PROCEEDINGS OF SCIENCE

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

Diane Cinca* **on behalf of the ATLAS collaboration**
SUPA, School of Physics and Astronomy, University of Glasgow, G12 8QQ, UK
E-mail: diane.cinca@cern.ch

After successful LHC operation at the center-of-mass energy of 7 and 8 TeV in 2011 and 2012, plans are actively advancing for a series of upgrades, culminating roughly 10 years from now in the high luminosity LHC (HL-LHC) project, delivering of order five times the LHC nominal instantaneous luminosity along with luminosity levelling. The final goal is to extend the data set from about few hundred fb^{-1} expected for LHC running to 3000 fb^{-1} by around 2030. Current planning in ATLAS also has significant upgrades to the detector during the consolidation of the LHC to reach full LHC energy and further upgrades to accommodate running already beyond nominal luminosity this decade. The challenge of coping with 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 an all-new inner-tracker, significant upgrades in the calorimeter and muon systems, as well as improved triggers and data acquisition. This document summarises the various improvements to the ATLAS detector required to cope with the anticipated evolution of the LHC instantaneous luminosity during this decade and the next.

XXII. International Workshop on Deep-Inelastic Scattering and Related Subjects,
28 April - 2 May 2014
Warsaw, Poland

*Speaker.

ATL-UPGRADE-PROC-2014-001
26 June 2014

PoS(DIS2014)262

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 $\mathscr{L}^0 = 10^{34}\mathrm{cm}^{-2}\mathrm{s}^{-1}$. 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.

The detector is composed of the Inner Detector, which includes the Pixel, SemiConductor Tracker (SCT) and Transition Radiation Tracker (TRT) inside a solenoid magnetic field of 2 T. Outside the solenoid, the Calorimeter System contains the Liquid Argon (LAr) electromagnetic (EM) calorimeter which provides a coverage up to $|\eta| < 3.2$. The hadronic calorimeter uses iron and scintillator in the central region (TileCal) with a coverage up to $|\eta| < 1.7$, whereas copper and LAr technology is used in the forward region ($1.7 < |\eta| < 3.2$). Finally, the very forward region uses copper and tungsten LAr calorimeters to measure both EM and hadronic showers in the region $3.2 < |\eta| < 4.5$. The Muon Spectrometer is located inside a toroidal magnetic field of 0.5 T. The trigger for muons is performed with Resistive Plate Chambers (RPC) in the central region and with Thin Gap Chambers (TGC) in the region up to $|\eta| < 2.4$. The Monitored Drift Tubes (MDT) is used for tracking in the region $|\eta| < 2$ and Cathode Strip Chambers (CSC) in the region $2 < |\eta| < 2.7$. The ATLAS trigger system is divided in three levels. The first level of trigger, based on custom electronics, uses the information with reduced precision and granularity provided by the calorimeters and muon systems and has a maximum event rate of 100 kHz. The second and third levels of trigger, also called High Level Trigger (HLT), is based on software algorithms using as input the result of the first level and the full granularity and precision signals from all the subsystems including the Inner Detector.

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 2022), to 3000 fb^{-1} by 2035. The foreseen higher luminosity at the HL-LHC is a great challenge for ATLAS. The significant detector optimisations, changes and improvements required are the subject of this document.

2. Motivation for HL-LHC and challenge

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 the studies or rare Higgs decays, precision studies of many Higgs couplings and properties, detailed Standard Model physics measurements and top quark rare decay searches. The harsher radiation environment and higher detector occupancies at the HL-LHC imply major

PoS(DIS2014)262

changes to most of the ATLAS systems, especially to those at low radii and large pseudorapidity, η. A general guideline for these changes is maintaining the same (or even enhance) 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 increase 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 (18 months) foreseen for 2018-2019, and finally, Phase-II (30 months) scheduled for 2023-2024.

