The ATLAS Muon Spectrometer upgrade for High-Luminosity LHC

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Abstract. The muon spectrometer of the ATLAS detector will undergo a major upgrade in order to cope with the operational conditions at the high-luminosity LHC. The trigger and readout system will need to support Level-0 trigger rates of 1 MHz and a latency of 10 µs. The readout electronics of all the trigger and precision chambers will be replaced and the precision chambers, currently not included in the hardware trigger, will be integrated into the Level-0 trigger in order to sharpen the momentum threshold and increase the system redundancy. New-generation RPC chambers will be installed in the inner barrel layer to increase the acceptance and robustness of the trigger. Some of the MDT chambers in the inner barrel layer will be replaced with new small-diameter MDTs. New TGC triplet chambers will replace the current TGC doublets in the barrel-endcap transition region to enhance the suppression of fake triggers in this region. A major upgrade of the power system is also planned. In this presentation the main detector technology developments of the project will be presented.

1. Introduction
In sight of High-Luminosity LHC program, the ATLAS Muon Spectrometer must be able to operate at instantaneous luminosity $L$ of $7.5 \times 10^{34}$ cm$^{-2}$s$^{-1}$ and at pile up around $< \mu > = 200$ maintaining its performance.

The present ATLAS Muon Spectrometer, shown in figure 1, consists of:

- Three large air-core superconducting toroidal magnets, two in the endcaps and one in the barrel, providing a field of about 0.5 T;
- Monitored Drift Tubes (MDTs) covering the region in pseudorapidity up to $|\eta| < 2.7$;
- Cathode Strip Chambers (CSCs), used in the region $2 < |\eta| < 2.7$;
- Thin Gap Chambers (TGCs) in the endcaps $1.05 < |\eta| < 2.7$ (in 1.05 < |\eta| < 2.4 for trigger);
- Resistive Plate Chambers (RPCs) in the barrel region $|\eta| < 1.05$.

The precision coordinate ($\eta$ direction) is measured via hits in the three layers of MDT chambers and CSCs in the endcaps. The $\Phi$ coordinate is provided in the barrel by three layers of RPCs and in the endcaps by TGCs and CSCs. The muon first-level trigger is based on hit coincidences between different RPC or TGC detector layers inside programmed geometrical windows which define the muon $p_t$ thresholds. The maximum latency and the rate of the first-level trigger are 2.5 µs and 100 kHz respectively.
For the HL-LHC program, the muon trigger should be able to trigger on single muons with high efficiency with a rate of less than 40 kHz for a $p_t$ threshold greater than 20 GeV. On the other hand, lower $p_t$ threshold (> 4 GeV) should be viable for multi-muon and combined triggers. Moreover the trigger and readout system should work a Level-0 trigger rates of 1 MHz and a latency of 10 µs.

2. General Muon Upgrade plans
The Muon Spectrometer (MS) upgrade consists in installing new detectors, improving the detector already installed and replace the trigger and readout electronics in order to maintain the MS performance as in Run2 and to keep low trigger thresholds and trigger rates at a manageable level in a higher radiation environment. The scheme of the MS including the new chambers is shown in figure 1 (b).

![Figure 1.](image)

(a) View of the present Muon Spectrometer layout. (b) Scheme of the Muon Spectrometer including the new detectors.

2.1. New Small Wheels
The Small Wheels will be replaced with the New Small Wheels (NSWs) during Phase-I upgrade in the years 2019-2021. The NSW is composed by MicroMegas (MM) and small-strip TGC chambers (sTGC), which will replace the Cathode Strip Chambers (CSC) and the MDT chambers of the innermost endcap wheels. These detectors can provide the muon Level-1 trigger system with online track segments of good angular resolution, in order to confirm that muon tracks originate from the IP. In this way the end-cap fake triggers will be considerably reduced.

2.2. Thin Gap Chambers upgrade
In order to obtain a uniform level of purity for triggered muons over all the regions covered by the endcap trigger, the current EIL4 TGC doublet chambers (not shown in figure 1 (a)) will be replaced by TGC triplets with finer readout granularity. In this way a more robust 2/3 majority logic and smaller coincidence windows can be used for confirmation of muons detected by the TGC trigger chambers, reducing considerably the rate of fake trigger in the acceptance of EIL4.

2.3. Monitored Drift Tubes and Resistive Plate Chambers
In order to maintain a high trigger efficiency, triplets of new RPC chambers with increased rate capability will be installed on the inner (BI) MDT chambers of the barrel. Because of the reduced space available, in the small sectors MDT chambers will be replaced with sMDT chambers with reduced overall thickness, in order to be coupled in the same envelope, as the original MDT chambers, with the BI RPCs.
2.4. Trigger and read out electronics

The trigger system, as well as the data acquisition, will be redesigned to have a Level-0 trigger working at a rate of 1 MHz, to maintain similar trigger thresholds as in Run-2 but at higher luminosity. Most of the present components have hard limits on the maximum first-level trigger latency and rate they can operate at, and therefore they have to be replaced. The trigger logic will be moved from on-detector custom ASICs to off-detector boards based on programmable FPGAs allowing for more complex and flexible algorithms. MDT hits will be used in the first level trigger to refine candidates based on RPC, TGC and NSW data.

