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Upgrade of the ATLAS Muon System for the HL-LHC

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Abstract

The muon spectrometer of the ATLAS detector will be significantly upgraded during the Phase-II upgrade in Long Shutdown 3 in order to cope with the operational conditions at the High-Luminosity LHC in Run 4 and beyond. Most of the electronics for the Resistive Plate Chambers (RPC), Thin Gap Chambers (TGC), and Monitored Drift Tube (MDT) chambers will be replaced to make them compatible with the higher trigger rates and longer latencies necessary for the new level-0 trigger. The MDT chambers will be integrated into the level-0 trigger in order to sharpen the momentum threshold. Additional 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 in the barrel-endcap transition region will replace the current TGC doublets to suppress the high trigger rate from random coincidences in this region. The power system for the RPC, TGC, and MDT chambers and electronics will need to be replaced due to component obsolescence, aging, and radiation damage. A high-η tagger is under consideration to extend the angular acceptance for muon identification. The Phase-II upgrade concludes the process of adapting the muon spectrometer to the ever increasing performance of the LHC, which started with the Phase-I upgrade New Small Wheel project that will replace the Cathode Strip Chambers and the MDT chambers of the innermost endcap wheels by Micromegas and small-strip TGCs.

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1. LHC and ATLAS upgrades

The LHC was designed to deliver proton-proton collisions at a center-of-mass energy of $\sqrt{s} = 14$ TeV and an instantaneous luminosity of 1×10^{34} cm^{-2} s^{-1}. The High-Luminosity upgrade of the LHC, the HL-LHC, will provide luminosities of 5–7.5 $\times 10^{34}$ cm^{-2} s^{-1} and a total integrated luminosity of 3000–4000 fb^{-1}. A major upgrade of the experiments is required to cope with these new conditions and to fully exploit the HL-LHC physics potential. The upgrade of ATLAS [1] is foreseen in two steps: the Phase-I upgrade during Long Shutdown 2 (LS2, 2019–20), followed by Run 3, and the Phase-II upgrade during LS3 (2024–26), followed by Run 4.

Muon signatures play a crucial role in the ATLAS physics program. The challenge for the muon spectrometer (MS) is to preserve its muon identification and tracking performance, and its standalone and combined (with the inner tracking detector) momentum resolution, in much harsher conditions in terms of particle rates, radiation, and pile-up (the number of inelastic pp interactions per bunch crossing). To take full advantage of the increase in luminosity, the trigger must become more selective, so that the low p_T thresholds required for many physics channels remain affordable, i.e. result in an acceptable trigger rate. The architecture of the ATLAS trigger and readout system will change fundamentally, necessitating a complete redesign of the trigger and readout of all detector systems, including the MS.

2. ATLAS muon spectrometer

The ATLAS MS consists of three large air-core superconducting toroidal magnets (two endcaps and one barrel) providing a field of approximately 0.5 T. The deflection of the muon trajectories in the bending plane of the magnetic field (the "precision coordinate") is measured via hits in three layers of monitored drift tube (MDT) precision chambers covering the region in pseudorapidity up to $|\eta| < 2.7$. In the innermost endcap wheels of the MS, cathode strip chambers (CSC) are used in-

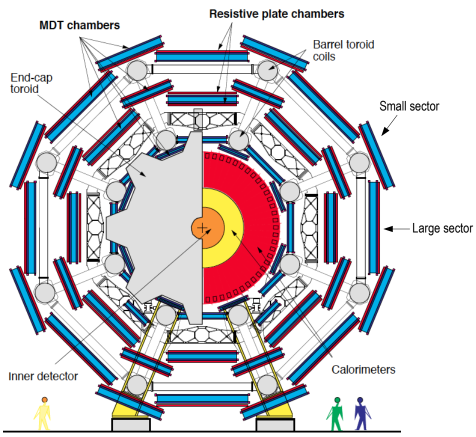

Figure 1: View of the present (Run 1/2) ATLAS muon spectrometer barrel layout in the plane transverse to the beam axis (X-Y plane) [2].

