Overview and Electronics Needs of ATLAS and CMS High Luminosity Upgrades

N.P. Hessey[a] on behalf of ATLAS and CMS Collaborations

[a] Nikhef, Kruislaan 409, 1098 SJ Amsterdam, The Netherlands

`nigel.hessey@cern.ch`

ATL-UPGRADE-PROC-2008-001
31 October 2008

Abstract

The LHC will begin collisions in Spring 2009, and build up to nominal luminosity (1.0×10^{34} cm^{-2}s^{-1}) over the next few years. This will be followed by a continuos programme of improvements leading eventually to a ten-fold increase above nominal with the super-LHC (sLHC). Within a few years of operation, the LHC experiments should discover or rule out a Standard Model (SM) Higgs, and could find supersymmetric particles if they exist below about 1.5 TeV mass. Several other discoveries are possible. However detailed knowledge of any new particles will be needed to understand exactly what the physics behind them is. Large data sets will be needed for this; these will also allow the mass limits for discovery of new particles to be increased. Upgrades to the general purpose experiments ATLAS and CMS will be necessary to deliver these large data sets with good performance. This paper presents some of the physics goals of the upgrade, LHC machine plans, the schedule, and summarises the changes and challenges for the detectors at the sLHC.

I. INTRODUCTION

Most measurements at the LHC will benefit from larger data sets, though not all since some will be systematics limited. The LHC is expected to increase in performance, initially to the nominal luminocity 1×10^{34} cm^{-2}s^{-1}, then with Phase-I upgrades to 3×10^{34} cm^{-2}s^{-1} with integrated luminosity 650 fb^{-1}, and Phase-II leading to the sLHC with a peak luminosity of around 10×10^{34} cm^{-2}s^{-1}. This will allow a much larger data set (target 3000 fb^{-1}) to be collected by each experiment. The physics goals and machine luminosity determine the performance requirements of the detectors. Much of the current detectors and all the magnets will work well at the sLHC, but several items including the inner trackers, forward detectors, and substantial amounts of readout electronics, will need upgrading to cope with the high particle and background rates, and integrated radiation doses. Note that the inner trackers at both experiments will have reached their radiation limits near the end of Phase-I and so need to be replaced independantly of an sLHC Phase-II upgrade.

This note summarises the physics goals and the expected machine luminosity development. It then discusses the detector changes planned, along with some of the main needs in electronics development.

II. PHYSICS MOTIVATION

Within a few years, the LHC should have delivered enough luminosity for discovery of the Standard Model (SM) Higgs if it exists in the mass range 100 to 1000 GeV; and if not seen, it will be ruled out at 95 % confidence level. The lightest supersymmetric particle could be observed if its mass is below about 1.5 TeV. Several other discoveries are possible over the following years. However, much more data will be needed to really probe what has been discovered. The physics opened up at the sLHC will depend on just what is found, and has been reported in several places, for example [1] and [2].

If a Higgs is found, it will be important to see if it behaves as a SM Higgs. Higgs decay branching ratios are determined in the SM; any deviation would signal new physics. While some ratios will already be systematics-limited, many will improve significantly with more data. Improvements of up to a factor two are possible in the precision of measurements of ratios of decays to gauge bosons, with somewhat less in ratios of decays involving top quarks. Couplings among the gauge particles are characteristic of the electroweak theory. There are 5 extra coupling parameters possible in a general model of Triple Gauge Couplings. Measuring any deviation from the SM value would signal new physics. Table 1 shows the significant improvements achievable in the precision with sLHC statistics. The Higgs self-coupling is also important. The LHC will have very few events with two Higgs particles, limiting the precision; the sLHC can make a large improvement reducing the uncertainty in the deviation from SM coupling $(\lambda - \lambda_{SM})/\lambda_{SM}$ from 200 % to about 10 % for the most favorable mass Higgs.

Table 1: Precision of measurements of Tripple Gauge Couplings with different integrated luminosities from [2]. In most cases, sLHC statistics give considerable improvement.

