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ATLAS Upgrades Towards the High Luminosity LHC: extending the discovery potential

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After the successful LHC operation at the center-of-mass energies of 7 and 8 TeV in 2010 - 2012, plans are actively advancing for a series of upgrades, 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 final goal is to extend the dataset from about few hundred fb^{-1} expected for LHC running to 3000 fb^{-1} by around 2030. Current planning in ATLAS also envisions significant upgrades to the detector during the consolidation of the LHC to reach full LHC energy and further upgrades to accommodate running beyond the nominal luminosity this decade. 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 inner-tracker, significant upgrades of the calorimeter and muon systems, as well as improved triggers and data acquisition. This document summarises 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

The ATLAS [1] experiment at the CERN Large Hadron Collider (LHC) [2] is a general-purpose experiment designed to explore the proton-proton (*pp*) collisions at the LHC 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 constructed to exploit the 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 will allow searches for new physics at the TeV scale.

As depicted in Fig. 1, ATLAS consists of three basic detector subsystems: the Inner Detector (Pixel, SCT, TRT), housed in a solenoid 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.

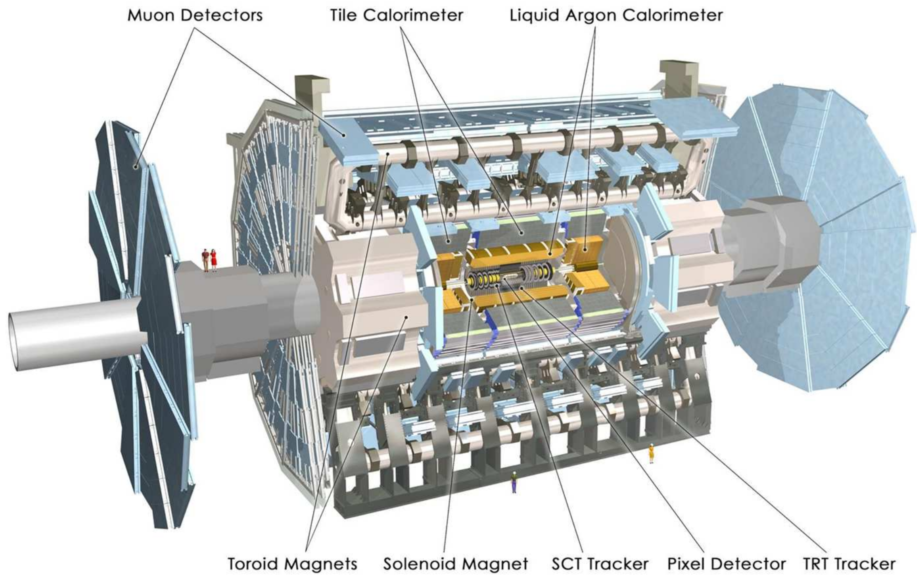

Figure 1: The ATLAS experiment.

A three-level trigger system is used to select the events of interest, providing a final average trigger rate of a few hundred Hz. The overall dimensions of 44 m in length and 25 m in diameter, make ATLAS the largest detector ever built in collider experiments.

As a result of the excellent performance and operation of the experiment, in 2011 and 2012 ATLAS successfully recorded 5 fb^{-1} with stable *pp* beams at $\sqrt{s} = 7$ TeV and 22 fb^{-1} at $\sqrt{s} =$ 8 TeV, respectively, corresponding to an overall data-taking efficiency of 94%.

In the coming years, 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 $\sim$ 2020), to 3000 fb^{-1} by $\sim$ 2030. 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 document.

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2. Motivation for HL-LHC and the ATLAS Upgrade Plans

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 problems 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 maintaining 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 replacement 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 upgrade is planned in three phases, corresponding to the three long technical shutdowns of the LHC towards the HL-LHC. *Phase-0* (duration 18 months) started in 2013 and will continue also during 2014, *Phase-I* ($\sim$ 14 months) foreseen for 2017-2018, and finally, *Phase-II* ($\sim$ 27 months) scheduled for 2022-2023.

3. ATLAS Upgrade: Phase 0

The main objective of the 2013-2014 shutdown of the LHC is to perform interventions which will permit the machine to operate at a center-of-mass energy of $\sqrt{s} = 13$ TeV and design luminosity of 1×10^{34} cm^{-2}s^{-1}.

ATLAS will use this two year period for installation of new pixel services, completion of the Muon Spectrometer and for detector consolidation works, including a new ID cooling system, a new neutron shielding of the MS, and a new beam pipe. The current beam pipe in the forward region is made of stainless steel which is a source of high backgrounds for the MS. The new beam pipe in the forward region will be of aluminum, thus reducing the backgrounds by 10-20%.

