The ATLAS Upgrade programme

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After the first successful years of LHC running, plans are actively advancing for a series of upgrades leading eventually to about five times the design-luminosity some 10-years from now. Coping with the high instantaneous and integrated luminosity will be a great challenge for the ATLAS detector and will require changes in most of the subsystems, specially those at low radii and large pseudorapidity, as well as in its trigger architecture. Plans to consolidate and improve the physics capabilities of the current detector over the next decade are summarized in this paper.

1 Introduction

ATLAS [1] is a general-purpose experiment designed to explore the *pp* collisions at the CERN Large Hadron Collider (LHC) [2] at center of mass energies up to $\sqrt{s} = 14$ TeV and a maximum peak luminosity of 10^{34} cm^{-2} s^{-1}.

ATLAS has been successfully collecting collision data at $\sqrt{s} = 7$ TeV since March 2010, recording an integrated luminosity of ∼5 fb^{-1} with a peak luminosity of 3.3×10^{33} cm^{-2} s^{-1}. In the next years, LHC will undergo a series of upgrades leading ultimately to five times increase of the instantaneous luminosity 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 2020), to 3000 fb^{-1} by 2030. The foreseen higher luminosity at the HL-LHC is a great challenge for ATLAS. Meeting it will require significant but gradual detector optimizations, changes and improvements, which are subject of these proceedings.

2 LHC and ATLAS Upgrade Plans

The main motivation for the LHC upgrades is to extend and improve the actual machine physics programme. A major focus is on the Higgs boson. Using data from the 2011 running, the allowed mass range has already been greatly constrained. With increased statistics, the SM Higgs should be either discovered or excluded in the coming year. In the first case, with larger luminosity, it will be possible to observe the various Higgs decay modes first and then to make precision measurements of the Higgs boson properties, in particular its couplings to fermions and bosons, its rare decays and its self-couplings. If the Higgs is excluded, WW scattering measurements will become essential to unveil the electroweak symmetry breaking mechanism. Other physics items of interest will be: performing a complete supersymmetry spectroscopy; searching for new heavy gauge bosons; searching for a quark and lepton substructure.

In all cases, ATLAS capability to maintain an optimal trigger system as the luminosity increases beyond its nominal design value requires a strong reduction of the main source of backgrounds: jets mimicking electrons in the calorimeters and misidentified muons in the forward spectrometer. Otherwise, increased threshold cuts would have to be deployed to control rates, reducing significantly the signal efficiency. The harsher radiation environment and higher detector occupancies at the HL-LHC imply major changes to most of the ATLAS systems, specially those at low radii and large pseudorapidity. A general guideline for these changes is maintaining the same (or better) level of detector performance as at the LHC. 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 will be gradual and flexible to accommodate a possible evolution of LHC operational parameters and hints from new physics signals. It is planned in three phases, which correspond to the three long, technical shutdowns of the LHC towards the HL-LHC.

3 Phase-0 upgrades

The repair of the splices in the main accelerator during a long shutdown in 2013-2014 (LS1) will allow the LHC to continue its operation (Phase-0) close to its design parameters with a center of mass energy $\sqrt{s}$ =13-14 TeV, 25 ns bunch spacing and peak luminosities $\sim 1 \times 10^{34}$ cm^{-2} s^{-1}, which would bring ATLAS to collect a dataset corresponding to an integrated luminosity $\geq$50 fb^{-1}.

ATLAS will use the shutdown period mainly for detector consolidation works, including a new Inner Detector (ID) cooling system, new power supplies for the calorimeter, completion of the Muon Spectrometer (MS) and a new beam pipe, in the central and forward region. Other activities are still under evaluation as the replacement of the Pixel services, a new diamond beam monitor, a new neutron shielding of the MS, the replacement of the Minumum bias trigger scintillators. The main ATLAS upgrade activity in Phase-0 is the installation of a new barrel layer in the Pixel detector that is briefly described in the next section.

IBL. The Insertable B-Layer (IBL) [3] is an additional, 4^{th} pixel layer, that will be built around a new beam pipe and then slipped inside the present Pixel detector in situ or, if the Pixel package is removed for services replacement, on the surface. The IBL will be therefore placed between the actual innermost pixel layer (the B-layer) and the beam pipe, at a sensor average radius of 33 mm (50.5 mm is the radius of the B-layer). 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, is envisaged.

