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ATLAS Upgrade: meeting the challenges of the sLHC

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With the Large Hadron Collider (LHC) providing pp collisions data at $\sqrt{s} = 7$ TeV, plans are already advancing for a series of upgrades leading eventually to about 5×10^{34} cm^{-2}s^{-1} some ten years from now in the super-LHC (sLHC) project. The goal is to extend the dataset from about few hundreds fb^{-1} expected by 2020 to few thousands fb^{-1} by around 2030. High instantaneous and integrated luminosities are the challenge that will require many changes to the ATLAS detector. The designs are developing rapidly for a new tracking detector, significant changes in the calorimeter and muon systems, as well as improved triggers and data acquisition system. These proceedings summarise the environment expected at the sLHC and the status of the improvements to the ATLAS detector.

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1. Introduction

In 2010 the Large Hadron Collider (LHC) has been providing pp collisions data at $\sqrt{s} = 7$ TeV. While ATLAS experiment [1] is presenting its first physics results, plans are already advancing for a series of LHC upgrades leading eventually to about five times the nominal peak luminosity ($\mathscr{L}_{peak}^{nominal} = 10^{34}$ cm^{-2}s^{-1}) some ten years from now in the super-LHC (sLHC) project. At the sLHC conditions ATLAS will need to cope with a few hundred pp interactions ("pile-up") per beam crossing, increased intensities and hence increased occupancies in detectors.

The ATLAS detector [1] at the LHC covers nearly the entire solid angle [2] around the collision point. It consists of an inner tracking detector (ID), which enables extended track reconstruction up to pseudorapidity [2] region $|\eta| = 2.5$, surrounded by a thin superconducting solenoid which provides a magnetic field of 2 T, the calorimeter system which covers $|\eta| < 4.9$, and an external muon spectrometer ($|\eta| < 2.7$) incorporating three large superconducting toroid magnet assemblies. To select events of interest, a three-level trigger system is used. The hardware-based level-1 (L1) uses a subset of detector information to reduce the event rate to a design value of at most 75 kHz. The two software-based trigger levels, level-2 and the event filter, together reduce the event rate to about 200 Hz.

The goal is to achieve at least the same detector performance at the sLHC as at the LHC, despite the large increase in event rate, so that we can continue searches as well as perform precision measurements. With the current LHC schedule the radiation damage is not an issue till 2020 when major upgrades to reach the nominal sLHC luminosity $\mathscr{L} = 5 \times 10^{34}$ cm^{-2}s^{-1} are planned. The major upgrades are implied by the harsher radiation environment and higher detector occupancies. The detectors at low radii and large η are most affected, including the ID, forward calorimeter and forward muon wheels. On the contrary, the barrel calorimeters and muon chambers are left largely untouched. As a result, at the sLHC conditions, higher granularity tracking detectors with higher bandwidth readout are required. As the detectors and the front-end (FE) electronics will sustain a signicantly increased radiation dose, the components should be radiation-hard. The trigger and data acquisition (DAQ) system should handle much higher event rates.

The ATLAS upgrade is tentatively planned in three phases: the "Phase-0" will take place from early 2012 to spring 2013, the "Phase-I" will take the entire 2016, and the "Phase-II" will start in the end of 2019 and finish in early 2021. These proceedings summarise some of the issues and studies underway to address the challenges of pursuing physics at the sLHC with the upgraded ATLAS detector.

2. Phase-0 Upgrade

By 2012, more than 1 fb^{-1} of integrated luminosity ($\int \mathscr{L} dt$) is expected to be delivered with the peak luminosity above $\mathscr{L}_{\rm peak} = 10^{32}$ cm^{-2}s^{-1}. Then the 15 months long shutdown is scheduled to start in 2012 to bring the LHC to the nominal energy $\sqrt{s} = 14$ TeV. ATLAS will take advantage of this shutdown to make a "Phase-0" upgrade.