3. RPC system upgrade in the inner barrel: the BI Project

In order to maintain the present excellent performance of the RPC system in the scenario of high luminosity, an upgrade will be developed during Phase-I and Phase-II, which consist of the installation of an additional layer of new generation of RPCs coupled to sMDT chambers in the inner layer, which will provide a lot of benefits in terms of acceptance, redundancy and selectivity of the trigger.

3.1. Limits of the present system

The present ATLAS RPC system consists in three concentric layers of doublet chambers around the beam axis. Two of three layers are mounted on both sides of the middle MDT chambers in the barrel (Barrel Middle region), while the third one is mounted on one side of the outer MDT chambers (Barrel Outer region). Each doublet is composed by two RPC chambers with gas gaps of 2 mm width and electrodes of 1.8 mm thickness with a resistivity of $10^{10}$ Ω cm. The induced signal is transferred to two panels of orthogonal strips (providing $\eta$ and $\phi$ coordinates) and read out by a Front End electronics based on GaAs technology. This features imply an intrinsic time resolution of about 1 ns and a space resolution of the order of 1 cm.

The RPC system provides the hardware muon trigger in the barrel. The low-$p_t$ trigger, used for muon signature, requires the coincidence between the innermost two RPC doublets and can select muons with $p_t$ thresholds between 4 and 10 GeV. The high-$p_t$ trigger, used in coincidence with other objects to select multi-object signature, requires an additional coincidence with the third layer and can select muons with $p_t$ thresholds between 11 and 20 GeV.

In sight of operation at HL-LHC, a substantial upgrade of the muon trigger system is expected in order to maintain high efficiency for muons with $p_t > 20$ GeV and to keep the rate of fake triggers under control. One of the limitation of the present system concern the RPC rate capability. The current ATLAS RPCs are certified to operate up to an integrated charge of 0.3 C/cm², which corresponds to ten years LHC operation at counting rate of 100 Hz/cm². The rates extrapolated from Run-1 data to HL-LHC for the middle layer chambers reach up to 340 Hz/cm² in chambers near $|\eta|=1$, therefore this integrated dose over 30 years will exceed the design specification by more than a factor of ten in some chambers. In order to maintain the RPCs in good working condition, the current must be lowered below the stable operation limits. This means that the charge per count must be reduced and this can be reached by lowering the operating voltage, which will results in a reduction of the single-hit efficiency of about 15 % up to 35% in chambers at large $\eta$. This affects the trigger performance and makes necessary to loose the trigger requirements to compensate the loss in efficiency.

In addition, high $p_t$ trigger requires hits on the three layers of RPCs, limiting the acceptance to only about the 80% in the region that are covered by these layers, at $|\eta| < 1.05$, mainly due to the barrel toroid coils and their support structures.

Moreover the current gas mixture for RPCs, composed by $C_2H_2F_4$, $C_4H_{10}$ and $SF_6$, has an high Global Warming Potential (GWP) of about 1430 and the RPC gas system release approximately 700 l/h into the atmosphere, mostly due to leaks. This could become a problem if some additional restriction on the greenhouse gas emissions will be imposed, or if these gases
become too expensive due to a reduction in the industrial demand. Alternative mixture with lower GWP, based on $C_3H_2F_4/CO_2/C_4H_{10}/SF_6$, are under test but the current ATLAS RPCs can not work with these mixtures because of the limited sensitivity of the Front End electronics and because they are not designed to work at significantly higher voltages than now. They can operate with lower GWP mixtures at decrease voltage but in this way the single gap efficiency would drop to 80%. Additionally, the electronics on the Pad boards have been designed for a maximum Level-1 readout latency of 6.4 µs and a maximum Level-1 trigger rate of 100 kHz, which are incompatible with the Phase-II requirements of the trigger, so they must be replaced.

### 3.2. RPC upgrade

In order to solve the problems discussed in the previous section, an additional layer of new generation of RPCs will be installed in the inner layer of the muon spectrometer. During Phase-I upgrade this installation will start with the BIS78 pilot project, where a total of 32 RPC triplets coupled with sMDT chambers (figure 2) will be installed in sectors 7 and 8 of the muon spectrometer, where the highest rate of fake triggers is expected. During Phase-II upgrade the chambers will be installed in the whole BI region.

