Outline of R&D activities for ATLAS at an upgraded LHC

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Abstract

This note gives an overview of the issues relevant for a possible upgrade of the ATLAS detector in view of a Super-LHC with an increase in the luminosity by up to an order of magnitude beyond the present design value of $10^{34}$ cm$^{-2}$s$^{-1}$. An assessment is made of the boundary conditions for detector operation at these luminosities and directions for relevant R&D are discussed, in order to arrive at a detector with a similar performance as the ATLAS detector being presently assembled, which is important to exploit the physics potential of such an upgraded machine.

1 Introduction

Over the last three years, an upgrade of the LHC towards higher luminosities ($10^{35}$ cm$^{-2}$s$^{-1}$) has been discussed (see Ref. 8.1) as an extension of the LHC physics programme. Studies (see Ref. 8.2 and 8.3) have been made to assess the possible extension of the physics potential of the LHC by such an upgrade. Various scenarios have been considered to achieve an increase in the peak luminosity by up to one order of magnitude. The impact of a doubling of the center-of-mass energy to 28 TeV was also investigated, both in terms of the physics potential and the implications for the machine. In the latter case, this would imply to replace the more than 1000 super-conducting dipoles by stronger magnets. In this document, only the upgrade in luminosity is considered further, as the energy upgrade would be even much more challenging and expensive.

Another motivation for an upgrade of the interaction regions, which is necessary to achieve significantly higher luminosities, stems from the fact that some of the machine elements close to the interaction point, such as the triplet of the focusing quadrupoles, have a radiation limit corresponding to an integrated luminosity of about 700 fb$^{-1}$. This limit could be reached already around the years 2012-14, setting a possible time scale for the development and deployment of such an upgrade of the machine and the experiments.

CMS has already started an assessment of possible upgrade projects and has held two workshops addressing possible technology advancements that could be seen as promising developments towards the deployment of upgraded detector components. The definition of a

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CMS R&D programme is in progress. It is natural that once the ATLAS goals and possible strategies for focused R&D activities are defined, an effort should be made to arrive at some common R&D projects, of use for both collaborations. Also already existing R&D projects (such as the RD50 collaboration) should not be duplicated, but taken into account in the planning of R&D activities.

In the following, firstly a brief summary of the extension of the physics potential is given. This also defines the requirements on the performance of an upgraded ATLAS detector, especially for the reconstruction of high $p_T$ objects, e.g. the tagging of jets with b-flavour. Next, descriptions of three classes of machine upgrade scenarios are given, together with the most relevant parameters that will impact the upgrade of ATLAS. Important constraints to be considered for an ATLAS upgrade from the beginning are issues related to Technical Coordination activities, including radiation background calculations, space for services, as well as integration and installation aspects. Afterwards, a brief compilation of issues for the various sub-systems is given, highlighting the boundary conditions and indicating expected limitations on the detector performance. Before concluding with various next steps to be taken, a list of suggested major directions for R&D activities targeted towards an ATLAS upgrade is presented.

## 2 Physics motivation

An increase by up to one order of magnitude in integrated luminosity should extend the LHC discovery reach by about 20-30% in terms of mass of new objects, and allow additional and more precise measurements to be performed.

In particular, an integrated luminosity of 3000 fb$^{-1}$ per experiment, as usually assumed in the SLHC studies, would enhance the discovery potential for e.g. Supersymmetric particles, MSSM Higgs bosons, new heavy gauge bosons, Extra-dimensions and Compositeness. The tenfold increase in statistics should improve the precision of several measurements within and beyond the Standard Model, such as couplings of the Higgs boson to fermions and bosons, rare top decays (via flavour-changing neutral currents), triple and quartic gauge boson couplings, and underlying parameters of supersymmetric models. In addition, by searching for the production of pairs of Higgs bosons, a process which is rate-limited at the standard LHC, the Higgs self-coupling $\lambda$, which gives direct access to the Higgs potential in the Standard Model Lagrangian, may be observed for the first time, and may be measured with the very interesting precision of $\sim 20\%$. More details on the SLHC physics potential can be found in Ref. 8.2 and 8.3.

