Preprint typeset in JINST style - HYPER VERSION

Plans for the Phase II Upgrade to the ATLAS Detector

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Proceedings for IPRD13, Sienna Italy, 6 October 2013
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ABSTRACT: CERN has planned a series of upgrades for the Large Hadron Collider (LHC). The last in this current series of planned upgrades is designated the High Luminosity LHC (HL-LHC) and as the name suggests will bring the Luminosity up to 5×10^{34} cm^{-2}s^{-1}. The ATLAS detector will be extensively changed to meet the challenges of this upgrade (termed the "Phase II" upgrade). There are many systems that require modification in this regime, but this paper focuses on the subsystems requiring the most radical changes.
The ATLAS inner tracker is being completely rebuilt for Phase II. The TRT is removed in favor of an all-new all-silicon tracker. The changes to the pixel system, barrel and end-cap strip detectors are explained. In addition, the muon detector will be modified and the muon and electron triggers will be modified to include tracking regions of interest and to improve muon resolution. In this way trigger rates can be brought under control while maintaining constant trigger thresholds.

KEYWORDS: HL-LHC, Phase II Upgrade, ATLAS, Inner Tracker, Muon System, Versatile Link, Electron Trigger.

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Contents

1. Introduction

On 4 July 2012 the ATLAS[1] and CMS experiments at CERN's Large Hadron Collider (LHC)[2] were able to claim the discovery of what is now accepted to be a Higgs boson[3] and directly leading to the awarding of the Nobel Prize in Physics to Profs. F. Englert and P. Higgs[4]. The Large Hadron Collider (LHC) completed operations in 2012 at a centre of mass energy of $\sqrt{s} = 8$ TeV.

Given this success the collider is planning at least two upgrades for the future. The first, known as "Phase I", is primarily an increase to the centre of mass energy to $\sqrt{s} = 14$ TeV planned for late 2014 and continuing with increases to the beam luminosity for the next 3.5 years.[5] A further upgrade to the accelerator will occur prior to the year 2022 where the beam luminosity will be significantly increased. Termed the High Luminosity LHC (or HL-LHC) this upgrade phase is also known as "Phase II" and is the focus of this proceeding. ATLAS[1] is one of four general purpose detectors surrounding one of the collision points of the Large Hadron Collider at CERN that will be undertaking a substantial upgrade for Phase II[6].

In the first section of this proceeding the proposed machine parameters of the HL-LHC will be shown along with an introduction as to how this impacts the plans for the ATLAS detector. Section 2 is all about the baseline hardware plans for the inner tracker. Section 3 focuses on two aspects of the upgrade that will improve the triggers on electrons and muons. The necessity for these types of trigger improvements will be explained after which Section 4 concludes.