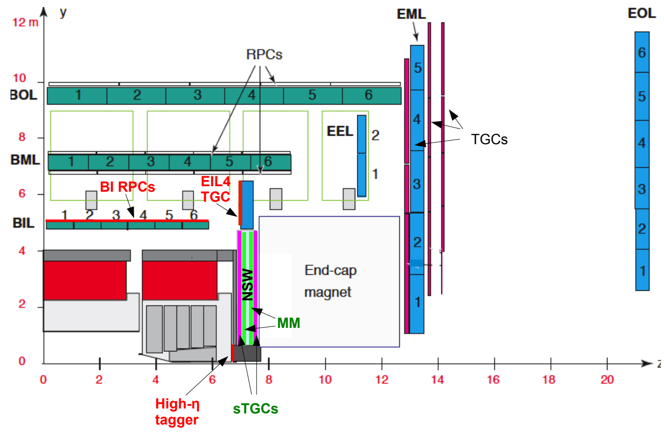

Figure 2: R-Z view of the MS layout in a large sector, showing the new detectors to be installed in LS2/LS3 (green/red text), and those that will remain unchanged from the present layout (black text) [2].

stead of MDTs in the region $2.0 < |\eta| < 2.7$. The magnetic field strength is such that the sagitta of a track, i.e. the maximum deviation of the curved track from a straight line joining its endpoints in the spectrometer, is on average 500 μm for a transverse momentum of $p_T = 1$ TeV. An optical alignment system monitors in real time the positions of precision chambers with respect to each other and to calibrated reference objects in the detector. The nominal stand-alone momentum resolution of the MS is better than $\Delta p_T/p_T = 4\%$ over a large range in momentum, increasing to 11% for a track of $p_T = 1$ TeV.

Three layers of resistive plate chambers (RPC) in the barrel ($|\eta| < 1.05$) and 3–4 layers of thin gap chambers (TGC) in the endcaps ($1.05 < |\eta| < 2.4$) provide the muon trigger, and also measure the muon trajectory in the non-bending coordinate of the magnets (the "second coordinate"). The muon first-level hardware trigger is based on hit coincidences between different RPC or TGC detector layers inside programmed geometrical windows (roads) which define the muon p_T. The maximum rate and latency of this first-level trigger are 100 kHz and 2.5 μs, respectively. The high-level trigger (HLT) performs a full track reconstruction by using precision chamber hits in addition to trigger chamber hits, resulting in a refined p_T measurement.

The inner, middle, and outer layers of the barrel and endcap muon chambers are labeled BI, BM, BO and EI, EM, EO, respectively, and muons are normally detected in those three layers. In the barrel-endcap transition region ($1.05 < |\eta| < 1.3$), muons are detected instead in the EIL4 or BIS7/8, EE (extra), and EM layers. In the CSC, MDT, and RPC systems the MS is sub-divided in azimuthal direction (ϕ) into 16 sectors, eight large (L) and eight small (S) ones. Large sectors are located inbetween the eight barrel toroid coils, and small sectors overlap in ϕ with the coils. In the TGC system, there are instead 24 or 48 equal-sized sectors in azimuthal direction, depending on the radial position. The endcap disks made of the CSC and EI1–3 chambers are also referred to as the Small Wheels (SW), the EM1–5 disks as the Big Wheels (BW).

In the Phase-I upgrade, foreseen for LS2, the Small Wheels will be replaced by the New Small Wheels (NSW) using small-strip TGC (sTGC) and Micro-Mesh Gaseous Structure (MicroMeGaS or Micromegas, MM for short) chambers used for both triggering and precision tracking. At the time of the Phase-II upgrade, there will thus be no CSC chambers any more in the detector, nor will there be the Small Wheel MDT chambers, which are the ones closest to the beam line and exposed to the highest rates. Also in LS2, the BIS7 and BIS8 MDT chambers will be replaced by integrated BIS78 stations of new RPC and small-diameter MDT (sMDT) chambers to enhance the trigger coverage in this region. The layout of the MS and the locations of the new detectors are shown in Figs. 1 and 2.