Parameter	100 fb^{-1}	1000 fb^{-1}
λ_γ	0.0014	0.0006
λ_Z	0.0028	0.0018
$\Delta\kappa_\gamma$	0.034	0.020
$\Delta\kappa_Z$	0.040	0.034
g_1^Z	0.0038	0.0024

If no Higgs is found, then something must happen before or around the TeV scale. Strong WW or ZZ scattering for example via a resonance at 1.5 TeV would only produce a few events at the LHC, but a clear discovery at the sLHC, with $S/\sqrt{B}$ around 10.

Several models predict more than one Higgs, for example in MSSM models there are five. Searching for more than one Higgs is therefore important. The sLHC can extend the region in the $(m_A, \tan\beta)$ plane in which more than one Higgs will be seen.

Searches for supersymmetric partners will increase the discovery region or push the limits further. Typically the reach can increase 40 %, with the limit for the lightest $m_{1/2}$ rising from about 1 to 1.5 TeV. If supersymmetric particles are discovered at the LHC, then spectroscopy to measure heavier partners will require the larger data set of the sLHC.

Several new forces have been proposed, resulting in new heavy gauge bosons W' and Z'. The mass range for discovery can be extended by around 20 % at the sLHC. If already discovered at the LHC, the sLHC should provide precise measurments helping to distinguish between the models, for example on decay widths.

In a few years from now, much more will be known about physics at the TeV scale, and we can expect a rich variety of physics goals requiring the sLHC machine.

III. EVOLUTION OF THE LHC ACCELERATOR AND INJECTORS

The LHC will start collisions in 2009 at low luminosity and ramp up to 40 % of nominal luminosity in 2 to 3 years, limited by the absence of the full collimation scheme. The collimators will be completed in the 2010-11 shutdown, and allow further rises in luminosity up to nominal.

Upgrades to the LHC and its injectors will allow further improvements planned in stages known as Phase-I and Phase-II.

Phase-I will introduce two major changes in the 2012-13 shutdown: new focussing magnets with larger apertures allowing a β^* reduction from 0.55 m to 0.25 m; and a new linac, called Linac4, allowing brighter beams to be fed through the injector chain and into the LHC. This will allow further increases in luminosity up to a maximum of about 3 times nominal.

Phase-II will introduce more new accelerators into the injector chain: a superconducting proton linac SPL to replace the PS-booster; and a new superconducting proton synchrotron, PS2, to replace the current PS. Superconducting magnets replacing the current SPS magnets are also envisioned later on. Each new component will allow brighter, more reliable operation, enabling the LHC current to go well beyond the so-called Ultimate level of 2.3×10^{34} cm^{-2}s^{-1} for which the LHC was designed.

The higher currents will be supplemented with other novel elements. Just which are best is being evaluated. The Large Piwinski Angle (LPA) scheme uses a high bunch charge (4.9×10^{11} protons compared to 1.15×10^{11} at the LHC) in bunches 50 ns apart, and a large crossing angle to reduce the beam-beam effects. Wire correctors are needed with this scheme to further reduce the beam-beam effects. The Early Separation scheme avoids the geometric reduction in luminosity caused by the large crossing angle by allowing head on collisions and rapidly separating the beams with dipoles close to the interaction point. The placement of machine magnets deep inside the detectors is technically difficult, can cause increased backgrounds in the experiments, and reduce forward calorimetry performance. By using Crab cavities, which rotate the bunches away from their direction of motion, a crossing angle can remain while still minimising the geometrical loss. These can allow the dipoles to be further from the interaction point, or even be omitted all together. These Crab schemes can achieve the luminosity increase without increasing the machine current beyond ultimate, and run at 25 ns bunch spacing. Whichever scheme is adopted, the expectation is for the sLHC to achieve a luminosity of 10×10^{34} cm^{-2}s^{-1}. Both schemes give very high pileup rates: the LPA scheme will give 400 pp scatterings (diffractive plus inelastic) per bunch crossing at the start of a spill; the Crab schemes will give 300.