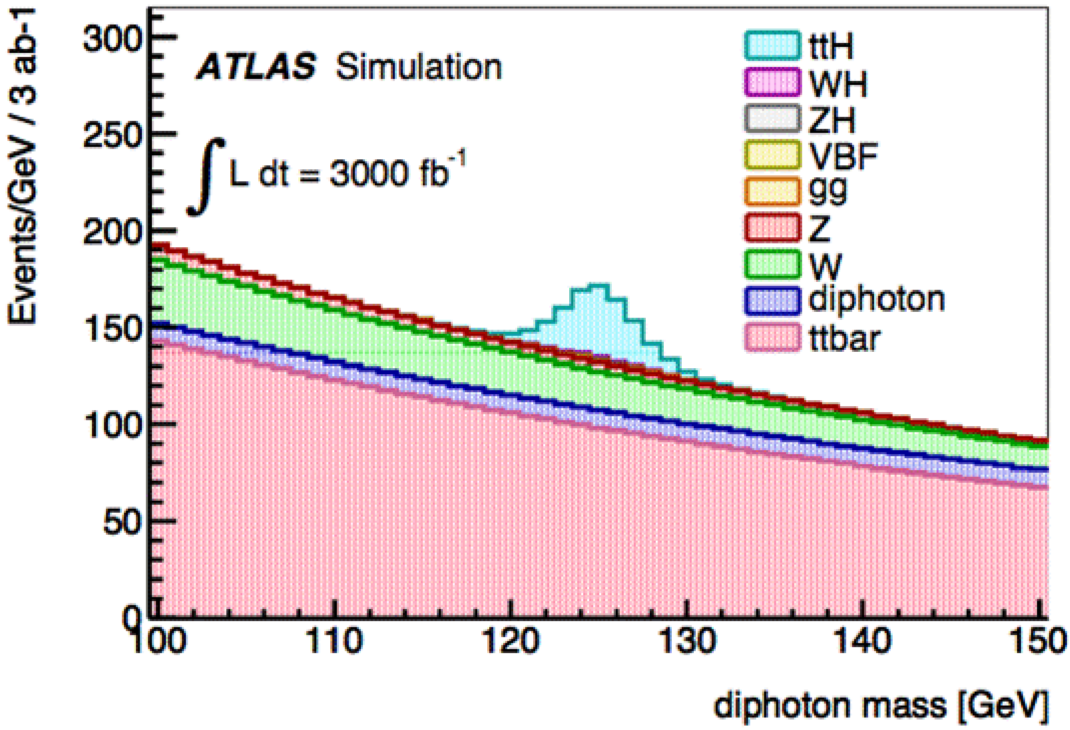

Figure 1. Shown from [6] is the expected Higgs signal from ttH production where the Higgs then decays into $\gamma\gamma$. With 3000 fb^{-1} of integrated luminosity the significance of this channel is expected to be $S/\sqrt{B} \sim 6$.

2. Upgrading to High Luminosity (HL-LHC)

The discovery of a boson that may be *The* Higgs boson of Standard Model fame makes certain aspects of the upgrade path for the LHC machine imperitive. As of this writing the Higgs has only been seen in a few channels, and with insufficient precision to determine for certain if this boson is actually coupling to them in the expected Standard Model (SM) proportions. Processes such as ttH which are exceptionally difficult to observe, but with the HL-LHC can be seen and measured with high significance and are critical to refining the SM and pointing us toward any new physics. A simulation of what this might look like in a channel that will be difficult to explore without the HL-LHC, along with the largest expected backgrounds, is shown in Figure 1.

Reducing the uncertainties in as many Higgs couplings as possible is the most important case for the upgrade projects. After all, the SM is very specific as to what a 125 GeV/c^2 Higgs should decay into and how often. Measuring any significant deviations from this expected behaviour would be highly exciting.

Ultimately, however, we are hoping that nature turns up something more unexpected than a SM Higgs, such as evidence for SuperSymmetry or even more exotic signatures. Both energy and luminosity upgrades would then be necessary to carefully study the new state since this would be one of those exciting times where the standard model is providing no guidance. The prospect that such states are awaiting discovery at the HL-LHC also needs to be mentioned even though, if they are produced via strong couplings, one would expect to obtain at least a hint of their existence

Table 1. A timetable of the upgrade plans for the LHC explaining the nomenclature and showing general machine parameters. The dates mark the years when the machine will cease operations in preparation for the upgrade in question.

Name	Date (yr)	$\int Ldt$	Inst. Lum. ($cm^{-2}s^{-1}$)	Other Properties
Phase 0	2013	75 fb^{-1}	6×10^{33}	$\sqrt{s} = 13 \sim 14$ TeV
Phase I	2017	350 fb^{-1}	2×10^{34}	full luminosity
Phase II	2022	3000 fb^{-1}	5×10^{34}	luminosity leveling

earlier.

2.1 Machine Upgrade Plans

The general plan for machine upgrades is as follows and is summarized in Table 1. We are currently (late 2013) within a shutdown period of the machine called "long shut-down one" (LS1) during which the "Phase 0" detector upgrades are taking place. This shutdown will end in the latter part of 2014 when the machine is expected to attain its original design energy.