The central ATLAS upgrade activity in Phase-0 is the installation of a new barrel layer in the present Pixel detector, the so called IBL project.

3.1 Insertable B-layer

The Insertable B-layer (IBL) is an additional, 4$^{\text{th}}$ pixel layer which will be inserted between the innermost pixel layer (the B-layer) and the beam pipe, as shown in Fig. 2, during the Phase-0 upgrade. To make the installation of the IBL possible, a new beam pipe in the central region, with reduced by 4 mm radius (r=29 mm $\rightarrow$ r=25 mm), built of beryllium (to reduce beam induced backgrounds), is envisaged.

As demonstrated in Ref. [4], it is expected that the IBL will improve the vertex resolution, secondary vertex finding and b-tagging, hence extending the reach of physics analyses. It will compensate for defects (irreparable failures of modules) in the existing pixel detector, assuring tracking robustness. Moreover, IBL will help to preserve the tracking performance at luminosities beyond $\mathscr{L}^0$, e.g. in Phase-1, when the B-layer will suffer from radiation damage and occupancies due to the high pile-up.

The IBL consists of 14 staves, mounted directly on the beam pipe with a tilt angle of 14°. On each stave there are 16 to 32 modules depending on the sensor type. Two silicon sensor types will be used: planar and 3D. The IBL modules will be equipped with a new readout chip, FE-I4 [5],

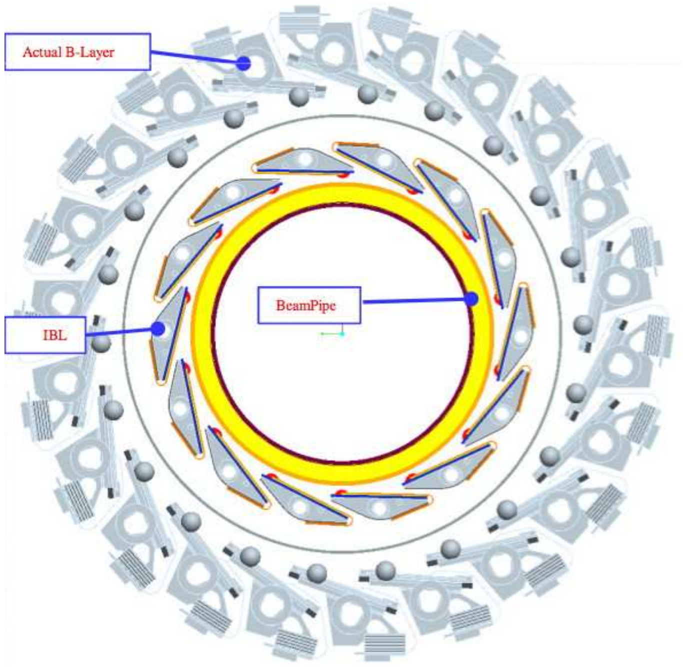

Figure 2: Cross-section view of the current Pixel B-layer, the new beam pipe and the IBL.

which has been specially developed to function at high data transfer rates ($\sim$ 160 Mb/s). The FE-I4 design allows an increase of the IBL segmentation by decreasing the pixel size from 50 μm $\times$ 400 μm to 50 μm $\times$ 250 μm.

4. ATLAS Upgrade: Phase-I

In 2017, 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 14 months shutdown with luminosity of $2-3\times10^{34}$ cm^{-2}s^{-1}. During the shutdown, ATLAS intends to accomplish the second stage of its upgrade program, the Phase-I, [11].

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.

4.1 New Muon Small Wheels

For the first endcap station of the Muon Spectrometer, the Muon Small Wheel (MSW), built of Monitored Drift Tubes (MDT) and Cathode Strip Chambers (CSC), a replacement is proposed. The concern is that for luminosities $\mathscr{L} > \mathscr{L}^0$, 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 [8].

Micro-MEsh GAseous Structures (MicroMEGAs) complemented with small-strip Thin Gap Chambers (sTGC) are the detector technologies considered, [9].

4.2 New Trigger Schemes

At Phase-I conditions, more sophisticated triggers will be required. For this, the Fast TracKer (FTK) trigger project has been initiated [10]. 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. The latter will strongly improve the triggering capabilities for electrons and photons at Level-1.

5. ATLAS Upgrade: Phase-II

The ATLAS Phase-II upgrade is scheduled for 2022 and 2023, [12]. 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 $\sim$ 2030.