With increasing luminosity the muon spectrometer is exposed to significant backgrounds from low-energy neutrons and photons. The present muon chambers shielding layout was optimised [3] and there is no simple improvement to the shielding that would significantly reduce background rates. Currently, the beam pipe in the forward region is made of stainless steel which produces high backgrounds in the muon system and becomes radioactive, thus restricting maintenance scenarios. To substantially minimise the beam pipe activation and to reduce the muon chamber background by 10-20%, the beam pipe will be replaced with an aluminium one. For the sLHC conditions, ATLAS considers putting an all-beryllium beampipe for a factor of two reduction in the muon background.

3. Phase-I Upgrade

By 2016 few tens fb^{-1} of integrated luminosity is expected to be delivered with the design peak luminosity. The "Phase-I" year-long upgrade is scheduled for 2016. For the LHC upgrade, it is foreseen to increase brightness of the beams by upgrading the Linac2 injector to Linac4, and increase the output energy of the Proton Synchrotron Booster.

The biggest ATLAS upgrade at the "Phase-I" is a new innermost pixel layer. Other upgrades include reinforcing the muon system and improving DAQ and triggers.

3.1 Insertable B-Layer

The innermost layer of pixels, a "b-layer", is the closest to the interaction region and therefore subject to the most severe radiation conditions. The original program of the b-layer replacement foresaw the extraction of the b-layer and its substitution with a new one. However, this turned out to be unfeasible, so it is planned now to exchange the beam pipe with a thinner one and use the additional space for a fourth pixel layer, an insertable b-layer (IBL). The IBL (Fig. 1) will serve as a backup in case of problems with the innermost layer, and will improve tracking and the determination of secondary vertices (b-tagging).

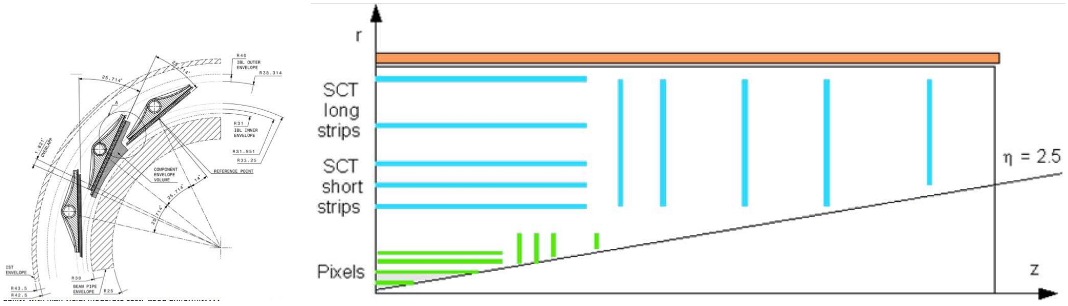
Several R&D studies are underway. The front-end chip foreseen for the IBL is called FE-I4 [4]. The "planar sensors" [5] have the advantage of low cost and well understood manufacturing sources. However, they have the lowest operating temperature and a high bias voltage. The "3D sensors" [6] have an intermediate working temperature, the lowest bias voltage and the highest geometrical acceptance due to the active ages. However, manufacturing of the 3D sensors is not well-understood. The "diamond sensors" [7] require the least cooling, have low leakage current and capacitance, a bias voltage is similar to the one of the planar sensors. However, manufacturing and cost might become an issue.

3.2 Muons

In the present detector, the forward Cathode Strip Chambers (CSC) were descoped from eight layers to four. In the "Phase-I" upgrade, all the chambers on the forward small wheels will be replaced with new chambers with more layers to secure tracking performance. New electronics is being developed for trigger improvements; moreover, muon drift tubes are considered to become part of the ATLAS L1 trigger. The R&D into new technologies that would also work for the "Phase-II" are in progress.