The Higgs was discovered at an energy that is substantially less than the design energy of the machine, increasing this energy will increase Higgs production relative to other backgrounds. Once the original design energy of $\sqrt{s} \simeq 14$ TeV has been achieved in the Phase I upgrade, then the remaining upgrade path available in Phase II (barring substantial breakthroughs in either technology or funding) is an upgrade to the luminosity of the machine.

The "Phase I" upgrade will begin during the next long shutdown starting in the year 2017 where the full design luminosity of the LHC will be implemented. The machine will then run up to an integrated luminosity of 350 fb^{-1}. By this time estimates show the beam focusing magnets near the detector areas will have taken so much radiation damage that they will need to be replaced. Indeed, this fact will likely drive the exact end date and final integrated luminosity collected during the run that follows the Phase I upgrade[5].

The "Phase II" upgrade to the machine and the ATLAS detector follows. Next the machine is expected to improve the luminosity primarily by several machine upgrades such as crab cavities and installing very high field superconducting quadrapoles. Thus far, in every colliding beam hadron accelerator this author has ever studied, the beam luminosity follows an exponentially decaying function with respect to the running time. The effect of this is to have some dynamic range built into the detector sensitivity to accommodate the beam luminosity decay during a store. "Leveling" this luminosity profile is one of the major improvements to the machine planned for Phase II[7]. If the design luminosity is achieved the HL-LHC will deliver a constant average of 140 proton interactions in every beam crossing. Detectors near the beam pipe will experience fluences up to 10^{16} n_{eq}/cm^2.

3. ATLAS Phase II upgrade summary

The ATLAS detector will undergo a significant set of changes in preparation for the HL-LHC. The baseline plan is set out in the ATLAS Phase II "Letter of Intent"[6]. This document and the references therein form the primary source for the rest of this proceeding.

Ultimately, all of the changes planned for the ATLAS detector are driven by the expected increases in beam luminosity. However, when one takes an overview of these changes and looks at them from a distance, they all tend to fall into roughly two categories. First there are changes to detector systems that are related to radiation damage. This comes either from the damage the existing systems will have already suffered or from the fact that these existing systems were not designed to accept the fluences that will result from HL-LHC. Secondly there are changes that are related to the increases in trigger rates and increased detector occupancy that comes about when large numbers of interactions occur within each beam crossing. The upgrades to the inner tracker (ITK) are largely being driven by the damage the detectors and system electronics will have suffered while the upgrades to the trigger and computer systems are driven by occupancy considerations. Rather than briefly mention every single plan for the upgrade this paper will focus upon the plans for the ITK and upon the changes to the muon and electron systems as these are the areas where the largest changes will occur for Phase II.

3.1 Phase II Inner Tracker

The ATLAS inner tracker for Phase II will be a silicon detector. The whole of the inner tracker (TRT and silicon) will be removed, and it will be replaced with an all-silicon tracker which fills the existing tracking volume. A schematic of the baseline layout for the ITK is shown in Figure 2. Notice the "stub layer" in the barrel region at 45 degrees with respect to the beam line and just inside the last barrel. Isn't that rather silly? This high services-to-sensor ratio layer is needed to maintain efficiency for tracking pattern recognition.

The ATLAS inner tracker is a strip and pixel system, both consisting of a barrel and each has two end-caps to provide tracking coverage at high $|\eta|$. There are three main working groups associated with different sensor technologies and different detector geographical locations. These are pixels, barrel strips, and end-cap strips systems. A great deal of the design expertise in mechanical, electrical, and thermal management systems is shared between the working groups. The mechanical design in all systems assumes that the unit which will be constructed at remote institutions will follow a stave-concept. This is a long row of sensor modules with electrical and thermal management services integrated within the mechanical mounting structure. All of the services have connection points at the end of the stave. In all ITK subsystems cooling will be supplied by a recirculating CO_2 system that will achieve a sensor temperature of $\simeq -25^o$ C.

This long stave unit is designed to be inserted within the already-present barrel or wheel supports at CERN. This is a very different model than employed for the original ATLAS tracker where entire barrel cylinders were assembled and instrumented remotely and then shipped to CERN for final assembly. Figure 3 shows an example of the stave concept for the strip barrel detector.