3. ATLAS Upgrade: Phase 0

The LS1 will be followed by the Run 2 which will last three years. The consolidation in the superconducting circuits in the LHC will allow to reach the design peak luminosity and a center-of-mass energy of $\sqrt{s} = 13$ TeV. In order to cope with the new conditions which will already exceed the design luminosity, some ATLAS subsystems are accomplishing a serie of upgrade or consolidation works, being the main one the insertion of an additional pixel layer (IBL), which is detailed in the next section. In addition to that, the muon spectrometer will be completed with the installation of addtional Endcap Extension Chambers, to improve the efficiency in the region of $1.0 < |\eta| < 1.3$, and a new neutron shielding in the gap between the forward calorimeter and the shielding disk to withstand the expected increase of particle fluences. The previous iron beam pipe has been replaced by a new Aluminum pipe tol reduce the activation of the detector material. The sensors and electronics will make use of a new evaporative cooling system based on CO_2 with a reduced mass and free of maintenance. The low voltage power supplies of the front-end electronics of the TileCal will be replaced by a new radiation tolerant design improving the reliability. A new Pixel Services Quarter (nSQP) will be installed to carry electrical power, cooling and optical data. It will allow the installation of additional features in the Inner Detector like the Diamond Beam Monitor (DBM) which will extend the current Beam Conditions Monitor (BCM) system.

3.1 Insertable B Layer

One of the main Phase-0 upgrades for ATLAS is the insertion of an additional pixel layer placed between the beam pipe and the current Pixel B-layer [4]. A new beam pipe, in Aluminium and Beryllium in the central region, with a smaller radius (25 mm) has been installed in this area to allow the insertion of the extra layer. The Insertable B Layer (IBL) will use two different types of sensors with reduced pixel size of 50 x 250 μm , and a planar technology for the low η region and 3D sensors for the high η. The IBL will help to improve the tracking, overtaxing and the b-tagging efficiency at high luminosities. Moreover, it will recover the performance losses with the increasing pileup and will provide redundancy in case of radiation damage of the present Pixel detector. The efficiency of the IBL for b-tagging with a pileup of 50 is similar to the efficiency of the present ATLAS detector with zero pileup.

4. ATLAS Upgrade: Phase-I

In 2018, 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 18 months shutdown with luminosity of 2-3 x 10^{34} cm^{-2}s^{-1}. During the shutdown, ATLAS intends to accomplish the second stage of its upgrade program, the Phase-I [5]. 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 L = 5 x 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 [6]. Micro-MEsh GAseous Structures (MicroMEGAs) complemented with small-strip Thin Gap Chambers (sTGC) are the detector technologies considered [7].

4.2 Fast Track Trigger

One of the biggest challenges of ATLAS in Phase-I is to keep an effective trigger for higher luminosities and pileup. The Fast Track Trigger (FTK) is a dedicated highly parallel hardware-based track finder making use of the Inner Detector (including the IBL) and providing track information with offline precision to the Level-2 trigger with a required reduction of the processing power. The system will make use of a full mesh AdvancedTCA backplane in order to cope with the large exchange of data required. The FTK is expected to improve the performance of track based isolation and b-tagging independently of pile-up interactions [8].

4.3 Finer granularity calorimeter trigger

The Level-1 EM calorimeter trigger in the current system applies E_T thresholds on $\Delta\phi$ x $\Delta\eta$ = 0.1 x 0.1 trigger towers. The usage of improved lateral and longitudinal segmentation can be used to apply isolation selections in order to increase the background rejection. The Phase-I Upgrade of the calorimeter will provide additional segmentation in the front and middle EM sampling layers. The improved granularity allows the computation of lateral and longitudinal shower shapes as well as a better discrimination power between electrons and jets. Furthermore, the current analog signals

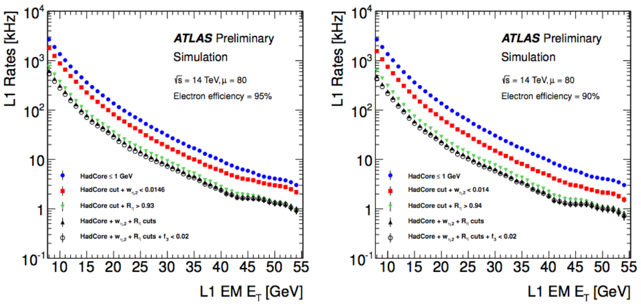

Figure 1: Trigger rates for $L = 3 \times 10^{34}$ cm^{-2} s^{-1} as a function of ET thresholds with optimized requirements on shower shape variables. Left and right plots correspond to trigger efficiencies of 95 % and 90 %, respectively, for electrons from simulated $Z \rightarrow e^+e^-$ decays.

transited to the Level-1 trigger system with a final quantization precision of 1 GeV will be replaced by a full digital system with a quantization precision of 125 MeV in the middle layer and 32 MeV in the other layers. Figure 1 shows the estimated Level-1 trigger rate as a function of the ET threshold for different conditions in Run 2 and Phase-I. In optimised conditions, the L1 EM threshold can be reduced by more than 7 GeV for a given rate [9].