In order to achieve the above-mentioned physics potential, and thus fully profit from a luminosity upgrade of the LHC, the detector performance must be similar to that presently foreseen for the baseline ATLAS detector. This implies in particular a fully-functional inner detector, with good tracking capabilities in an environment with much higher particle multiplicities than at the design LHC, since efficient reconstruction and identification of electrons, taus and b-jets is mandatory to maximize the SLHC physics potential. Concerning calorimeters, it should be noticed that the increase of the event pile-up will deteriorate the energy resolution (and identification criteria in some cases) of electrons, photons and jets with moderate $p_T$, whereas objects with several hundreds GeV will be little

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affected by the harsher conditions. Here the challenge is therefore to maintain good reconstruction capabilities (through more sophisticated and focussed analysis strategies) and signal-to-background ratios for processes already observed at the LHC and for which improved precise measurements can potentially be achieved at the SLHC.

### 3 Machine scenarios

In the following, a brief overview of various scenarios for an upgraded LHC will be given, including a discussion of some limiting parameters. It should be noted that the scenarios listed below are not definite proposals, in the sense that all parameters are fixed to the given values. The various scenarios should rather be seen as indications of different possible directions and the expected increase in luminosity associated with a given route.

#### Table 3-1: Parameters for various machine upgrade scenarios

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Nominal</th>
<th>A</th>
<th>B</th>
<th>C</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Ultimate</td>
<td>IR-upgrade</td>
<td>IR-upgrade-Piwinski</td>
</tr>
<tr>
<td>$n_b$</td>
<td>2808</td>
<td>2808</td>
<td>4680</td>
<td>7020</td>
</tr>
<tr>
<td>$N_p [10^{11}]$</td>
<td>1.15</td>
<td>1.7</td>
<td>2.6</td>
<td>1.7</td>
</tr>
<tr>
<td>$\Delta T_{sep} [\text{ns}]$</td>
<td>25</td>
<td>25</td>
<td>15</td>
<td>10</td>
</tr>
<tr>
<td>$I [\text{A}]$</td>
<td>0.58</td>
<td>0.86</td>
<td>1.32</td>
<td>1.43</td>
</tr>
<tr>
<td>Profile (z)</td>
<td>Gauss.</td>
<td>Gaussian</td>
<td>Gaussian</td>
<td>Flat</td>
</tr>
<tr>
<td>$\sigma_z [\text{cm}]$</td>
<td>7.55</td>
<td>7.55</td>
<td>3.78</td>
<td>7.55</td>
</tr>
<tr>
<td>$\beta^* [\text{m}]$</td>
<td>0.55</td>
<td>0.5</td>
<td>0.25</td>
<td>0.25</td>
</tr>
<tr>
<td>$\theta_c [\mu\text{rad}]$</td>
<td>285</td>
<td>315</td>
<td>445</td>
<td>485</td>
</tr>
<tr>
<td>$\sigma_\text{lum} [\text{cm}]$</td>
<td>4.5</td>
<td>4.3</td>
<td>2.2</td>
<td>4.3</td>
</tr>
<tr>
<td>Piwinski param.</td>
<td>1.43</td>
<td>1.50</td>
<td>3.27</td>
<td>1.50</td>
</tr>
<tr>
<td>$L [10^{34}\text{cm}^2\text{s}^{-1}]$</td>
<td>1.0</td>
<td>2.3</td>
<td>4.6</td>
<td>7.2</td>
</tr>
<tr>
<td>Events/crossing</td>
<td>19</td>
<td>44</td>
<td>88</td>
<td>132</td>
</tr>
</tbody>
</table>

Table 3-1 gives an overview of various types of upgrade scenarios. From the point of view of the experiment the most important parameter is probably the bunch spacing and thus we have grouped the different scenarios in terms of the bunch spacing. We have identified three categories: ‘A’ for upgrades which keep the current bunch spacing of 25 ns, ‘B’ for changes involving shorter bunch spacing (10 respectively 15 ns) and ‘C’ for a scenario with a longer bunch spacing of 75 ns. The second very important quantity for the upgrade considerations is the number of interactions per bunch crossing, which is derived from the machine parameters and the value of the total pp cross-section. In the table, the basic parameters influencing the expected peak luminosity and the main parameters important for the experiment are listed:

- Number $n_b$ of proton bunches in one ring
- Number $N_p$ of protons per bunch
- Spacing $\Delta T_{sep}$ between two bunches

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• Average current $I$ in one ring
• Longitudinal shape of the profile of the bunches
• R.M.S $\sigma_z$ of the longitudinal bunch length
• Value $\beta^*$ of the $\beta$-function at the IP
• Total crossing angle $\theta_c$ of the beams at the IP
• Value of the Piwinski-parameter ($= \theta_c \sigma_z / \sigma^*$, where $\sigma^*$ is the transverse beam size at the interaction point)
• Length $\sigma_{lum}$ of the luminous region
• Peak luminosity $L$
• Average number of inelastic events per bunch crossing

For all scenarios, the normalized transverse emittance of the machine is assumed to have a value of $\epsilon_n = 3.75 \mu m$. As a point of reference, the parameters for the nominal design luminosity are indicated as well. In all upgrade scenarios, it is assumed that the beams are colliding in only two interaction points (IR1 and IR5).

