, calculated using three selections of hits, is of the order of 1%, as shown in Figure 2 for η and ϕ panels respectively. This is a proof of the good timing and alignment performance of this particular pair of read-out strip panels.

The efficiency distribution of all the working RPC read-out strip panels is shown in Figure 3. The working panels are about 90% of the total. The remaining 10%, instead, belong to RPC gas volumes disconnected from the HV, mostly due to gas leaks. No requirements are used to select the RPC hits (*all hits*). The so-called *gap efficiency*, computed requiring at least 1 hit on a η or ϕ strips, is also shown.

Figure 1: Hit time distribution for a pair of representative η (left) and ϕ (right) read-out strip panels, belonging to the same gas-gap [10].

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Figure 2: Hit multiplicity and detector efficiency for a pair of representative η (left) and ϕ (right) read-out strip panels, belonging to the same gas-gap [10].

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Figure 3: Distribution of the detector efficiency of all the working RPC read-out strip panels. Gap efficiency is also shown [10].

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3.1. Detector stability

One of the main test to evaluate the status of the RPC detector apparatus and potential ageing effects consist in the measurement of the detector efficiency as a function of the time. The time evolution of the detector efficiency for two representative η and ϕ read-out strip panels, belonging to the same gas-gap, is shown in Figure 4 (left). These two panels have shown a stable efficiency around 96.5% throughout the 2018 data taking. Figure 4 (right) shows the mean value of the panel efficiency of all working RPC panels, separately for η and ϕ views, as a function of time during 2018. An obvious improvement can be observed since August and it is due to an intervention on the RPC Detector Control System (DCS), during which many of the Front-End (FE) electronics threshold settings have been re-tuned. No signs of ageing have been observed across the 2018.

Figure 4: Detector efficiency of two single RPC panels belonging to the same gas volume (left) and average detector efficiency for all the live RPC read-out strip panels (right) as a function of time in 2018 [10].

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4. Level-1 muon barrel trigger efficiency

Trigger efficiency is one of the key parameters to evaluate the performance of the L1 muon barrel trigger and for this purpose it has been monitored continuously during the data-taking. Unbiased muons from Z boson decays are used to compute the trigger efficiency using the *Tag&Probe* [7] method.

Figure 5 (left) shows the muon barrel trigger efficiency as a function of the probe muon transverse momentum, for six trigger thresholds: three for low transverse momentum muons, which require a coincidence of hits between the two inner RPC stations, and three for high transverse momentum muons, with a further coincidence on the outer RPC station. For this measurement, $|\eta| > 0.1$ selection is used in order to reject probe muons falling in a region of the detector which is not totally instrumented by RPC detectors. The plateau of the turn-on curve is then fitted (from 27 GeV/c on) with a constant line and the corresponding value is plotted as a function of time. This is shown in Figure 5 (right), where each point corresponds to a different proton-proton physics run recorded by ATLAS in 2018. Only runs with the whole RPC system running and with integrated luminosity greater than 50 pb $^{-1}$ are used, altogether amounting to the integrated luminosity of $L = 60.8$ fb $^{-1}$. Small drops in the, overall stable, trigger efficiency are due to some parts of the detector (gas-volumes) or TDAQ system (trigger boards) that can be off during part of the run and successfully recovered, whenever possible, at the end of the LHC fill.

Figure 6 shows the trigger efficiency as a function of η (left) and ϕ (right), for MU10 and MU20 trigger thresholds. In order to avoid any bias to this measurement, only muons with transverse momentum greater than 25 GeV/c have been used. The $|\eta| > 0.1$ selection is not applied here. Visible drops on the trigger efficiency are due to the presence of ATLAS cables and services, such as gas pipes, water pipes and cryogenic lines at $\eta \sim 0$, and to the toroid ribs in the small sectors.

Figure 5: L1 muon barrel trigger efficiency as a function of the muon transverse momentum (left). Plateau value of the L1 muon barrel trigger efficiency during 2018 ATLAS data-taking (right) [11]. Natural units are used for the transverse momentum. Copyright 2020 CERN for the benefit of the ATLAS Collaboration. CC-BY-4.0 license.

Figure 6: L1 muon barrel trigger efficiency as a function of the muon η (left) and ϕ (right) coordinates [11]. Natural units are used for the transverse momentum. Copyright 2020 CERN for the benefit of the ATLAS Collaboration. CC-BY-4.0 license.

5. Performance studies in prospects of High Luminosity LHC program

5.1. RPC operating at lower voltage

At HL-LHC the instantaneous luminosity is expected to be $7.5 \cdot 10^{34} \text{ cm}^{-2} \text{ s}^{-1}$ and the resulting integrated charge, collected by a fraction of RPC strip panels, will degrade the detector performance. In particular, over the expected HL-LHC data-taking period, the integrated charge collected by the detectors located at $|\eta| \sim 1$ will exceed the design specifications by more than a factor of 3 [4].

In order to keep the performance of the RPC system stable during HL-LHC data taking, the operating voltage will be lowered from the nominal value of 9.6 kV to approximately 9.2 kV, with subsequent reduction of the muon detection efficiency. The study presented in this section demonstrates that lowering the threshold settings of the FE discriminators allows to gain part of the efficiency lost by the HV drop. Figure 7

shows the muon detector efficiency as a function of the threshold-related parameter V_{FE} § for two representative RPC read-out strip panels, with the applied voltage set to 9.6 kV and 9.2 kV. At nominal voltage, in the plateau of the detector efficiency, the RPC response is not sensitive to the change of the FE threshold. At reduced operating voltage, these strip read-out panels show an efficiency gain of about 25% in η view (left) and 30% in ϕ view (right), when V_{FE} settings are increased from 1.0 V (higher threshold) to 1.2 V (lower threshold).