Luminosity levelling schemes are also under investigation. These detune a parameter such as bunch-length, Crab rotation, or β^* at the start of a spill to reduce the peak luminosity. As the bunch charge reduces, the parameter is tuned to maintain a constant luminosity. Levelling is attractive at the sLHC where the spill length can become shorter than the machine filling time: the integrated luminosity need not be much lower than the maximum. Furthermore, some of these schemes reduce the beam-beam interaction, allowing a higher machine fill: this allows luminosity levelling to actually increase the integrated luminosity at a much lower peak pile-up rate, and is clearly very interesting to the experiments.

Recent discussions between the LHC, ATLAS and CMS have led to an understanding of the most likely scenario for the evolution of the LHC luminosity. Whilst there are many uncertainties, this represents the best current estimate [3]. Figure 1 shows the peak luminosity evolution, and figure 2 shows the anticipated integrated luminosity assuming 60 fb^{-1} per year of nominal luminosity running. This value takes into account the pp running time planned for the LHC, and typical fill times allowing for machine down-times.

The machine will require a longer shutdown than usual (8 compared to 5 months) for the installation of Phase-I equipment; the experiments will need a long shutdown at the end of 2016, consisting of a year's running time plus two winter shutdowns (18 months total) in order to install major new detector elements. The experiments will work towards this schedule, adjusting their programmes as experience with the machine evolves.

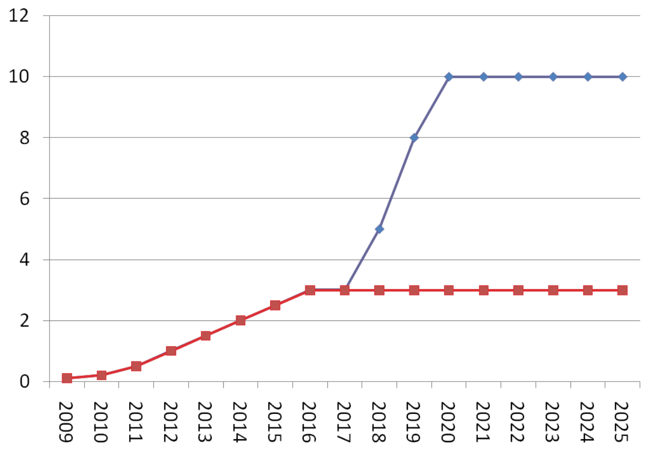

Figure 1: Best estimate of LHC peak-luminosity evolution in future years in units of nominal LHC (1×10^{34} cm^{-2}s^{-1}). The upper curve assumes Phase-II is implemented; the lower curve is with only Phase-I machine upgrade.

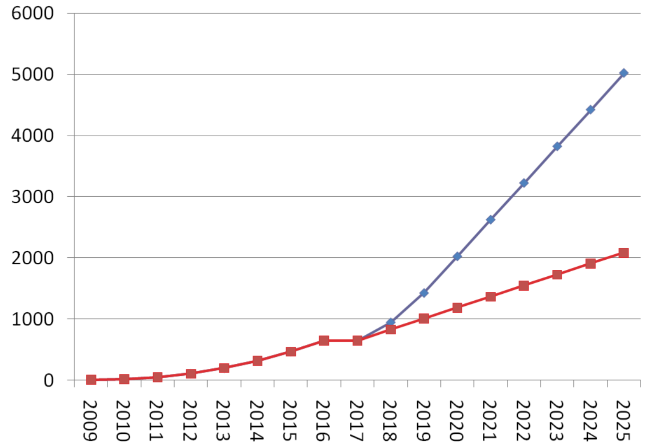

Figure 2: Best estimate of integrated luminosity evolution (in fb^{-1}) over the coming years. Upper curve assumes Phase-II sLHC and lower curve is without.

IV. DETECTOR CHANGES

ATLAS and CMS detectors will have to cope with extremely demanding conditions at the sLHC: these are greatest for the B-layers. Depending on the final scheme, there could be up to 30 charged tracks per cm^2 per bunch crossing or 13,000 tracks. After 3000 fb^{-1} data recorded the integrated ionising dose will be tens of MGray and the non-ionising dose will be over 10^{16} 1 MeV neutron-equivalent cm^{-2}. These doses tail off with distance, but remain much higher than the current detectors were designed for.