IBL will help to preserve the tracking performance at high luminosity when the B-layer will suffer from radiation damage and high pile-up occupancies. Moreover, it will compensate for defects (irreparable failures of modules) in the existing detector, assuring tracking robustness. It is expected that the IBL will also improve the vertex resolution, secondary vertex finding and b-tagging, hence extending the reach of the physics analysis.

The IBL will consist of 14 pixel staves surrounding the beam-pipe, see Fig. 1. Each carbon-fibre stave carries and provides cooling to 32 read-out chips, which are bump-bonded to silicon sensors, corresponding to a pseudo-rapidity coverage of $|\eta|$ <3. Two types of sensors will be used: planar n-in-n sensors, similar to the present Pixel detector, and 3D silicon sensors. The staves are inclined by 14° with respect to the radial direction in order to achieve overlap of active area between staves and to compensate for (a) the Lorentz angle of drifting charges in the 2 T magnetic field in case of planar sensors or (b) the effect of partial column inefficiency with perpendicular tracks in case of 3D sensors. There is no shingling of sensors along z due to the lack of radial space. To cope with a larger fluence and peak luminosity, higher hit rate and occupancy, a new generation of read-out chip, FE-I4, has been developed using a new architecture, IBM 130 nm CMOS process manufacturing and smaller pixel size (50×250 μm^2).

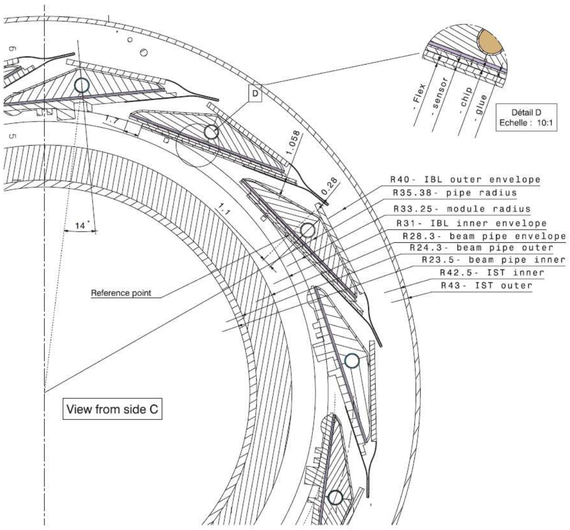

Figure 1: Section view of the IBL, the new beam-pipe and the IBL support tube (IST). Radii of envelopes are given in mm.

4 Phase-I upgrades

A second shutdown (LS2) is being planned in 2018 to integrate the Linac4 into the injector complex, to increase the energy of the PS Booster to reduce the beam emittance, and to upgrade the collider collimation system. When data taking resumes in 2019 (Phase-I), the peak luminosity is expected to reach $\sim 2-3 \times 10^{34}$ cm^{-2} s^{-1} corresponding to 55 to 80 interactions per crossing (pile-up) with 25 ns bunch spacing, well beyond the initial design goals. Phase-I will allow collection of an integrated luminosity of $\sim$ 300 fb^{-1}, extending the reach for discovery of new physics and the ability to study new phenomena and states. In Phase-I, ATLAS proposes the installation of new Muon Small Wheels and new trigger updates (Fast TracK , topological triggers, improved L1Calo granularity) to handle luminosities well beyond the nominal values. Detailed plans are described in Ref. [4].

New Small Wheels. In the muon spectrometer trigger rates, detector occupancy and momentum resolution are strongly affected by the level of background present in the cavern, both from particles generated at the interaction point, and from halo particles in the proton beams. This effect will increase as the peak luminosity evolves. While the implementation of an aluminium beam pipe (Phase-0 upgrade) will reduce the background rate in the forward region by 30%, a replacement of the first endcap station of the Muon Spectrometer, see Fig. 2, the Muon Small Wheel (MSW), is proposed. The new Muon Small Wheels must ensure efficient tracking at high particle rate (up to 5×10^{34} cm^{-2} s^{-1}) and larger $|\eta|$, with position resolution of < 100 μm. Furthermore, the new MSW will be integrated into the Level-1 trigger, resulting in a rate reduction to 20% with similar signal efficiency. Several detector technologies have been investigated: the final choice being Micro-MEsh GAseous Structures (MicroMEGAs) complemented with fast trigger chambers Thin Gap Chambers (TGC).