3.1.1 Silicon Sensor Radiation Studies

There have been on-going tests of silicon sensors over the last several years. It was not clear at the outset whether depleted silicon could withstand the fluences expected at the HL-LHC. Several things have been discovered about silicon sensors during this extensive R&D programme but the short summary is that, with some care in the sensor design, they are sufficiently radiation-hard to withstand the HL-LHC environment.

A list of some of the important necessary (but not sufficient) conditions to achieve this is:

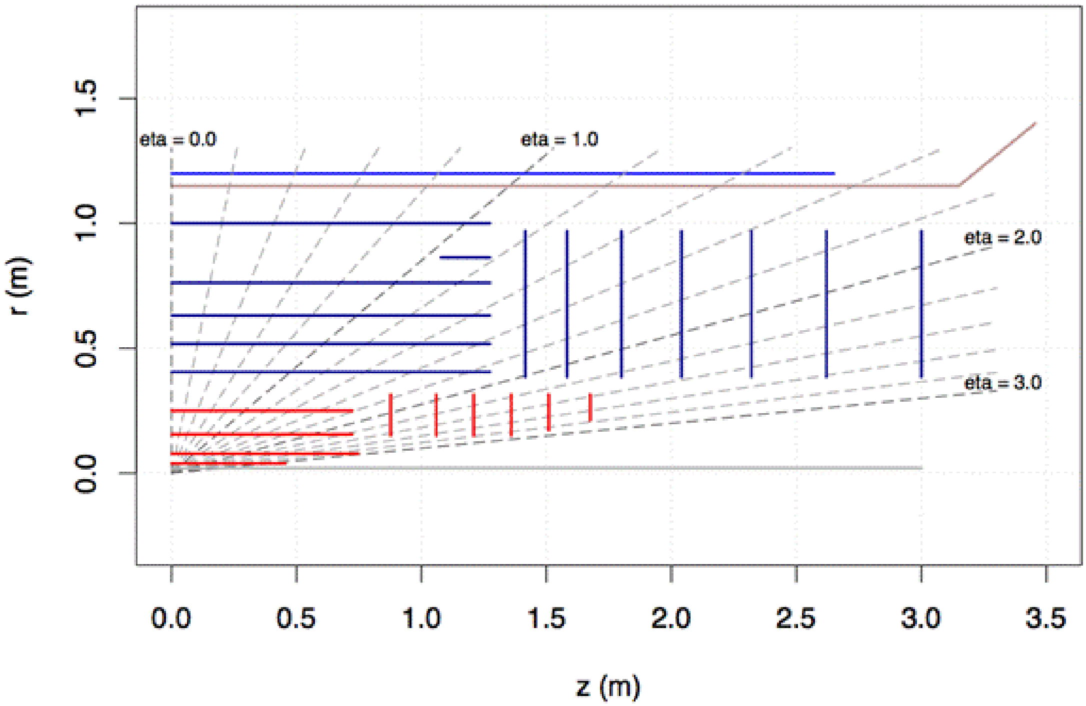

Figure 2. The proposed baseline layout design for the ATLAS inner tracker (ITK) in the Phase II upgrade. The ITK will be entirely a silicon detector. It consists of two main sections. Pixels in red and Strips in blue. The final silicon layer extends to 1 m radius.