5. ATLAS Upgrade: Phase-II

The ATLAS Phase-II upgrade is scheduled for 2023 and 2024, [10]. 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 2035. 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, 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 of about 140. 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 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 about 1 m and the limiting existing gaps for services. The current baseline design of the ITk, Figure 2, described and studied in detail in [10] and [11], 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 x 150

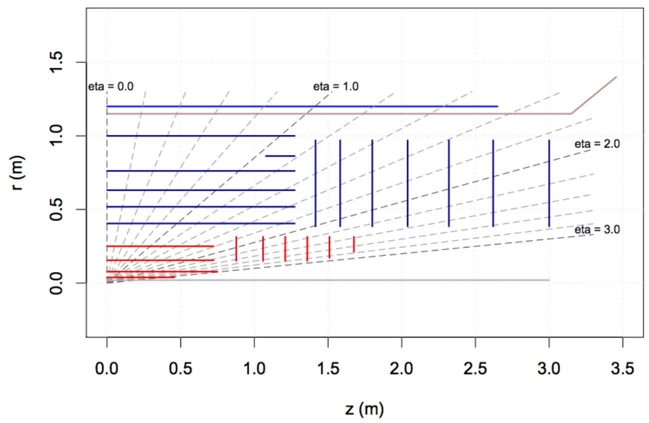

Figure 2: The baseline layout of the replacement tracker showing the active areas of silicon detectors arranged on cylinders and disks.

μm (for the two inner layers) and 50 x 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.

5.2 Trigger and calorimeter 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. Both the LAr and TileCal will afford a complete replacement of the on- and off-detector electronics including a new readout architecture. Full digital information for all the calorimeter cells will be transmitted for every bunch crossing to the off-detector system, thus reducing the front-end functionalities and components that will operate in the high radiation environment. The transmission data bandwidth will be increased to up to 200 Tbps for the entire calorimeter. The back-end system will be responsible for feeding the Level-0 and Level-1 trigger systems with preprocessed digital information. It will include also the pipeline memories with programmable depth to cope with the latencies and rates specified in the new trigger schema [10]. 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. Conclusion

The ATLAS collaboration has envisaged an upgrade program divided in 3 phases aligned with the scheduled LHC long shutdowns. The different upgrades and consolidation works reflect the changes in the LHC conditions with the aim of maintaining or improving the present detector performance, ensuring optimal physics acceptance with the increasing luminosity. The main upgrade foreseen for the Phase-0 is the installation of an additional pixel layer in the Inner Detector whereas for Phase-I the upgrades are mainly focusing on the trigger functionalities. Finally, for the HL-LHC, ATLAS will prepare the detector for another 10 more years of operation, where the main tasks are the complete replacement of the Inner Detector, an new trigger level and readout architectures and the complete replacement of the calorimeter electronics.

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, *ECFA High Luminosity LHC Experiments Workshop: Physics and Technology Challenges*, ECFA/13/284, CERN, Switzerland.

[4] ATLAS Collaboration, *ATLAS Insertable B-Layer Technical Design Report Addendum, CERN-LHCC-2012-09*. ATLAS-TDR-019-ADD-1, CERN (Geneva, 2012)

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

[6] 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

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

[8] M. Hochet et al., *Fast TracKer (FTK) Technical Design Report, Tech. Rep. CERN-LHCC-2013-007*. ATLAS-TDR-021, CERN (Geneva, 2013), ATLAS Fast Tracker Technical Design Report.

[9] ATLAS Collaboration, *ATLAS Liquid Argon Calorimeter Phase-I Upgrade Technical Design Report, CERN-LHCC-2013-017*, ATLAS-TDR-022, CERN (Geneva, 2013).

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

[11] 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

PoS(DIS2014)262