Some high-mass physics such as W' and Z' involve very high energy particles with little background, and can tolerate some reduction in detector performance. However, most channels of interest need the current resolution, efficiency and fake rates maintained or improved. For example, figure 3 shows a decay chain of supersymmetric particles involving many particles in the final state, which are relatively low in energy. These final state particles include neutralinos, b-quarks, electrons, muons, and jets. So missing tranverse energy resolution, vertexing performance, electron identification and resolution, muon tracking and the trigger all need to be maintained. Studies of WW and ZZ scattering need measurement of very forward jets ($\eta \approx 4.5$) and central jet vetoes, requiring calorimetry performance to be maintained even at the very forward regions.

Despite the much increased luminosity, most of the ATLAS and CMS detectors can stay and are expected to perform well throughout the life of the sLHC: all magnets, and most of the muon detectors and colorimeters will stay. Both will need completely new inner trackers: they will have reached their radiation limit, have too low a granularity for pattern recognition at 10×10^{34} $\mathrm{cm}^{-2}\mathrm{s}^{-1}$, and have insufficient band-width to read-out the data. Note that even in the absence of an sLHC programme, continuing ATLAS and CMS will require new inner trackers around 2017 due to radiation damage.

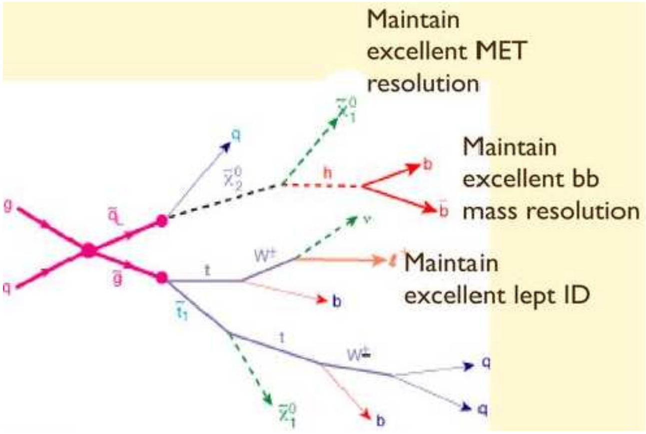

Figure 3: Example of a SUSY decay chain with many particles in the final state, including b-jets, missing energy, and leptons.

A. Phase-I Detector Upgrades

The Phase-I LHC upgrade will lead to instantaneous luminosities of 3×10^{34} $\mathrm{cm}^{-2}\mathrm{s}^{-1}$ and a data set of about 700 fb^{-1}. The B-layers of both experiments will not survive this. Also they will loose hits because of limited bandwidth in the front-end readout chips: The CMS B-layer will be about 12 % inefficient, and the ATLAS B-layer will be somewhat worse, on a very steeply rising inefficiency curve. Therefore both experiments plan new B-layers. The best opportunity to insert these is the 6 to 8 month shutdown foreseen for the Phase-I improvements in 2012-13. CMS is also considering more ambitious plans, with a range of options under study including replacing the whole pixel detector.

There are several other changes planned, such as adding some forward muon trigger chambers in CMS which were staged for financial reasons but become very important at higher luminosities. In both experiments, the triggers will develop continuously, taking advantage of cheaper processing power. New ideas such as topological triggers, which combine trigger items, are investigated; also at ATLAS a study is underway for a fast track trigger using associative memory to recognise hit patterns from tracks using data read-out at the level-1 trigger, and providing level-2 with high quality track parameters early on. CMS investigates the use of silicon photo-multipliers (SiPM, which are avalanche photo-diodes) to replace their tile-calorimeter hybrid photo-multipliers. These are very low noise reducing false triggers, large dynamic range allowing muons to be seen, and allowing more segmentation which can benefit calibration especially if radiation damage reduces light output of front scintillators more than others.

