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ATLAS Future Upgrade

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After the successful operation at the center-of-mass energies of 7 and 8 TeV in 2010 – 2012, the LHC is ramped up and successfully took data at a center-of-mass energy of 13 TeV in 2015. Meanwhile, plans are actively advancing for a series of upgrades of the accelerator, culminating roughly ten years from now in the high-luminosity LHC (HL-LHC) project, delivering of the order of five times the LHC nominal instantaneous luminosity along with luminosity leveling. The ultimate goal is to extend the dataset from about few hundred fb^{-1} expected for LHC running to 3000 fb^{-1} by around 2035 for ATLAS and CMS. In parallel, the experiments need to be kept lockstep with the accelerator to accommodate running beyond the nominal luminosity this decade. Along with maintenance and consolidation of the detector in the past few years, ATLAS has successfully added an inner b-layer to its tracking system. The challenge of coping with the HL-LHC instantaneous and integrated luminosity, along with the associated radiation levels, requires further major changes to the ATLAS detector. The designs are developing rapidly for a new all-silicon tracker, significant upgrades of the calorimeter and muon systems, as well as improved triggers and data acquisition. ATLAS is also examining potential benefits of extensions to larger pseudorapidity, particularly in tracking and muon systems. This document summarizes various improvements to the ATLAS detector required to cope with the anticipated evolution of the LHC luminosity during this decade and the next.

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1. Introduction

ATLAS [1] is a general-purpose experiment designed to explore the proton-proton (*pp*) collisions at the CERN Large Hadron Collider (LHC) [1] with center-of-mass energies of up to $\sqrt{s} = 14$ TeV at a nominal luminosity of $\mathscr{L}^0 = 10^{34}$ cm^{-2}s^{-1}. ATLAS is devised to exploit the full physics potential of the LHC, which includes discovery of the Higgs particle and measurement of its properties, as well as searches for effects beyond the Standard Model (SM). The extremely high collision energy along with the high luminosity at the LHC allows an effective pursuit of new physics at the TeV scale.

As shown in Fig. 1, ATLAS consists of three basic detector subsystems: the Inner Detector (Pixel, SCT, TRT), housed in a solenoid magnet creating a magnetic field of 2 T, the Calorimetry system (Liquid Argon and Tile) and the Muon Spectrometer (MS) with its associated superconducting toroidal magnets supplying an average magnetic field of 0.5 T. With its overall dimensions of 44 m in length and 25 m in diameter, ATLAS is the largest detector ever built in collider experiments.

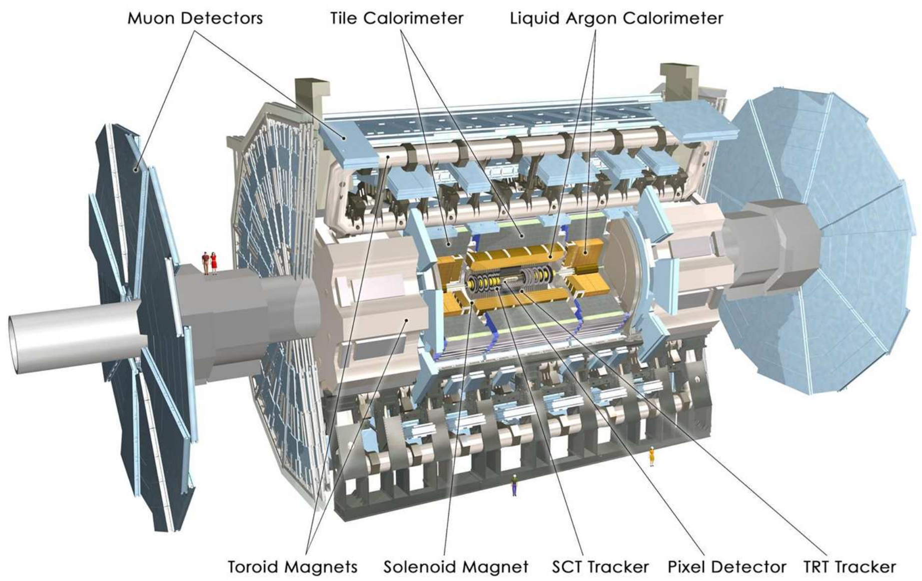

Figure 1: The ATLAS experiment.

A trigger system of two levels (hardware-based first level trigger, Level-1, and a software-based high level trigger, HLT) is used to select the events of interest, providing a final average trigger rate of a few hundred Hz[1].