In addition, in order to compensate the loss of efficiency, new RPC detectors will be also installed in the innermost layer of the barrel MS to improve redundancy of the RPC system and to increase muon trigger efficiency, in view of HL-LHC [4].

Figure 7: RPC detector efficiency as a function of the Front-End discriminator setting V_{FE} for two different values of the HV applied to the gas-gap for η strip panel (left) and ϕ strip panel (right). This is a representative RPC panel showing an efficiency gain of about 25% in η and 30% in ϕ view [10].

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5.2. RPC current measurements

Efficient RPC gas-gap performance at various LHC running conditions is crucial for the detector operations. RPC current density is used in these studies to check the stability of the detector as function of the instantaneous luminosity (L_{inst}). RPC current at nominal working voltage and without proton-proton collisions are subtracted to show the net effect of the instantaneous luminosity. An expected linear increase of gap current densities is observed up to $L_{inst} = 2.1 \times 10^{34} \text{ cm}^{-2} \text{ s}^{-1}$, with RPCs working smoothly.

Figure 8 (left) shows the gas-gap current densities as a function of L_{inst} for side-A (detector side towards positive z-axis values) BML RPCs belonging to the same ATLAS sector but different stations at increasing pseudo-rapidity. As expected, the current increases with $|\eta|$ since the rate of particles produced by proton-proton collisions increases. Additionally, charged particles have longer tracks inside the gas volumes at larger $|\eta|$, producing more gas ionization.

§ Note that higher values of V_{FE} correspond to a lower Front-End discriminator threshold.

Figure 8 (right) shows the averaged current densities over gas-gaps of different RPC chambers (BML, BMS, BOL and BOS), belonging to ATLAS sectors 1 and 2 of side-A and at the same pseudo-rapidity, as a function of instantaneous luminosity. The figure shows that the current density decreases with increasing distance from the proton-proton interaction point. This effect is associated with particle fluxes reduction at larger radii. Discrepancies in current densities between small and large chambers at the relatively same distance from the interaction point is explained by their different orientation with respect to ATLAS toroidal magnet, which systematically shadows the small sectors. Moreover, small chambers are located at slightly larger radii from the interaction point than the large chambers.

Figure 8: Gas-gap current densities as a function of instantaneous luminosity [10].

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6. Conclusions

The measurement of the RPC detector efficiency is presented, as well as its behavior as a function of the data-taking period. No ageing effects are observed. The performance of the L1 muon barrel trigger is studied, using events containing a Z boson decaying to a muon pair. The results of the trigger efficiency as function of the muon transverse momentum, pseudo-rapidity and azimuthal angle are presented. The RPC detector response at different voltages and Front-End discriminator threshold settings is studied in detail, in the context of the expected detector performance after the High Luminosity LHC upgrades. Finally, the measurement of the gas-gap current as a function of the LHC instantaneous luminosity confirms the expected functionality of the RPC system at the highest luminosity conditions reached during the second period of LHC operations.

7. References

- [1] ATLAS Collaboration, Journal of Instrumentation 3 (2008) S08003 - DOI:10.1088/1748-0221/3/08/S08003
- [2] F. Anulli et al., The level-1 trigger muon barrel system of the ATLAS experiment at CERN, Journal of Instrumentation 4 (2009) P04010 - DOI:10.1088/1748-0221/4/04/P04010
- [3] ATLAS Collaboration, Atlas muon spectrometer technical design report, CERN-LHCC-97-22, ATLAS-TDR-10 (1997)
- [4] ATLAS Collaboration, Technical Design Report for the Phase-II Upgrade of the ATLAS Muon Spectrometer, CERN-LHCC-2017-17, ATLAS-TDR-026 (2017)
- [5] M. Corradi, Performance of ATLAS RPC Level-1 muon trigger during the 2015 data taking, Journal of Instrumentation 11 (2016) C09003 - DOI:10.1088/1748-0221/11/09/c09003
- [6] ATLAS Collaboration, Performance of the ATLAS muon trigger in pp collisions at $\sqrt{s} = 8$ TeV, Eur. Phys. J. C 75 (2015) 120 - DOI:10.1140/epjc/s10052-015-3325-9
- [7] ATLAS Collaboration, Muon reconstruction performance of the ATLAS detector in proton–proton collision data at $\sqrt{s} = 13$ TeV, Eur. Phys. J. C 76 (2016) 292 - DOI:10.1140/epjc/s10052-016-4120-y
- [8] <https://gitlab.cern.ch/atlas/athena/-/tree/master/Tracking/TrkExtrapolation>
- [9] G. Chiodini and S. Spagnolo, Off-line time calibration of the ATLAS RPC system, Journal of Instrumentation 8 (2013) T02004 - DOI:10.1088/1748-0221/8/02/t02004
- [10] <https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/PLOTS/MUON-2018-09/index.html>
- [11] <https://twiki.cern.ch/twiki/bin/view/AtlasPublic/L1MuonTriggerPublicResults>