B. Phase-II Detector Upgrades

For Phase-II, both experiments will replace their entire inner trackers; also changes in the forward calorimeters and forward muon systems are under investigation. These changes need a long shutdown, and both experiments have agreed to do the changes in 18 months. This is challenging, and requires careful design and planning early on.

1) *Inner Trackers*

The radiation damage at the inner-most region, the B-layer, will be much higher than for any LHC active sensor. This requires either new technology for the sensors to survive the full dose after 3000 fb^{-1}, or planar silicon can be used and replaced frequently. Several technologies are under investigation: diamond, 3D-edgeless sensors, thin-silicon, and Gossip (micro-pattern gas detectors).

There will be a very large number of tracks and a large number of primary vertices in each bunch crossing at the sLHC. To do pattern recognition and maintain good track-finding efficiency with low fake rate requires increasing the granularity of the inner trackers, ideally to the point where occupancies are much less than 1 %, limited by cost and also the amount of material that has to be introduced.

Both experiments will add extra pixel layers at larger radii, replacing a region currently using silicon strip detectors. The pixel sizes will also be reduced; for example, the current ATLAS pixel size is 50 μm by 400 μm and will be reduced to 50 μm by 250 μm. This is possible by taking advantage of the availability of 130 nm read-out chip technology in place of the current 250 nm versions. It gives significant improvement in the z-vertexing, needed to separate the primary vertex from pile-up vertices.

In the regions just outside the pixels, either short-strip detectors (about 25 mm long in ATLAS case) or "strixels" – pixels $\sim$ 2 mm long – will be used. At outer regions, long strips (about 100 mm long) will have low enough occupancy. The TRT straws of ATLAS will be removed and replaced with such long strips. The strip sensors about 400 mm from the beam need to cope with non-ionising doses up to 10^{15} $\mathrm{n}_{eq}/\mathrm{cm}^2$ (including a safety factor of 2). This requires very high bias voltage (600 V) for full depletion. Irradiated sensor prototypes for ATLAS have recently been shown to hold this.

Front end chips are under development for the strip detectors at both experiments. The goals here are high radiation hardness and single-event upset tolerance; and also low power, while still coping with the high data rate. Low power is important to save material bringing the power in and in cooling sytems to remove it.

Powering remains a very important issue. There is no space for the present solution of one set of power cables per module; powering will have to be multiplexed, bringing in current at high voltage for low cable losses. Serial and DC-DC options are under study. System aspects – control, monitoring, and safety – are very important.

Data links also need developing, to find rad-hard optical communications at much higher rates (about 4 Gbit/s) than now (40 Mbit/s), and using multiplexing. High voltage and detector control systems also would benefit from more multiplexing.

2) *Calorimeters*

The barrel and most of the endcap calorimeters will perform well at the sLHC. Some re-optimisation of signal processing will be needed in view of the higher pile-up.

The electromagnetic calorimeter at CMS can suffer darkening of the crystals and vacuum photo triode light detectors; the effect depends strongly on pseudorapidity.

At ATLAS, the liquid argon (LAr) forward calorimeter FCAL will have increased heat-load, higher ionisation in the argon, and higher electrode currents; these could lead to boiling, signal deterioration, and voltage drop across the high-voltage resistors. The limits are being explored in a test-beam at Protvino. Two solutions are under investigation for use if necessary: to put a new, warm calorimeter in front of the current one; and to replace the FCAL altogether with a detector with more cooling and smaller gaps between electrodes. The latter requires careful development of tooling to be able to carry out the change in the time available, but engineering studies show it can be done. ATLAS considers reading out all data at 40 MHz from the detector, for both LAr and Tiles. High speed links to achieve this are being developed. Such a scheme can greatly simplify the front-end electronics and allow higher granularity giving increased flexibility in the trigger.

The detector sensitive elements and fibres of the hadronic tile calorimeters in both experiments will perform well at the sLHC. Light loss after 3000 fb^{-1} will be significant, but the photon statistics are sufficient to maintain acceptable performance. The electronics however will probably need replacing - both power supplies and readout. The current versions are insufficiently radiation hard, and will be reaching their end-of-life, with spares hard to find.