In 2015, Run 2 for the LHC has started, during which the *pp* collision energy has reached 13 TeV. The beam intensity has been increased too, as by the end of 2015 it has reached values of 2240 proton bunches per beam. For 2016, further increase of the number of bunches per beam to 2748 is forseen, as the goal is to collect ~ 25 fb^{-1} of integrated luminosity by the end of the year. As a result of the excellent performance and operation of the experiment in 2015 ATLAS

[1]During the LHC Run 1 (2009 – 2013), the ATLAS trigger was a three-stage system with two stages in the HLT.

has successfully recorded over 3 fb^{-1} with stable pp beams at $\sqrt{s} = 13$ TeV, corresponding to an average data-taking efficiency of 92.1%.

In the coming years, the LHC will undergo a series of upgrades ultimately leading to five times increase of the instantaneous luminosity (with leveling) in the High-Luminosity LHC (HL-LHC) project. The goal is to extend the dataset from about 300 fb^{-1}, expected to be collected by the end of the LHC run (in $\sim$ 2023), to 3000 fb^{-1} by $\sim$ 2035. The foreseen higher luminosity at the HL-LHC is a great challenge for ATLAS. Meeting it will require significant detector optimizations, changes and improvements, which are subject of this article.

2. High-Luminosity LHC and the Future ATLAS Upgrade

The main motivation for the HL-LHC is to extend and improve the LHC physics program [3]. Depending on the results from the LHC data, some of the physics topics that could be addressed at the HL-LHC are: measuring of the Higgs rare decays and Higgs self-coupling; performing top-quark and heavy-flavor production precision physics; performing a complete supersymmetry spectroscopy; searching (extending limits) for new gauge bosons (W', Z'); searching for a quark and lepton substructure.

The harsher radiation environment and higher detector occupancies at the HL-LHC imply major changes to most of the ATLAS systems, specially to those at low radii and large pseudorapidity, η. A general guideline for these changes is to maintain the same (or better) level of detector performance as at the LHC. The Inner Detector (ID), forward calorimeter and forward muon wheels will be affected the most by the higher particle fluxes and radiation damage, requiring replacements or significant upgrade, whereas the barrel calorimeters and muon chambers are expected to be capable of handling the conditions and will not be modified. New radiation-hard tracking detectors with higher granularity and higher bandwidth, as well as radiation-hard front-end (FE) electronics are foreseen. The higher event rates and event sizes will be a challenge for the trigger and data acquisition (DAQ) systems, which will require a significant expansion of their capacity.

The ATLAS future upgrade is planned in two phases, corresponding to the remaining two long technical shutdowns of the LHC towards the HL-LHC. *Phase-I* (duration $\sim$ 24 months) will take place in 2019 – 2020 and *Phase-II* ($\sim$ 30 months) is scheduled for 2024 – 2026.

3. ATLAS Future Upgrade: Phase-I

In 2019, the LHC will be stopped for an upgrade of the injectors and the collimators. Replacement of the current Linac2 with the more powerful proton linear accelerator, Linac4, and increase of the Proton Synchrotron Booster output energy are planned. The data-taking will be resumed after 24 months shutdown with luminosity of $2-3\times10^{34}$ $\text{cm}^{-2}\text{s}^{-1}$. During the shutdown, ATLAS intends to accomplish the second[2] stage of its upgrade program, the Phase-I, [12].

[2] The first stage of ATLAS upgrade program, Phase-0, took place during the LHC long shutdown in 2013-2014. Core activity in the ATLAS Phase-0 upgrade was the installation of a new, 4^{th} barrel layer in the Pixel detector, the so-called IBL project [4].

In Phase-I, installation of new Muon Small Wheels and introducing of new trigger schemes (Fast TracKer, topological triggers, improved L1Calo granularity) are proposed to handle luminosities well beyond the nominal values.

3.1 New Muon Small Wheels

For the first (innermost) endcap station of the Muon Spectrometer, the Muon Small Wheel (MSW), built of Monitored Drift Tubes (MDT) and Cathode Strip Chambers (CSC), as shown in Fig. 2, a replacement is proposed. The concern is that for luminosities higher than $\mathscr{L}^0$, in addition to the higher number of pile-up events per bunch-crossing, large amounts of cavern background will be induced, affecting a large $|\eta|$ region of the MSW. The current system in this region will struggle to cope with this and therefore a replacement is required.

The new Muon Small Wheels must ensure efficient tracking at high particle rate (up to $\mathscr{L} = 5 \times 10^{34}$ cm^{-2}s^{-1}) and large $|\eta|$, with position resolution of < 100 μm. Furthermore, the new MSW will be integrated into the Level-1 trigger [7].