3. Requirements for the muon system at the HL-LHC

The MS detector and electronics components have originally been designed for 10 years of operation at a luminosity of 1×10^{34} cm^{-2} s^{-1}, corresponding to an integrated luminosity of 1000 fb^{-1}. Conservative safety factors for radiation tolerance and rate capability were assumed, and components have been tested up to and above levels corresponding to the doses and rates predicted by simulations, multiplied by safety factors. After the start of LHC operation, detector hit rates and radiation doses were measured directly, and the previous simulations have been found to agree with the measurements to within a maximum deviation of about 50%. Based on this observation, the original safety factors were reduced, and as a consequence the original irradiation and high-rate tests have qualified the detectors for longer running and higher rates than anticipated – in many cases, up to the levels expected at the HL-LHC.

The MS must be able to operate at an instantaneous luminosity of 7.5×10^{34} cm^{-2} s^{-1} and at a pile-up of 200 without significant performance losses. The muon identification and reconstruction performance should not be degraded by the higher particle rates and backgrounds, and the reconstruction efficiency, fake rates, and momentum resolution should be similar to the present ones. The reconstruction efficiency and momentum resolution of the MDT system are robust against high pile-up and high background rates. The muon trigger, on the other hand, requires significant upgrades if low trigger momentum thresholds are to be maintained while keeping the trigger rates at a manageable level. The muon trigger should be able to trigger on single muons with high efficiency, with a rate of less than 40 kHz for a threshold of $p_T > 20$ GeV. In addition, lower p_T thresholds, as low as $p_T > 4$ GeV, should be viable for multi-muon and combined triggers. The sharpness of the turn-on curve of the trigger, and thus the rate of fake triggers from low-momentum muons which dominates the total muon trigger rate, is limited by the spatial resolution of the RPC and TGC trigger chambers. The efficiency of the trigger is high in the endcap regions, but is limited in the barrel region by the geometrical acceptance of the RPC system, which is below 80% for tracks detected in three RPC chambers.

The design of the ATLAS Phase-II trigger and readout system foresees an evolutionary scheme, starting with a single-level hardware trigger (L0 trigger), which might later evolve into a two-level design by adding a second-stage hardware trigger (L1 trigger). The L0 trigger is based on muon and calorimeter information and has a latency of 10 μs so that more complex trigger algorithms than in the present first-level system are feasible. In the single-level design, L0 will send events to the HLT at a rate of 1 MHz. In the two-level design, the L0 trigger rate will increase to up to 4 MHz, which will be filtered by an L1 trigger making use of an extended latency of up to 35 μs and of information from the inner tracking detector to provide an output rate of up to 800 kHz to the HLT. Many aspects of the existing trigger and readout electronics of the MS are incompatible with either of these Phase-II schemes.

4. Muon spectrometer Phase-II upgrades

The Phase-II upgrade of the MS is described in depth in a Technical Design Report [2]. It comprises the installation of new chambers, the replacement of some existing chambers, and the replacement of a large part of the front-end and trigger and readout electronics. The electronics upgrades are required to provide the needed improvements to muon triggers, and to make the electronics compatible with the new ATLAS trigger and readout scheme. The chamber upgrades address weaknesses of the present chambers and their layout, in order to keep the MS performance at a high level in a much more challenging environment.

4.1. Upgrade of trigger and readout electronics

The trigger and readout electronics chain of the RPCs and TGCs will be completely re-designed for improved performance using modern technologies. For each bunch crossing, all data from the TGC and RPC detectors will be transmitted to the counting room, where the full information will be available for trigger processing. In such a scheme, more refined and flexible algorithms can be used compared to the present ones based on simple coincidences. In the NSW region ($1.3 < |\eta| < 2.7$), the MM and sTGC chambers both take the dual role of trigger and precision chambers. Trigger primitives (track segments) from these detectors will be combined with TGC hits to provide the endcap trigger candidates.