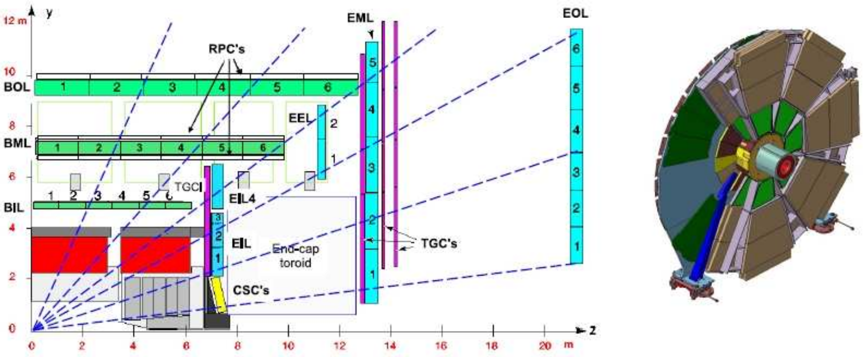

Figure 2: Left: A $z-y$ view of 1/4 of the ATLAS detector. The blue boxes indicate the end-cap MDT chambers and the yellow box CSC. Right: A view of a small wheel.

Level-1 Trigger calorimeter. Suggestions are also in place for combining trigger objects at Level-1 (topological triggers) and implementing higher granularity readout of the calorimeter. Preliminary studies show that shower shape algorithms based on finer granularity *Supercells* ($\Delta\eta \times \Delta\phi = 0.025 \times 0.1$) in the EM calorimeter's second layer achieve a background rejection factor for jets faking electrons similar to what is currently achieved in the Level-2 trigger with the full cell granularity.

Fast Track Trigger (FTK). The Fast TracKer Trigger [5] will perform the track finding and fitting at a hardware level, instead of the Level-2 software farm, which makes it extremely faster. FTK will then provide the track parameters at the beginning of the Level-2 processing thus releasing extra resources for more advanced selection algorithms, which ultimately could improve the b-tagging trigger performances. Commissioning of a barrel slice is on-going in the current data-taking.

5 Phase-II upgrades

The Phase-I upgrades are designed to be fully compatible with the physics program of the high luminosity HL-LHC (Phase-II), when the instantaneous luminosity should reach $\sim 5-7 \times 10^{34}$ cm^{-2} s^{-1}, up to 200 interactions per crossing (pile-up) and a total integrated luminosity of 3000 fb^{-1}. A third long shutdown (LS3) in 2022-23 will be necessary to upgrade the accelerator to this ultimate operation mode. ATLAS is being planning major updates in all its subsystems and trigger architecture.

New Inner Tracker. The present ATLAS Inner tracker will have several limitations in Phase-II when up to 200 pile-up events per bunch crossing are expected. The gas-based

TRT outer tracker has a limit due to instantaneous luminosity because of very high occupancy. The functionality of the silicon-based parts of the tracker will be deteriorated due to the total radiation dose affecting both sensors and read-out electronics and also by the instantaneous luminosity, too high for the present limited band-width. 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 resistivity of the readout components. The current baseline design of the ITk, with a layout similar to the present detector, consists of 4 Pixel and 6 Si-strip double layers of variable length 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. Other layouts are still under study.

Calorimeters upgrades. Instantaneous and integrated luminosity will create potential problems related to rates and average energy deposited in the Forward Calorimeter (FCal) and issues related to long-term radiation damage on the on-detector electronics in LAr Hadronic endcap (HEC). Since a replacement of the HEC cold electronics also requires an opening of the end-cap cryostat, which is a major high-risk intervention, it is essential to accumulate more experience on the level of radiation doses in this region. Three scenarios are envisaged: first, if HEC cold electronics needs replacement, the large cold cryostat cover will be opened and then also FCal will be replaced by a new cold sFCal; second, if HEC is fine, but the FCal lost performance, either replacement with a new sFCal or add a small warm calorimeter, MiniFCal in front of the present one; third, if performances are good enough, leave both as they are.

Trigger.

The planned trigger upgrades for Phase-II foresee applying full granularity of calorimeter at Level-1 and improving the muon trigger coverage. Moreover, work is underway to quantify the benefits of a Level-1 track trigger (L1Track) and to evaluate alternative designs. The main design challenge is to reduce the bandwidth of data coming out of the tracker, as it is unrealistic to read out the whole tracker for every bunch crossing. The architecture that is currently preferred is an region of interest-seeded L1Track, fitting into a two step hardware trigger.

6 Conclusions

A coherent overall upgrade program for ATLAS from Phase-0 through Phase-II has being planned to allow ATLAS to fully exploit the LHC energy and instantaneous luminosity at up to 5-7 times the design one. The planned approach is gradual and accommodates flexibility based on the experience and indication from physics results.

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