![Figure 2. Picture of one BIS78 station, composed by a BIS7-type triplet (top left), one BIS8-type triplet (top right) and sMDT chambers (under the RPCs triplets).](image)

Each RPC station is composed by three independent singlets of RPCs mounted all together in the same envelope to form a triplet, each equipped with an improved Front End electronics. Each singlet is composed by a 1 mm gas gap with electrodes of 1.2 mm. The signal is read out by two panels of strips, where configuration will be different for BIS78 RPCs and BI RPCs. The configuration for the BIS78 is the same as the present ATLAS RPCs, with two panels of orthogonal strips, one in the $\eta$ direction and one in the $\Phi$ direction; the BI configuration consists in two panels of parallel strips, both in the $\eta$ direction, due to the limited space available to install the detectors. The $\Phi$ coordinate in this case will be measured with the difference in time between signals read out on the parallel strip panels.

The reduction of the gas gap width allows to work approximately at half of the currently high voltage and improves the time resolution from 1 ns to 0.4 ns, as seen in figures 3 and 4. The thinner electrodes allow to reduce the total thickness and the total weight and to improve the signal to noise ratio, increasing the charge fraction transferred to the pick-up electrodes.

The minimum threshold of the new Front End electronics of 0.3 mV and a detectable signal of 1-2 fC provides a reduction of about a factor ten in the charge produced inside the gas gap, resulting in an increase of the rate capability. The reduction of the gas gap, the thinner
electrodes and the new Front End electronics allow to reduce the total charge per hit generated inside the gas for a given efficiency, resulting in an improvement of the rate capability and of the detector lifetime.

![Figure 3](image)

**Figure 3.** Efficiency as a function of the high voltage for a BIS7 singlet, where the high voltage working point is shown by the dashed line. The curves show the $\eta$ layer efficiency (black), the $\Phi$ layer efficiency (red), the AND (blue) and the OR (green) efficiency of the two as a function of the high voltage.

![Figure 4](image)

**Figure 4.** Time resolution of a BIS7 singlet calculated with the time of flight measurement before (a) and after (b) the time walk correction.

The installation of the BI chambers will increase the geometrical acceptance and the robustness of the barrel muon trigger, allowing to compensate the effects derived from the lowering of the high voltage, necessary to ensure the longevity of the present detectors. In fact the installation of the BI will improve the redundancy of the trigger, using nine measurement planes instead of six, provided by four layers of RPCs as shown in figure 5: one BI triplet (RPC0), two BM doublets (RPC1 and RPC2) and one BO doublet (RPC3).
Figure 5. Scheme of the four layers of RPCs in a small sector. The different trigger logic are also shown.

The current high $p_t$ trigger is based on the 3/3 chambers logic, shown in figure 5, which requires hits in at least two out of four planes of the RPC1 and RPC2 chambers and at least in one out of two planes of RPC3. To take advantage from the improved redundancy of the trigger, new trigger logic schemes, in addition to the 3/3 logic, have been developed and are shown in figure 5. The first one is the 3/4 majority which consists in the 3/3 logic in a logical OR with the requirement of hits in at least 2/3 planes in RPC0 and in at least 3/6 in RPC1+RPC2+RPC3. In this way all combinations of three chambers coincidence are accepted. The second one is the 3/4 majority + BI-BO and consists in the 3/4 majority in a logical OR with the requirements of at least two hits in BI RPCs and at least one hit in BO RPCs. The development of these new trigger logics will balance the effect of the efficiency reduction of the old chambers, as can be seen in figure 6 (b), which shows that the installation of the BI allows to work at trigger efficiency times acceptance more than 90% even in the worst case scenario, with the old RPCs at the lowest voltage. In addition the geometrical acceptance is improved and most of the holes mainly due to the calorimeter feet and rails and toroidal magnets supports are covered, as can be seen in figure 6 (a).

Figure 6. (a) Geometrical acceptance of the L0 barrel trigger with respect to the reconstructed muons with $p_t=25$ GeV in the $\eta-\Phi$ plane for the 3/4 chambers + BI-BO trigger scheme. (b) Efficiency times acceptance of the Level-0 barrel trigger with respect to the reconstructed muons with $p_t=20$ GeV as a function of $\eta$ assuming the worst case scenario, which represents the limit in which the old RPCs operate at very low voltage.
The trigger efficiency times acceptance as a function of the muon $p_t$, for $p_t > 10$ GeV and $p_t > 20$ GeV rises of 10% including BI, as shown in figure 7, resulting in an improvement of the trigger selectivity.

![Figure 7. Trigger efficiency times acceptance as a function of the $p_t$ for a threshold of 10 GeV (a) and 20 GeV (b).](image)

The installation of the BI will give also further benefits. The transverse momentum of the muons which cross all the three stations can be calculated using a 3-point sagitta measurement, resulting in an improvement of the momentum selectivity. In addition, there will be the possibility to measure the $\Phi$ coordinate in the Inner Barrel region, which is not available from MDT chambers, gaining in terms of pattern recognition and track finding in a high-background conditions. Moreover, thanks to the better time resolution, it will be possible to perform time of flight measurements. This is very important for instance in the search of long lived particles, giving the possibility to measure their velocity $\beta$ and to distinguish a New Physics signal from the Standard Model one.

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