### 3.1 Scenario A (25 ns bunch spacing)

In this scenario, the bunch spacing would be kept at the same value as presently foreseen and various changes would be made in order to increase the luminosity. As indicated in the table, two options are possible: stretching the machine to its limits ('ultimate') without major upgrades and one including a major upgrade of the two interactions regions ('IR upgrade'). In the first option the number of protons per bunch is increased to the beam-beam limit requiring a slight increase of the crossing angle. This option would provide an increase in the peak luminosity by a factor of slightly more than 2. In order to achieve a larger increase in luminosity, significant changes to the hardware are needed, while keeping several of the improvements already made for the ultimate case.

The major feature of the second option would be the installation of new focusing quadrupoles to achieve smaller transverse beam sizes at the IP (it might be desirable from the machine point-of-view to move these quadrupoles closer to the interaction point by up to a few m). This option also includes modifications of the RF system to reduce the bunch length by a factor of 2. With this combination one could reach almost an increase by a factor of 5 wrt the nominal design luminosity. The third option would be to have a large Piwinski-Parameter (to avoid the beam-beam limit) and thus to obtain possibly an increase by a factor of 7.2 in peak luminosity.

### 3.2 Scenario B (shorter bunch spacing)

This scenario would be based on shorter bunch spacing than the present 25 ns one. Two possibilities are presently envisaged, a spacing which is a multiple of 5 ns (e.g. 10 or 15 ns) or (as already described in Ref. 8.3) a spacing of 12.5 ns. The latter would be more expensive, as a new RF system would be needed for the SPS. Further assessment of the machine changes needed is necessary, to differentiate between these options. Also here, the interaction regions would be upgraded to achieve stronger focusing, and this might imply again that machine elements could be moved closer to the IP. The major uncertainty on the viability of shorter bunch spacing stems from the electron cloud effect, which is getting more severe for shorter bunch spacing. It is unlikely that the final word on the relevance is going to be said before the first year(s) of operation of the LHC. The scenarios with shorter bunch lengths also implies a
high total current in the machine and today it is not clear how far the limits on machine protection and collimation can be stretched. Depending on the value of the bunch spacing, the peak luminosity might increase by a factor between 7.7 and 11.5 relative to the nominal value (Ref. 8.7).

3.3 Scenario C (longer bunch spacing of 75 ns)

In order to avoid the impact of the electron cloud effect and ease the machine protection issues, the use of longer bunch spacing has been proposed by the machine groups. In this scenario proposed very recently, the bunch spacing would be increased to 75 ns. By doubling in addition the bunch length, it should become now possible to flatten the longitudinal bunch profile to a rectangular distribution (instead of a Gaussian one) and thus to gain a factor of \( \sqrt{2} \) in luminosity. The expected increase in peak luminosity would then amount to a factor of almost 9.

3.4 Superbunches

During the last two years, also a different scenario has been proposed, which would foresee to collide a low number of long bunches, so-called super-bunches. An early scenario, with two very long bunches having a length of about 300 m, would not allow sensible measurements due to the very high number of interactions in a finite time window (up to 25000 events per 25 ns window for 1 superbunch of a length of 1 \( \mu \)s). This option is not considered further in the following, as the conditions presented in this scenario would not allow a modest upgrade of the ATLAS detector, but would require a complete rebuild to possibly achieve the physics goals with a radically new detector design.

4 Radiation backgrounds and Technical Coordination issues

The ATLAS upgrade that is being considered will involve the minimal changes to the overall experiment design. Thus we do not expect to change any of the magnets in the experiment and or the mechanical parts of the calorimeters. We expect that the tracker will require extensive upgrade and for the purpose of TC studies we assume that it and most of its services will have to be replaced. The calorimeters mechanical construction will stay intact but upgrades to the readout are now under study. This could have an impact on the services. We assume that most of the infrastructure will stay as is but that there might be some modifications in the readout electronics, power distribution etc. Possible changes to the muon chambers will need to be studied and need to be optimized together with the shielding upgrades being considered. An upgrade of the beampipe will most likely also be required. All this will have significant impact on the installation and integration of the upgraded experiment.