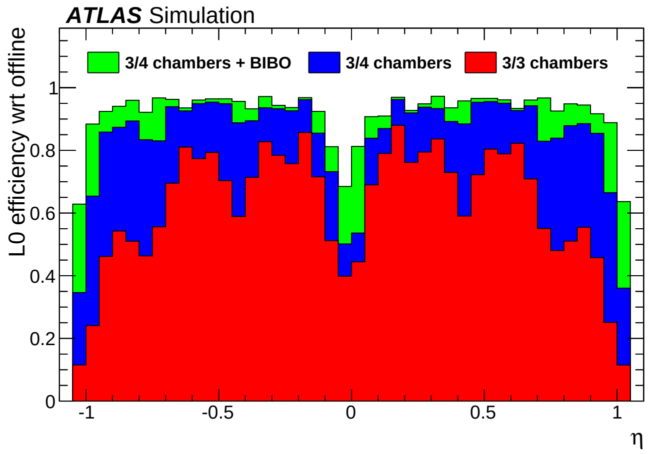

Figure 3: Efficiency times acceptance of the L0 barrel trigger for muons with $p_T = 25$ GeV as a function of η, assuming the worst-case scenario in which the RPC HV has been reduced such that the single-hit efficiency is 65–85% depending on η. The histograms show the efficiency of the 3-out-of-3 (3/3) chambers trigger used in Run 2, the 3/4 chambers trigger including the BI layer, and the additional gain from the 2/4 chambers BI-BO trigger [2].

The electronics chain of the MDT chambers will be completely re-designed as well. All MDT data will be sent to the counting room, and the MDT-measured precision coordinates will be used in the L0 trigger to filter the trigger candidates provided by RPCs and by TGCs plus NSW. The MDT hits can also be used as confirmation of loose trigger candidates from the RPC or TGC-NSW to maximize the acceptance by including regions with limited trigger detector coverage, adding redundancy to the system. For this upgrade, the entire electronics chain of the MDT chambers, including the front-end (mezzanine) cards on the chambers, needs to be replaced.

4.2. RPC and MDT chambers upgrade in the inner barrel

To maintain a high trigger efficiency, new RPCs will be installed on the inner (BI) MDT chambers of the barrel. This addresses a fundamental issue of the present (old) RPCs: to ensure their continued operation at the HL-LHC, these chambers will have to be operated at reduced performance (i.e. efficiency), in order to respect the original design limits on currents and integrated charge. This can be achieved by reducing the gas gain through lowering the operating voltages. In the areas of highest backgrounds, the gas gain will have to be reduced to such low levels that hit inefficiencies up to 35% will be encountered. This would reduce the trigger efficiency in the barrel region to an unacceptable level if no compensating measures were taken. In addition, due to changes in regulations, the present gas mixture used in ATLAS RPCs may need to be replaced by one with lower global-warming potential, which too would imply operation of old RPCs at a reduced efficiency. Despite the lowered single-hit efficiencies, a high trigger efficiency and purity can be maintained by loosening the requirements on hit coincidences in the old chambers, if at the same time a coincidence with the new BI RPCs is introduced (Fig. 3). The installation of these chambers will also close most of the acceptance holes of the present barrel muon trigger, which amount to more than 20%

of the η-ϕ coverage for $|\eta| < 1.05$. The new BI RPCs will have a thinner gas gap than the old RPCs (1 mm instead of 2 mm), and operate at 5400 V instead of 9600 V. This produces smaller signals, compensated by a higher sensitivity of the front-end electronics, and results in a much increased rate capability.

Adding new RPCs in the barrel is challenging in terms of available space. In small sectors, the BI RPC chambers can only be installed if the present MDT chambers are replaced by new sMDT chambers with reduced overall thickness so that the sMDT chambers and the new RPCs fit in the same envelope as the original MDT chambers. In the large sectors, there is sufficient space available to add the new RPCs without replacing the MDTs, if on-detector services are re-arranged. The tubes of the sMDT chambers have half the diameter of the old MDT (15 mm instead of 30 mm), and operate at 2730 V instead of 3080 V, resulting in the same field strength around the wire. Their rate capability is higher by a factor of eight.