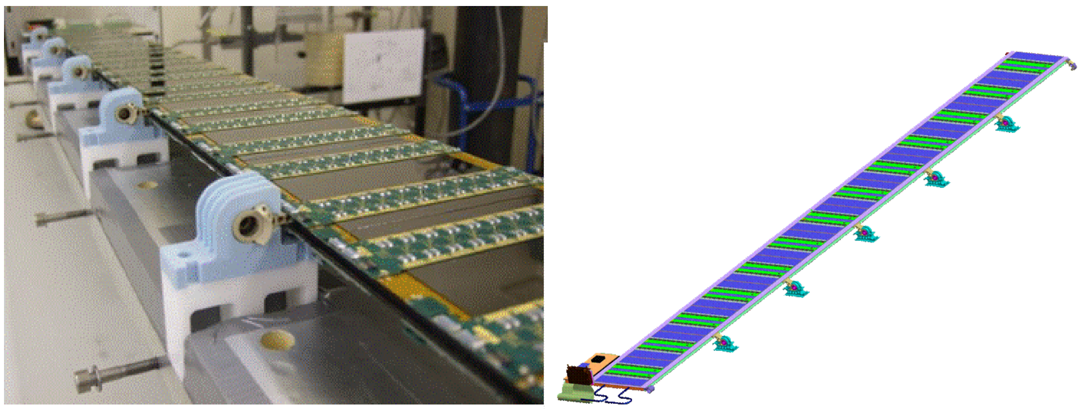

Figure 3. The ITK will take advantage of a "stave concept" design in the barrel pixel and strip detectors. Shown here are a picture of a prototype strip stave (left) and a schematic view of the barrel strip stave (right).

- Sensors need to be kept cold in order to control thermal run-away and to mitigate the effects of reverse-annealing. -25^o C is the target temperature for the sensors.

- The collection of electrons, rather than holes, survive radiation damaged sensors better because their speed helps them to avoid traps. This leads to designs with either n^+ - in-n sensors or n-in-p. For p-in-n sensors as in the current ATLAS detector, the charge collection drops to less than 5k electrons per minimum-ionizing particle through 300 μm by 10^{15} n_{eq}/cm^2.

- Fully depleting sensors at high fluences requires many hundreds of bias volts (up to 1 kV in some cases). In order to stand this off safely from the inputs to the readout amplifiers special guard-ring structures need to be implemented on the sensor.

This is a brief summary of much research on various sensor types from multiple manufacturers. The interested reader can consult the publications listed in [8] for more details.

3.1.2 ITK Pixel Detector

The inner pixels will use n^+-in-n sensor technology very close to the beam pipe. They have an I-beam structure for stiffness and stability with a sensor on the flat portions of the I-beams. The pixel size here is $25 \times 150\ \mu m^2$. Some conceptual drawings and pictures of this design are shown in Figure 4.

The outer pixels and pixel discs will use the more standard n-in-p technology which does not require double-sided processing and therefore helps to reduce costs as the sensor areas increase. The outer pixel size is $50 \times 250\ \mu m^2$. Both inner and outer pixel sensors will be read out with a version of the FE-I4 chip[9] electrically with a high speed differential serial signal along the beam line for $4 \sim 6$ m where the digital signal will be converted to optical pulses by the Versatile Link[12] for transmission off detector. The Phase II pixel detector will have 8.2 m^2 of active silicon area and 638 million channels. A more complete description of the baseline pixel design is given in [11].

3.1.3 ITK Strip detector

The Phase II barrel silicon strip detector will have 193 m^2 of active silicon area and 74 million channels in 5 full-length barrel layers and one "stub" layer (see Figure 2). Not shown in Figure 3 is the fact that the sensor modules will be mounted on both sides of staves that will run parallel to the beam-pipe upon cylindrical support structures still under design. The staves are designed to allow insertion from one end and are 1.3 m in length. The inner most cylinder will be 405 mm from the beam-line while the outermost cylinder will be 1000 mm in radius. The three inner barrel layers will use short strips 23.8 mm long in order to maintain a hit occupancy $\leq 1\%$ while the outer two barrels will have long-strips (47.8 mm long) as will the stub layer. One side of the stave will have sensors with strips oriented axially while the other side will have the same sensors oriented such that they form a small stereo angle with the axial sensors in order to improve z resolution. Consequently, the barrel sensors will be uniform and this will help reduce costs and improve assembly reliability since all barrel sensor modules will be identical.