Micro-MEsh GAseous Structures (MicroMEGAs) complemented with small-strip Thin Gap Chambers (sTGC) are the detector technologies considered [8].

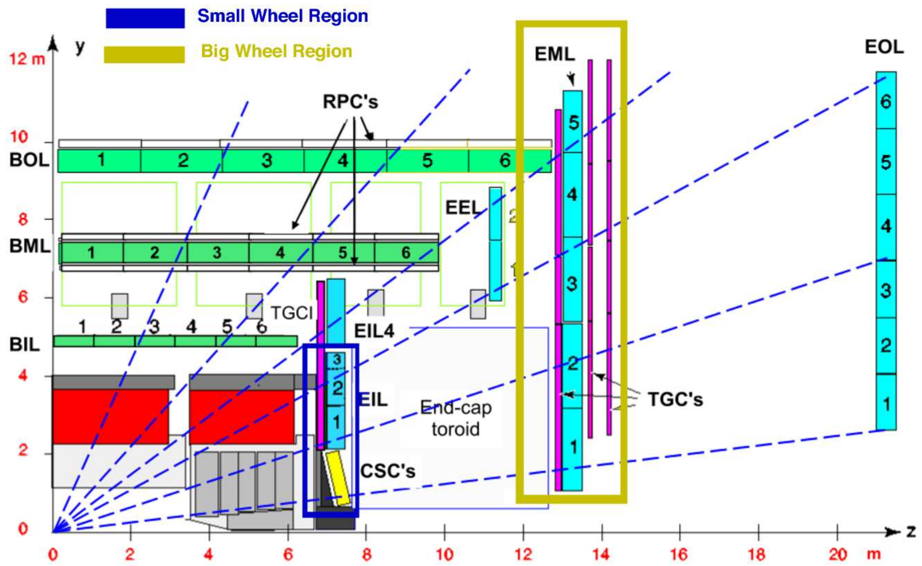

Figure 2: A z-y view of 1/4 of the ATLAS detector. The blue boxes indicate the end-cap Monitored Drift Tube chambers, MDT, and the yellow box in the Small Wheel area the Cathode Strip Chambers, CSC. The green boxes are barrel MDT chambers. The trigger chambers, Resistive Plate chambers, RPC, and Thin Gap Chambers TGC, are indicated by the outlined white and the magenta boxes. This is a cut-out on the muon spectrometer at the large sectors, hence the names 'End-cap Inner Large' (EIL), 'End-cap Middle Large' (EML) and 'End-cap Outer Large' (EOL). The detector regions of the Small Wheel and Big Wheel are also outlined [8].

3.2 New Trigger Schemes

At Phase-I conditions, more sophisticated triggers will be required [10]. For this, the Fast TracKer (FTK) trigger project has been initiated [9]. At the FTK, the track finding and fitting are conducted at a hardware level, which makes it extremely fast (a latency of less than 100 μs is expected for input rates up to 100 kHz). With the current ATLAS detector, this task is performed by the trigger Level-2 software farm. FTK will provide the track parameters at the beginning of the Level-2 processing. This way, the load on Level-2 will be diminished and extra resources will be available for more advanced selection algorithms, which ultimately could improve the b-tagging, lepton identification, etc.

Suggestions are also in place for combining trigger objects at Level-1 (topological triggers) and for implementing full granularity readout of the calorimeter, [11]. The latter will strongly improve the triggering capabilities for electrons and photons at Level-1.

4. ATLAS Upgrade: Phase-II

The ATLAS Phase-II upgrade [13, 14], is presently scheduled for 2024 – 2026. During this time, LHC will be out of operation for furnishing with new inner triplets and crab cavities. As a result, an instantaneous luminosity of 5×10^{34} cm^{-2}s^{-1} along with luminosity leveling should be achieved. The goal is to accumulate 3000 fb^{-1} of data by $\sim$ 2035.

ATLAS Phase-II preparations include a new Inner Detector and further trigger and calorimeter upgrades.