4.3. TGC upgrade in the barrel-endcap transition region

To obtain a uniform level of purity for triggered muons, the current EIL4 TGC doublet chambers will be replaced by TGC triplets. The trigger rate in the endcaps is dominated by fake muon triggers from low-p_T charged particles generated inside the endcap toroid cryostats. Requiring a coincidence of the Big Wheel TGCs with chambers in front of the cryostats greatly reduces the rate of these fake triggers, and this is one of the motivations for the NSW and BIS78 projects. The EIL4 TGCs cover the region around the NSW, at $1.05 < |\eta| < 1.3$ in large sectors (small sectors will be covered by the BIS78 RPCs). The present doublet chambers have a coarse readout granularity, which in high-background conditions results in a large rate of random coincidences with background hits, rendering them useless for trigger purposes. Also, doublets are not sufficiently robust for use in a trigger: if one plane becomes inoperable, the entire chamber has to be excluded from the trigger to prevent loss of trigger efficiency, resulting in a local increase of the fake trigger rate. With the new triplet chambers a more robust coincidence logic can be used, requiring hits in two out of three planes, and smaller coincidence windows will reduce the rate of random coincidences to a negligible level.

4.4. High-η tagger

The replacement in LS3 of the Inner Detector (ID) by the Inner Tracker (ITk) extends the coverage for tracking up to $|\eta| < 4.0$. As a consequence, it becomes interesting to identify muons at such large $|\eta|$ values. Micro-pattern gaseous or silicon pixel detectors between the endcap calorimeters and the shielding disks in front of the NSW in the region $2.7 < |\eta| < 4.0$ would increase the MS acceptance, albeit in a region without magnetic field. These detectors could be used to tag ITk tracks as muons, relying on the ITk for momentum measurement. Different proposals for the instrumentation of this region are currently under consideration. Once this project has reached sufficient maturity and its feasibility is demonstrated, ATLAS will decide whether it has the necessary financial and manpower support, and a strong enough performance case.

4.5. Power system replacement

In addition to the upgrades of the detectors and the electronics, their HV and LV power system will also be replaced, to ensure reliable operation through the full operation period of the HL-LHC. Using updated safety factors, irradiation tests performed before the start of ATLAS have certified the present components up to a radiation dose corresponding to 1500 fb^{-1}. Apart from aging and radiation damage, it will become increasingly difficult and expensive to have the existing system components covered by maintenance contracts with the manufacturers, because spare parts will become obsolete or unavailable.

4.6. Installation, technology choices, and risk mitigation

The work in the experimental cavern for the Phase-II upgrade of the MS will be difficult and time-consuming. The organization of the work program requires a careful evaluation of the time and manpower needed for each operation. The dominant contribution comes from the MDT mezzanine cards: about 15,000 cards have to be replaced, with an estimated time of 15–30 minutes per card. Many chambers are difficult to access, some are even impossible to access in situ and have to be moved inside the detector or removed from the detector. Some chambers have to be moved so that others can be moved. Existing access platforms have to be modified or temporarily removed, and new platforms have to be temporarily installed. This, as well as the installation of new BIL RPCs and the replacement of the BIS MDT chambers by sMDT+RPC stations, is heavy mechanical work in the vicinity of fragile detectors and services. This process will require careful scheduling, skilled personnel, and a significant amount of manpower, and has therefore been studied in detail. Solutions have been found that are compatible with the expected duration of LS3 and are considered technically feasible. In comparison, the replacement of the remainder of the electronics chains of MDT, RPC, and TGC chambers will be more light-weight. Services will be re-used wherever possible, and replacement chambers and electronics will be designed to be compatible with the present cable routing and interfaces.

Many technology choices have been made in the process leading to the definition of the muon system upgrade program. Preference has been given to proven and well-established technologies that fulfill the requirements, rather than cutting-edge technologies for which significant R&D work would still be required before reaching maturity. The chamber upgrades employ an evolution of technologies already used in the muon system and for which expertise exists in the community. This approach should mitigate the risk of delays in the R&D up to and including the start of production, and it should ensure the timely commissioning of new detectors and the re-commissioning of upgraded old ones at the start of Run 4.

References

[1] ATLAS Collaboration, The ATLAS Experiment at the Large Hadron Collider, 2008 JINST 3 S08003.

[2] ATLAS Collaboration, Technical Design Report for the Phase-II Upgrade of the ATLAS Muon Spectrometer, LHCC-2017-017, http://cds.cern.ch/record/2285580.