The strip end-caps will consist of 7 disks using a "petal" concept as an analog to the stave concept. In the end-caps it is the petal that will be the remotely assembled unit that will incorporate the thermal management, power, control and data acquisition services. The forward tracker will permit track reconstruction out to $|\eta| < 2.7$. A schematic drawing showing these ideas for theh petal is shown in Figure 5. Due to the wedge-shape requirements of building disks however, it appears to be impossible to make all of the sensor modules populating a petal identical. Efforts are underway to minimize differences in sensor modules as part of the design effort for Phase II.

3.1.4 Optical Readout

In addition to changes to the sensors so that greater radiation and occupancies can be tolerated. The ITK will change from the current modest optical readout rate (40 Mbps or 80 Mbps) on a

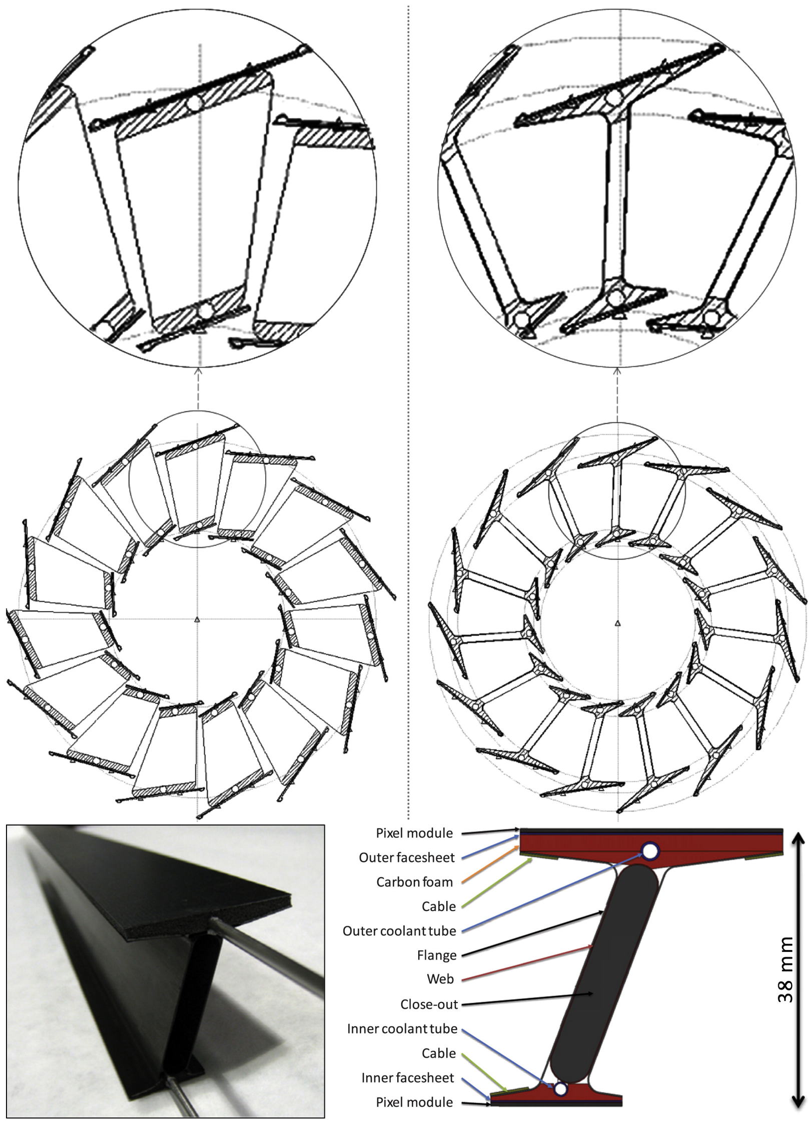

Figure 4. The pixel system has inner and outer components. These diagrams show the inner components that mount the sensor modules on the top and bottom faces of a carbon composite I-beam with an integrated cooling channel. The outer pixel system (not shown) follows a stave concept design similar to the barrel strip detector.

step index optical fibre to a single high-speed optical transceiver. The current detector has three fibres per module while the upgrade multiplexes the signals from 13 modules and the detector control system data on to one fibre for each side of a stave. This “GBT + Versatile Link”[10, 12] will provide timing, clock, and control for an entire stave or petal and will also have a channel that can read out $\frac{1}{2}$ of a stave. The Versatile Link will be driven by the GBT which is a high speed multiplexer with redundant circuitry, zero balancing encoding, and forward error correction in order to mitigate the effects of single event upsets and radiation damage.