This section discusses some of the global issues and constraints in the upgrade plan as well as the expected fluences of the radiation background and possibilities to increase the shielding and improve the beampipe. One has also to consider that in an upgrade of the interaction regions, the machine might want to move e.g. the focusing quadrupoles closer to the experiment, by amounts of one or a few meters.

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4.1 Flux of background particles

The fluxes of background particles have been estimated in some detail by the ATLAS Radiation Task Force. On its web-site (Ref. 8.8) and in its report (Ref. 8.9) are tables and contour plots of various particle fluxes but also ionising dose, 1 MeV neutron equivalent fluence and single event effect fluence. For all calculations a p-p inelastic cross section of 80 mb and a luminosity of $10^{34} \text{ cm}^{-2} \text{s}^{-1}$ was assumed but the fluxes can of course be easily scaled up to a higher luminosity.

![Figure 4-1: The neutron flux (kHz/cm$^2$) in a quarter of the inner detector, the calorimeters and the small muon wheel (Ref. 8.9).](image)

4.1.1 The background flux in the inner detector

While the background of charged hadrons is mostly coming from the IP, the neutron flux in the inner detector is mostly due to albedo from the endcap calorimeters. This can be seen in Figure 4-1 which shows the neutron flux in the central part of the ATLAS experiment. Due to the moderating properties of the polyethylene in the JM shielding and the material in the TRT a large amount of thermal neutrons are produced which fill the inner detector cavity as an almost uniform gas. In addition to these thermal neutrons, a large amount of higher energy neutrons reach the ID due to backsplash from the FCAL. The photon flux is also larger close to the FCAL as can be seen in Figure 4-2 that shows the photon flux in one quadrant of ATLAS. This figure also shows the broad photon flux distribution coming from the beampipe. If the TRT and its moderating material would be removed in an upgrade of the tracker, it is...
possible that the background flux in the inner detector would increase also due to this upgrade and not only due to the luminosity increase.

4.1.2 The background flux in the muon spectrometer

There are three major sources of background in the muon spectrometer: The FCAL, the beampipe and the TAS collimator. The latter is the largest source of background but it is also the most shielded and is therefore of the least concern. The purpose of the TAS collimator is, however, to shield the quadrupoles behind it. The radiation from the TAS could become a problem if it had to be re-designed to stop more of the particles from the IP at highest luminosity. The highest background rates are not surprisingly found in the endcap part of the muon spectrometer closest to the beamline. The very highest background rates are expected in the CSC region of the small muon wheel and here the dominating source are the calorimeters while the background in the rest of the endcap muon system is coming mostly from the beampipe. The beampipe is a linear source of background and it is therefore difficult to overcome the background problem simply by reducing the $\eta$-coverage of the muon spectrometer. If a tenfold reduction of background rate is required the coverage has to be limited to $|\eta|<1.5$ (Ref. 8.10), i.e. most of the forward muon spectrometer has to be abandoned.

![Figure 4-2: The photon flux (kHz/cm$^2$) in a quadrant of ATLAS (Ref. 8.9).](image-url)
4.2 Activation

The induced activation in ATLAS will seriously reduce the amount of time that people will be able to spend close to the beamline already at $10^{34} \text{ cm}^2 \text{s}^{-1}$. Hundreds of radiation maps are available on the ATLAS activation web-site (Ref. 8.11) and the problem is also discussed and summarized in the Radiation Task Force report (Ref. 8.9). It is different for the two access scenarios: Inner Detector Access and Standard Access. In the latter scenario it is the beampipe which is the major source of radiation and since this is a linear source the dose rate is proportional to the inverse distance to the beamline. At very high luminosity running the region of about 1-2 m distance to the beamline cannot be accessed except for a very limited time and for specialized and highly trained maintenance work. This means that the Inner Detector might not be accessible for maintenance after very high luminosity running and that when work on the ID has to be carried out, the beampipe has to be first removed (the so-called Inner Detector Access scenario). This will, however, give large doses to the vacuum technicians that have to remove the beampipe. In order to improve the situation it has been suggested (Ref. 8.10) that the beampipe material should be changed from stainless steel to aluminium or even beryllium. The latter case would reduce the activation with a factor of a thousand but would also be very costly.