3.3 DAQ/Trigger

To preserve L1 sensitivity to high-p_T leptons despite pile-up and cavern background, various projects for data acquisition (DAQ) and trigger upgrades are pursued. DAQ should be able to read out and transport larger events. There are various new trigger schemas and new architecture designs such as combining trigger objects at L1 and topological analysis. A hardware-based fast track finder is being developed which will provide quality helix parameters of all tracks to the L2 processors right after an L1 trigger. To further improve triggering capabilities for electrons and photons, full granularity readout of the calorimeter is required. Changes such as increased granularity, improved resolution and increased latency, are viable only if electronics are upgraded.



(a) IBL

(b) Inner Detector for Phase-II

Figure 1: (a) Baseline of IBL layout: r-ϕ view; (b) Baseline of the Phase-II ID layout: r-z view.

4. Phase-II Upgrade

By the end of 2019 300fb^{-1} of $\int \mathscr{L} dt$ is expected to be delivered with the peak luminosity $\mathscr{L}_{\rm peak} = 2 \times 10^{34}$ cm^{-2}s^{-1}. The "Phase-II" upgrade is scheduled to start in 2019 and end in 2021, and then the LHC is expected to deliver approximately $\int \mathscr{L} dt = 3000$fb^{-1} of data at peak luminosity of $\mathscr{L}_{peak} = 5 \times 10^{34}$ cm^{-2}s^{-1} with long luminosity lifetime obtained by luminosity levelling.

ATLAS major upgrades are scheduled for the ID, forward calorimeter and muon systems.

4.1 Inner Detector

At the sLHC conditions, the ATLAS transition radiation tracker would experience extremely large occupancies, while radiation damage to the sensors and FE electronics of the silicon and pixel subsystems would seriously degrade their performance by 2020. For the Phase-II upgrade, the ID will be entirely replaced with an all-silicon system (Fig. 1). One of the consequences of replacing the TRT with silicon is the loss of its neutron-absorbing properties. However, lining the calorimeter with 5 cm polyethylene moderator is expected to reduce this to an acceptable level.

Increased granularity will help to reduce detector occupancy and thus preserve its ability to recognise charged tracks and displaced vertices. Improved resolution along the beamline will help to distinguish between associated and unassociated features in a beam crossing. At the same time, it is necessary to minimise the material profile of the ID: efforts are already underway to investigate increased service multiplexing and different construction techniques. In addition, increased heat generated by FE and readout electronics will require an upgraded cooling system.

4.2 Calorimeters

The high radiation environment of the forward calorimeter (FCAL) dictates the use of inherently radiation-hard liquid argon technology, as well as very small gap sizes, down to 250 μm, in order to limit the build-up of space charge. At the sLHC conditions, for the innermost modules this might be insufficient. Therefore the space charge effects are investigated using test modules with gap sizes down to 100 μm [8].

The forward modules face an additional problem due to beam heating and radiation effects. Replacing forward calorimeter modules represents a serious logistical challenge, since it would require opening the endcap cryostats and will take few years. To avoid this, ATLAS considers installing a "warm" forward calorimeter module in front of the current innermost module. This new forward calorimeter module would take the brunt of the heat load, and would require new technology as well as additional shielding on its inner face, in order to protect the ID. Electronics changes are foreseen for better performance and a finer granularity, as well as for trigger improvements.

4.3 Muons

The forward region of the muon system has to be upgraded. A candidate option is to replace the current Monitored Drift Tubes (MDT) and CSC muon system with smaller tubes with radius reduced from 30 to 15 mm. About 8 times less space charge is expected because of the smaller cross section of the tube. Alternative options are to do both tracking and triggering with a single chamber. Technologies under study are Micromega, GEMs, and TGCs as currently used in the forward trigger system but optimised for higher rate operations.

5. Summary

The harsh environment of the sLHC will be a significant challenge to the ATLAS experiment. A number of R&D efforts are actively progressing to address the challenge. It is planned that the entire Inner Detector will be replaced with an all-silicon tracker. Major upgrades are also envisioned for the forward calorimeters, muon chambers, and the beam pipe. In light of these challenges a number of R&D efforts have been in progress.

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