The first Versatile Link prototypes exist and run at 4.8 Gbps. This is already sufficiently fast

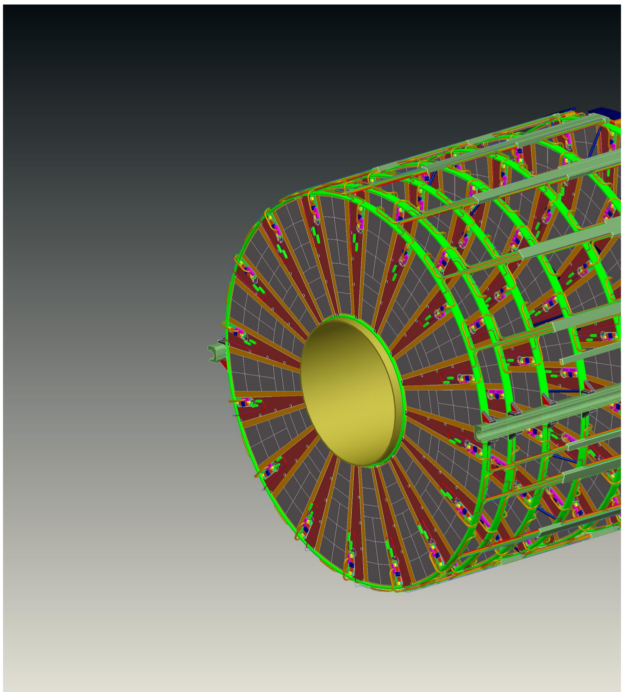

Figure 5. The strip end-cap ITK will be constructed with disks. Shown here is a schematic view of the end-cap. Each disk is made of "petals" each of which will have incorporated services within the support structure for data acquisition, control, monitoring and thermal management. Under construction at the moment (2013) are sub-units of this object known as "petalettes" which are also shown. All of the services for a petal are incorporated within the structure just as with the stave concept.

for the barrel and forward strip detectors, and is also fast enough for the pixel system if forward error correction is turned off for the returning data. There is a planned upgrade path for Phase II to produce a 10 Gbps link that would also satisfy the pixel systems even with forward error correction. Extensive radiation testing of the transceiver unit components[13] and the passive optical components[14] on this device continues. This is a joint project involving ATLAS, CMS, and CERN but the project is being implemented as a general purpose link.

3.2 The Muon and Electron trigger upgrades

A consequence of higher luminosity running apart from radiation flux is increased trigger rate. As a result there are significant changes planned to the trigger architecture for the Phase II upgrade. As is currently the case, the trigger will be multi-staged but in Phase II ATLAS will move most of the functionality currently at Level 1 to a Level 0 trigger. Level 1 will become more sophisticated, with firmware tracking information informing some triggers such as for muons and electrons. The trigger rate at Level 0 will be up to 500 kHz and 200 kHz at Level 1.

One of the important trigger goals for Phase II is to ensure that the trigger threshold for muons and electrons can remain at 20 GeV/c despite the increase in the trigger rates. The plan to do this involves sharpening up the rise in the trigger turn-on for the muon system. Because the background spectrum always falls with momentum by a strong power law, it is possible to dramatically reduce