Figure 4-3: One half of the inner region of the ATLAS experiment during standard access. The predicted dose rates in the two access areas are also shown. The calculation was done for one year of running at $10^{34} \text{ cm}^2 \text{s}^{-1}$ and five days of cooling off.
4.3 Strategy for reducing the radiation and background rates

4.3.1 The beampipe

The beampipe in ATLAS has a smaller radius than in CMS since the FCAL has to be able to be moved back during access without removing the beampipe. The very low angle that the particles have when they traverse the beampipe in the forward region means that they pass through a lot of material. An upgrade of the beampipe, either by increasing its radius or by changing its material, could lead to a significant reduction of background in the endcap part of the muon spectrometer and would also, as mentioned above, reduce the problem of activation.

A change from stainless steel to aluminium has been proposed as an upgrade already before running at $10^{34}\,\text{cm}^2\text{s}^{-1}$ and at even higher luminosities one could consider using beryllium or carbon fiber as beampipe materials. A simulation in which a large part of the beampipe was turned into beryllium and its radius was doubled is presented in Ref. 8.10. The reduction factor was typically 2-3 in the endcap and the high-z barrel regions of the muon spectrometer. The reduction was close to the one obtained if the beampipe was removed, i.e. it was close to optimum. An increase in beampipe radius would, however, make it necessary to remove the beampipe every time an access to the inner detector region is required.

4.3.2 Shielding modifications

An increase of the shielding thickness in the small and large muon wheels has also been studied (Ref. 8.10). In both cases a redesign of the muon detectors has to be made in order to incorporate the additional shielding. A more than doubling of the radius of the shielding surrounding the beampipe in the small wheel would cut the single counting rate in the small wheel in half but would as expected not change the background rate in any other parts of the muon spectrometer. There would be a significant rate reduction even if the beampipe would in addition be changed to beryllium since the main source of background in this region is the calorimeters. This is not the case in the large muon wheel were an increased shielding radius in combination with a change to a beryllium beampipe has almost the same effect as only the change to beryllium. The reason is that the beampipe is the major source of background in the large wheel and after it has been removed it does not help much to increase the shielding.

4.3.3 Radiation in USA15

The ATLAS counting room (USA15) should be accessible during running and be classified as a simple controlled radiation area so that people can have an unlimited access to it. The wall between USA15 and the experimental cavern is 2 m thick and was designed for a luminosity of $10^{34}\,\text{cm}^2\text{s}^{-1}$. A recent study has been made to check the original calculation (Ref. 8.12). The new highest estimations of the dose rate are some 30% higher than the design calculations. This is not a cause for concern but what is a concern is that the allowed limits for a simple controlled area might be reduced and if the luminosity would in addition be increased tenfold then it is doubtful if USA15 could remain as a cavern with unlimited access.

The obvious way of decreasing the radiation in USA15 is by increasing the wall thickness. Calculations have been made with an additional 20 cm thick layer of steel or polyethylene attached to the wall (Ref. 8.12). It was found that a polyethylene layer in USA15 would reduce the effective dose rate by 40%. Polyethylene doped with boron had the same effect as pure polyethylene and so it was concluded that is was the moderating effect on the neutron
radiation that was beneficial. If the concrete in the wall was made 20 cm thicker that would reduce the rate by only 25% and so a polyethylene layer is more efficient. A 20 cm thick steel layer would reduce the dose rate by 60% but only if it was placed in the ATLAS cavern. On the USA15-side of the wall the steel layer would increase the dose rate due to cascades and interactions of high-energy neutrons. The conclusion is that in order to reduce the dose rate with an order of magnitude the wall thickness would have to be increased by one meter of concrete and that is clearly not possible. Polyethylene or steel layers could decrease the radiation levels but not with much more than a factor of two.

4.4 Moving the TAS

The machine is considering moving the last focusing quadrupoles closer to the IP by as much as a few meters. For ATLAS such a move is not feasible without major changes to the experiment. Access to the experiment (both standard and or long access) requires moving the End cap Toroid away from the IP close to the TAS. The clearance that exists today is already very limited. A detailed study will need to be done to determine the maximum allowed move, at present it looks like one might be able to accommodate a move of up to ~10-20 cm in the position of the last quadrupole.

4.5 De-installation / installation

The replacement of the ID will mean a change of all or most of the ID services (this include cables as well as pipes). The change of the calorimeter readout that is being considered might require a change in the calorimeter services. We assume that the calorimeter electronics infrastructure will not need to be changed (cooling, crates etc.)

In Figure 4-4 the conceptual routing of the ID services and the location of the main patch panels is shown. In order to remove the ID services (and definitely to re-install them) the first layer of the muon chambers will need to be removed (i.e. BIS and BOS). Once the chambers are removed there should be sufficient access to both the front face of the calorimeter/ID as well as the Tile outer surface.