3) *Muon Systems*

For both experiments most of the muon systems should perform well. CMS will install some new trigger chambers which were staged from the original design. At CMS, the iron for the magnetic return provides good shielding from background, and only some of the very forward cathode strip chambers will need replacing.

At ATLAS the air-core toroid has less shielding. The background rate estimates have large uncertainties. The chambers can handle five times the current background prediction at nominal LHC luminosity. If the backgrounds are as predicted, then at the sLHC only a small fraction will have to be replaced - the cathode strip chambers on the small wheels. But if backgrounds are five times higher than anticipated, far more chambers will need replacement, or solutions will have to be found that reduce the background. It is therefore very important for the backgrounds to be understood in early running at the LHC. Several radiation monitors are in place for this.

The current ATLAS muon chamber read-out architecture has some places with insufficient band-width for the sLHC. To minimise changes, a scheme where only chambers in regions with a level-1 muon trigger are read out is being developed.

New detector technologies under investigation include micromegas, drift-tubes with smaller diameter, and thin-gap chambers (TGC) for higher rates. Micromegas and TGCs can provide both trigger and precision measurement in one chamber. This can save space, allowing more shielding.

4) *Triggers and Data Acquisition*

Trigger processing power and network band-width will be expanded as it becomes cheaper and is needed. Additional ideas are under investigation. Increasing the level-1 trigger rate looks to be very difficult, but increasing the latency may be possible. This gives time to do more at level-1, reducing the burden on higher levels.

In addition, maintaining trigger rates will require raising thresholds. However at CMS the level-1 muon trigger rate becomes almost constant once the threshold rises above about 30 GeV. Higher trigger levels do give good reductions well above 30 GeV, by including inner tracker information. It is therefore interesting to develop track triggers at level-1. Read-out at 40 MHz is not possible. Instead several ideas are being investigated, including novel read-out chips looking at coincidences between pixels or strips at fixed azimuth in sensors separated radially by about 2 mm. Such coincidences can be communicated to the end of a stave, and further processing can look for pairs of such coincidences at the same azimuth but in different layers. This can give a sharp threshold to a high transverse-momentum trigger.

Other ideas are also under investigation, such as topological triggers - for example the combination of muon and calorimeter information to find isolated muons. ATLAS is investigating the use of a large associative memory to spy on the level-1 to level-2 data transfer, and provide level-2 early on with quality helix parameters for tracks.

5) *Shielding*

Clearly it would be good to improve shielding so that backgrounds do not rise in proportion to the luminosity. However, this is very difficult since both experiments already have highly optimised shielding. Some improvements are nevertheless possible. CMS can install borated polyethylene in their forward shielding, improving muon system backgrounds. The most important for ATLAS is to substitute the stainless steel beam-pipe sections which pass through the end-cap calorimeters and toroid magnets with berylium. This reduces muon backgrounds a factor 2 or more. Also 50 mm of polythene moderator on the outside of the inner tracker volume will reduce neutrons in the tracker a factor 2. Other improvements could come if muon chambers can be made smaller, making more space for shielding.

V. SUMMARY

A few years from now, there is likely to be a rich field of physics to study, that will benefit from a ten-fold luminosity increase. The sLHC will set demanding conditions for the detectors, requiring substantial upgrades. The timescale is challenging, particularly to install new inner trackers in 2017, needed even without the sLHC due to radiation damage of the present trackers. Several research and development projects are underway. Electronics developments are essential throughout the subdetectors, and are often on the critical path.

REFERENCES

[1] Talk by Michelangelo Mangano at SLHC Kick-off Meeting, http://indico.cern.ch/conferenceDisplay.py?confId=30583

[2] F. Gianotti *et al.*, *Eur. Phys. J.* **C39**:293-333, 2005, http://arxiv.org/pdf/hep-ph/0204087.

[3] Talk from R. Garoby at LHCC meeting, http://indico.cern.ch/conferenceDisplay.py?confId=36149