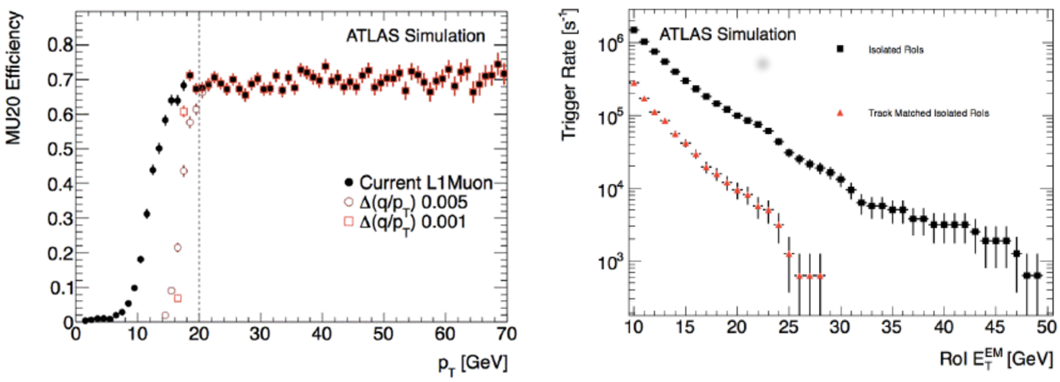

Figure 6. The effect of the ROI and improved trigger resolution on the electron and muon triggers for Phase II. The left hand plot shows how the muon upgrades of the new small wheel and ROI tracking improve the trigger threshold resolution. The right hand plot, for electrons, shows how the rates of electron triggers drop substantially when ROI information is included in the trigger decision.

the trigger rate by sharpening up the trigger turn-on. Meanwhile the background rejection for the electron system will control the trigger rate.

For the muon system several upgrade paths are envisioned. The forward region is the source of much background in the muon trigger. A "new small wheel" will be added in Phase I to the muon system in the forward region that will improve the muon track resolution in the trigger and this will reduce the rate substantially by giving a more accurate measure of the muon momentum. With no changes the trigger rate of the muon system would be expected to be 50 kHz, with the addition of the new small wheel and the improvements from Phase I upgrades including adding tracking information it is expected that the trigger rate for muons will be 13 kHz.

Both the muon and electron triggers will, at Level 1, now have fast tracking information matching tracks to regions of interest (ROI) so that they can make a higher resolution cut on the momentum of the muon candidates and remove backgrounds from the electron candidates. Among the Phase I upgrades that will remain are the implementation of small thin gap chambers (sTGC's) to aid in the ROI trigger. Figure 6 shows the effects of these changes. We see a substantial predicted improvement in the trigger turn-on for the muon trigger after making these changes. Also shown is the decrease in the trigger rate of electrons for a given threshold when ROI information is included in the trigger decision. Such reductions in trigger rate without loss of signal are important to optimize the physics reach of the ATLAS detector within the Phase II upgrade.

4. Conclusions

The further study of a newly discovered Higgs boson provides the current, best physics case for the LHC upgrade programme. However, during the coming era of increased centre of mass energy running we can remain optimistic that other, unexpected physics signatures will be found.

Regrettably there simply is not space or time to give a full treatment of the even the baseline ATLAS detector upgrades planned for Phase II and the HL-LHC. In addition to the upgrades mentioned here there are changes to be made in computing, databases, and the front-end electronic systems most of the sub-detectors within ATLAS. Substantial changes will occur within the trigger electronics that could not be mentioned here and so the author encourages the reader to consult [6] for a more complete document explaining, not only the baseline intentions of the ATLAS collaboration, but also some interesting alternatives that are under consideration as well.

For Phase II the TRT is removed and the entire inner tracker is replaced with an expanded pixel and strip silicon detector system. Extensive studies of the radiation hardness of silicon detectors have determined that silicon, if kept cold and properly designed, is certainly radiation hard enough for HL-LHC fluences and ionizing radiation doses. Attention is being paid at early stages in the ITK as to how the larger structure and the service infrastructure are to be implemented. This is expected to improve assembly time and efficiency of the final detector. In addition upgrades to the muon system and inclusion of ROI information for tracking at Level 1 in the trigger for electrons and muons will be needed to control trigger rates while maintaining a trigger momentum threshold for leptons at 20 GeV/c. With all of these plans brought to completion, the ATLAS detector will be ready to meet the challenges of the HL-LHC in the next decade.

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