The present plan calls for most of the ID services to be installed either above or beside the calorimeter services. Some of the ID pipes do have calorimeter services crossing them but it looks like taking the old services out will not be a major problem.

The main issue regarding the new ID services will be the volume of services. Already in the present ATLAS detector the volume of services is such that there are a few critical areas or "choke points" that will not allow for a significant increase in the volume. As we expect the new ID to have a significantly larger number of channels, a more efficient way of using the available space will have to be developed (see section on ID). This will require an integrated approach to the R&D in order to optimize the space available.

Installation of the new services will require detail studies and will clearly depend on the detailed solution found for the ID and the calorimeter readout. Apart from space considerations one has to be careful about the power dissipation of the services and their potential effects on the Muon system, about the grounding rules for ATLAS that have to be obeyed and about the electromagnetic interference for services of the same systems as well as the neighboring systems.
4.6 Infrastructure Limitations

The design of the overall system needs to take into consideration limitation on the space in USA15 for racks and patch panels. The cooling system limitation is two fold: (1) the air-conditioning in the cavern is already close to the limit in the present experiment and this means that we will have to be more efficient in removing heat using chilled water than we are now; (2) the cooling capacity of the water cooling system is close to the limit. The End cap calorimeters have special limitations on the volume of services that is given by the size of the cable schleps. In all probability they will not be changed both due to cost and space limitations.
Thus the design of the different systems will have to be designed in an iterative procedure taking into account the above constrains. It is important that these iterations are done early so that the space allocated to the different systems is optimized.

5 Issues for various subsystems

Based on the machine parameters for the upgrade scenarios considered in this note, the following sub-sections describe the major issues and boundary conditions for an upgrade and give indications of limitations on the performance to be expected.

5.1 Electronics

The main issues for the ATLAS electronics are:

- Radiation hardness of existing electronics to be kept;
- Radiation hardness of the new tracker electronics;
- Maintaining reasonable services volume despite the increased number of channels of the tracker;
- Running the existing electronics at different bunch crossing period (e.g. 30 ns).

5.1.1 Radiation hardness of existing electronics

The level of radiation that the existing electronics will be receiving is in between 5 and 10 higher than the anticipated level. The existing electronics has been characterised with safety factors (Ref. 8.13) and it may be that it will be radiation hard enough; however some changes must be anticipated. In particular, the slow control electronics (ELMB) and some of the low voltage power supplies cannot sustain an increase of the radiation level by a factor 10.

5.1.2 Radiation hardness of the new tracker electronics

The new tracker electronics has to be extremely radiation hard. Preliminary measurements have shown that very deep sub-micron CMOS technologies (below 0.13 µm) are able to sustain very high radiation levels. However additional work has to be done to make sure that the obtainable analogue performances meet the requirements (Ref. 8.14). An important parameter is the very high non engineering expense (NRE) that is incurred as shown in Figure 5-1.

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Other BiCMOS technologies (SiGe) present also very interesting characteristics, but a thorough study of their radiation hardness would be needed.

5.1.3 Services volume

The volume of the electronics services is dictated by two main parameters:

- The power distribution;
- The number of read-out links.

Although new technologies are less demanding in power this does not translate directly in a reduction of the current consumption because of their reduced working voltage (for instance the Vdd for a 0.13 µm CMOS technology is 1.3V). In addition the very deep sub-micron CMOS technologies are exhibiting leakage currents which contribute in increasing the power supply current (see Figure 5-2).
Figure 5-2: Power dissipation in CMOS deep sub-micron devices, showing the increased contribution of leakage currents (from P. Gelsinger, Intel Corp. Presentation at the ISSCC 2001)

As the size of the power cables is directly related to the amount of current flowing in these, it is necessary to find solutions for designing very low power front-end electronics and to lower the current in the power lines. The later can be achieved in using power converters (such as DC-DC converters fed with relatively high voltage) at the level of the front-end or in powering serially the front modules for instance, both solutions requiring a lot of development as there is no available radiation hard power converter and the magnetic field in the tracker volume is high, and the serial powering needs to be proven.

The amount of services needed for extracting the data is of course related to the amount of channels involved. Their reduction requires to implement efficient data compression schemes and/or to regroup the read-out of as many channels as possible and to use high bandwidth links.