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

5.1 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 2022, the Pixel and the SCT subsystems would seriously degrade their performance due to the radiation damage of their sensors

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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, 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 ~ 1 m and the limiting existing gaps for services.

The current baseline design of the ITk, depicted in Fig. 3, and described and studied in detail in Ref. [12] and Ref. [13], consists of 4 Pixel and 5 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 2 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 process 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 [7].

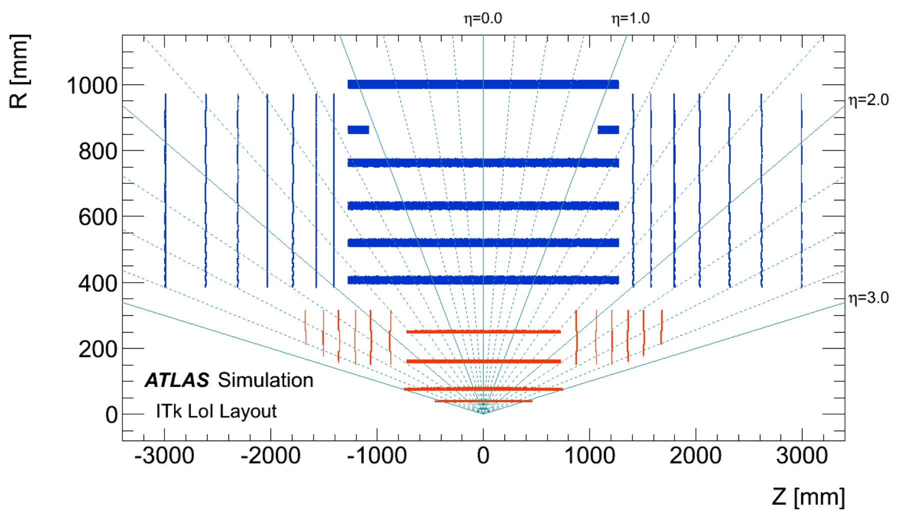

Figure 3: The baseline layout of the new Inner Detector for Phase-2 upgrade.

5.2 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 [6]: 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.

6. 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 3 phases of the upgrade program, actions will be undertaken to reassure the stable and efficient performance of the ATLAS detector.

References

[1] ATLAS Collaboration, *The ATLAS Experiment at the CERN Large Hadron Collider*, J. Instr. 3 (2008) S08003.

[2] L. Evans and P. Bryant, *LHC Machine*, J. Instr. 3 (2008) S08001.

[3] K. Jakobs, *Physics at the LHC and sLHC*, Nucl. Instr. and Meth. A (2010), doi:10.1016/j.nima.2010.04.077

[4] ATLAS collaboration, *Insertable B-Layer, Technical Design Report*, CERN/LHCC-2010-013

[5] M. Barbero *et al.*, *A new ATLAS pixel front-end IC for upgraded LHC luminosity*, Nucl. Instrum. Meth. A 604 (2009) 397.

[6] J. Turner, *Upgrade Plans for ATLAS Forward Calorimetry for the HL-LHC*, ATL-LARG-PROC-2011-002

[7] A. Affolder, *Silicon Strip Detectors for the ATLAS HL-LHC Upgrade*, ATL-UPGRADE-PROC-2011-005

[8] B. Bittner, *et al.*, *Tracking and Level-1 triggering in the forward region of the ATLAS Muon Spectrometer at sLHC*, ATL-UPGRADE-PROC-2011-008

[9] ATLAS Collaboration, *New Small Wheel Technical Design Report*, CERN-LHCC-2013-006; ATLAS-TDR-020

[10] ATLAS Collaboration, *Fast TracKer (FTK) Technical Design Report*, CERN-LHCC-2013-007; ATLAS-TDR-021

[11] ATLAS Collaboration, *Letter of Intent for the Phase-I Upgrade of the ATLAS Experiment*, CERN-LHCC-2011-012 ; LHCC-I-020

[12] ATLAS Collaboration, *Letter of Intent for the Phase-II Upgrade of the ATLAS Experiment*, CERN-LHCC-2012-022, LHCC-I-023

[13] S. Burdin, T. Cornelissen, C. Debenedetti, S. Elles, M. Elsing, I. Gavrilenko, N. Hessey, A. Huettmann, A. Korn, S. Miglioranzi, M. Lisovyi, P. Maettig, A. Schaelicke, A. Salzburger, K. Selbach, N. Styles, U. Soldevila Serrano, T. Todorov, J. Tseng, N.Valencic, P. Vankov, P. Wells, *Tracking Performance of the Proposed Inner Tracker Layout for the ATLAS Phase-II Upgrade*, ATL-UPGRADE-PUB-2013-001