4.1 New Inner Detector

Running at nominal $\mathscr{L}^0$ for the LHC, will bring, on average, $\sim$ 28 primary interactions (pile-up events) per bunch crossing, every 25 ns. The number of pile-up events at 5×10^{34} cm^{-2}s^{-1} is therefore expected to be $\sim$ 140. Should luminosity leveling not be fully effective, or some other scheme adopted, 7×10^{34} cm^{-2}s^{-1} should at least be accommodated. This will result in detector occupancies beyond the TRT design parameters. Furthermore, by 2024, the Pixel and the SCT subsystems would have seriously degraded performance due to the radiation damage of their sensors and FE electronics. Because of all these factors, ATLAS has decided to replace the entire Inner Detector with a new, all-silicon *Inner Tracker* (ITk). The ITk must satisfy the following criteria (w.r.t. ID): higher granularity, improved material budget and increased radiation hardness of the readout components. At the moment, the ITk project is in an R&D phase. Different geometrical layouts are simulated and their performance is studied in search for the optimal tracker architecture. A major constraint on the design is the available space, defined by the volume taken by the ID in ATLAS. This implies a maximum radius of $\sim$ 1 m and the limitation of existing gaps for services.

The current baseline design of the ITk, depicted in Fig. 3, and described and studied in detail in Ref. [13] and Ref. [15], consists of four Pixel and five full length Si-strip layers in the barrel part. The two endcap regions are each composed of 6 Pixel and 7 Si-strip double-sided disks, built of rings of modules. The pixel modules are with pixels of sizes 25×150 μm (for the two inner layers) and 50×250 μm (for the two outer layers). Similarly, the Si-strip barrel modules also come in two types, with short (24 mm) for the first three layers and long (48 mm) strips for the outmost two layers. As in the current SCT, the Si-strip modules are designed to be of two pairs of silicon microstrip sensors, glued back-to-back at an angle of 40 mrad to provide 2D space-points.

Intensive R&D studies are also in progress to select the most suitable pixel sensor technology out of Si-planar, 3D and diamond, and to find the optimal layout of the Si-strip modules [6].

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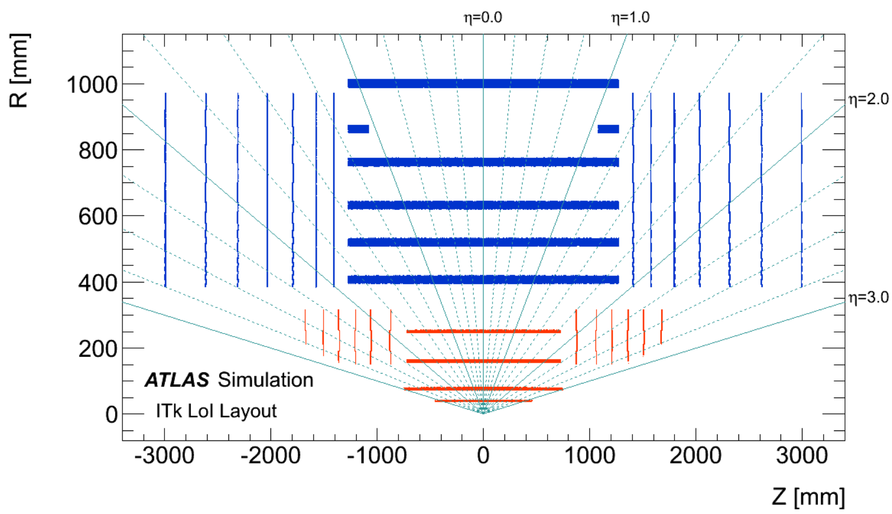

Figure 3: Sensitive layers (simulated hit positions in the R-z plane) in the baseline (Letter of Intent) layout of the new Inner Detector for Phase-2 upgrade. The Pixel and Strip systems are shown in red and blue, respectively [15].

4.2 Calorimeter and trigger upgrades

The HL-LHC conditions will have a major impact on the Calorimetry system. To ensure an adequate performance, a replacement of the cold electronics inside the LAr Hadronic endcap, as well as a replacement of all on-detector readout electronics for all calorimeters may need to be anticipated. Also, the operation of the Forward Calorimeter (FCal) could be compromised. To maintain the FCal functioning at the HL-LHC, two possible solutions are considered [5]: first, complete replacement of the FCal, and second, installation of a small warm calorimeter, Mini-FCal, in front of the FCal. The Mini-FCal would reduce the ionization and heat loads of the FCal to acceptable levels.

The planned trigger upgrades for Phase-II, are connected with implementing a Track Trigger at Level-1/Level-2, applying full granularity of calorimeter at Level-1 and improving the muon trigger coverage.

5. Conclusions

The ATLAS collaboration has devised a detailed program to reflect the changes in the LHC conditions towards the High-Luminosity LHC, characterized by high track multiplicity and extreme fluences. At each of the remaining two phases of the upgrade program, actions will be undertaken to reassure the stable and efficient performance of the ATLAS detector.

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