5.1.4 Running the current electronics at different bunch crossing rates

It is very likely that in order to increase the luminosity, the machine will change the beam crossing rate, one option being a spacing of 15 ns between two interactions. If it were the case, ATLAS would study the possibility of running the existing read-out electronics with a clock period of 30 ns and disentangle the data coming from the two bunch collisions with software.

So far no show stopper for implementing such a scheme has been seen, however several changes will be needed. The current TTC system is using in different places electronics devices very much linked to the current 40.08MHz bunch crossing frequency (crystals in different places and in particular the one attached to the QPLL chip). All these devices would require modification or redesign. Some details have still to be studied by each sub-detector; for instance the Tile calorimeter is now relying on the capability for their digitiser to sample...
the peak of the pulse and a way of recovering this information at the back-end level must be found.

5.2 Tracking

5.2.1 Issues for the ATLAS Tracker Upgrade

For ATLAS an upgrade means a replacement of the entire Inner Detector (ID): the Transition Radiation Tracker (TRT) at large radius will have prohibitively large occupancy, and the Semiconductor Tracker (SCT) and Pixel System at smaller radii will have reduced performance because of radiation damage to the sensors and front-end electronics. The upgraded ID tracker would likely have about 200m$^2$ of semiconductor detectors, similar to the CMS inner detector. Because of the increased particle fluence, the search for rad-hard sensors will be a high priority. The increased occupancy will require a new optimization of the detector layout with respect to radius and increased granularity. A major constraint on the tracker is the existing ATLAS detector, implying a maximum radius of about 1m and a 2 Tesla magnetic field, as well as the limiting existing gaps for services. The outer silicon layers would have to fit into the service area provided for the TRT they would be replacing, which means that the space available seems to preclude an increase in services due to granularity, implying that the multiplexing must be improved compared to the present ATLAS tracker.

5.2.2 Tracker Regions in the ATLAS Upgrade

Due to the 10 fold increase in overlapping minimum bias events the tracker layout is governed by two considerations: a high instantaneous rate causing pile-up of tracks, and the integrated particle flux leading to radiation damage and nuclear activation.

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### 5.2.2.1 Pile-up and Occupancy

Figure 5-3: Fluence as a function of radius \( R \) for an integrated luminosity of 2500 \( \text{fb}^{-1} \). The approximate radial extend of the proposed tracker regions are indicated.

Figure 5-3 shows the expected radial fluence distribution for a SLHC detector after an integrated luminosity of 2500 \( \text{fb}^{-1} \). At a radius \( R \) of about 5cm, the fluence is about \( 10^{16} \text{ cm}^{-2} \), at 20cm it decreases to about \( 10^{15} \text{ cm}^{-2} \), and at 50 cm it is about \( 2 \times 10^{14} \text{ cm}^{-2} \). This suggests three different regions for a tracker with different technologies and layouts as indicated in Figure 5-3: an Outer Region at 50 cm = \( R = 1 \text{ m} \) where the present SCT technology can be used, a Middle Region at 25 cm = \( R = 50 \text{ cm} \), where present pixel detector technology might work, and an Inner Region at 6 cm = \( R = 20 \text{ cm} \) requiring new sensor technology. The exact radial extent of these regions and number of layers should be defined through a final optimization. Initial simulation efforts indicate that an occupancy of less than 1% everywhere can be achieved with such a layout. The survival of the detector (and of the electronics and optical readout) is a crucial issue, and the suitability and availability of p-type substrates should be explored. Like the more expensive n-on-n detectors, n-on-p detectors would give head room in depletion voltage. They have no type inversion and allow operation with partially depleted sensors.
5.2.2.2 Differentiation between various radial regions

5.2.2.2.1 Region of Outer-Radius R > 50 cm
This region could be covered by 4 layers of “long” strips and a single coordinate measurement might be adequate. Such issues need to be carefully looked at in a simulation of a complete tracking detector. No sensor problems are expected for the outer region, but the limited space for services for the outer region will require careful tradeoffs between detector length, front-end electronics power/noise and amount of multiplexing and granularity.

5.2.2.2.2 Region of Mid-Radius 20 cm < R < 50 cm
This region could be covered by 3 or 4 layers of short strips, which provide space points. The options include very short strips (long-pixel's) with dimension of order 80 µm x 2 mm, which requires a very large number of readout channels, or strips of longer length, coupled with faster electronics and using small angle stereo for the z coordinate. The goal for the resolution along the beam direction is about 0.5 mm as in the present SCT.

5.2.2.2.3 Inner Region: R< 20cm
Here 3 or 4 layers with pixel style readout at small radii might provide adequate pattern recognition. Survival of the sensors and all the local electronics is a major issue.

5.2.3 Specification of Sensor Performance

Based on present performance, one can draw up an initial specification of the collected charge needed in the three regions. This is shown in Table 5-1, which indicates that sensor technologies for both the outer and mid-radius regions are in hand, while the sensors for the inner regions will be limited by charge trapping during collection. They will require intensive R&D, and there might be a need for new structures like 3-D detectors.

<table>
<thead>
<tr>
<th>Radius [cm]</th>
<th>Fluence [cm$^{-2}$]</th>
<th>Specification for Collected Signal (CCE in 300 um)</th>
<th>Limitation due to</th>
<th>Detector Technology</th>
</tr>
</thead>
<tbody>
<tr>
<td>&gt; 50</td>
<td>$10^{14}$</td>
<td>20 ke$^-$ (~100%)</td>
<td>Leakage Current</td>
<td>“present” LHC SCT Technology, “long” strips</td>
</tr>
<tr>
<td>20 - 50</td>
<td>$10^{15}$</td>
<td>10 ke$^-$ (~50%)</td>
<td>Depletion Voltage</td>
<td>“present” LHC Pixel Technology ? “short” strips -“long” pixels</td>
</tr>
<tr>
<td>&lt; 20</td>
<td>$10^{16}$</td>
<td>5 ke$^-$ (~20%)</td>
<td>Trapping Time</td>
<td>RD50 - RD39 - RD42 Technology 3-D</td>
</tr>
</tbody>
</table>

Table 5-1: Signal Specification for the Upgrade Tracker
5.2.4 Radiation Damage in Silicon Sensors

New measurement of the charge collection efficiency in 280 µm thick p-type SSD has been reported. After a fluence of high-energy protons of $7.5 \times 10^{15}$ p/cm$^2$ (corresponding to about $4 \times 10^{15}$ n$_{eq}$/cm$^2$), the collected charge is $> 6,500$ e$. This indicates that trapping times are about two times larger than extrapolated from previous measurements. The fluence in this measurement corresponds to the one expected at the SLHC at a radius of about 10 cm (Figure 5-3), and one might expect that the charge collection in planar silicon detectors at fairly high bias voltages might be sufficient for all but the inner-most pixel layers. At a radius of 20 cm, one would expect a collected charge of about 14,000 e$. For a 3-D detector placed at a radius of 5 cm, the predicted charge collected will be about 9,000 e$ after a fluence of $1 \times 10^{16}$ n/ cm$^2$.

5.2.5 Front-end electronics for SLHC

5.2.5.1 Material Challenge

The present ATLAS detector has a large amount of material in the tracking region. Reducing the amount of material poses a significant challenge because most of the material is directly connected to the large number of electronics channels and the associated services. Thus reducing the power consumption of the electronics channels and increasing the multiplexing to reduce the number of cables and cooling pipes will be an important aspect of the tracker upgrade. For the pixels the use of smaller design structure (0.13 µm or smaller) will reduce the operating voltages but the current will stay the same or will even increase. This will have impact in the electrical services unless a more ambitious powering scheme, such as transmission of power at higher voltages, with efficient DC-DC conversion locally in the pixel modules, or a “serial powering” scheme.

5.2.5.2 Front-end Electronics

The deep sub-micron (DSM) CMOS technologies provide a low-power solution for the front-end electronics for small capacitance sensor elements. CMOS technologies with mixed-mode (analog and digital) look to be the most promising for the Pixel detector, where high density and low power is required. The most advanced CMOS process presently available for prototyping use is the 0.13 µm CMOS8RF process from IBM. The next generation process in this family will be the 90 nm CMOS9RF that might be available in late 2005. There are first indications that the 0.13 µm process can be made rad-hard to very high fluences. Single Event Upset (SEU) will be a very challenging issue for the Pixel detector, where more than a billion of configuration/data bits are stored in the whole detector. Bipolar (BiCMOS) has been shown to provide a power-noise advantage for large capacitances and fast shaping times. However the technology used in the ATLAS SCT is not sufficiently rad-hard beyond a fluence of about $10^{14}$ cm$^{-2}$ and is no longer available. The newer BiCMOS technologies based on SiGe bipolar transistors are very fast ($f_T > 50$GHz and $\beta >200$). They are used widely in cell phones, and are available from IBM and through MOSIS “married” to a variety of DSM CMOS processes. Their radiation hardness has been measured to fluences of $10^{14}$ p/cm$^2$ and when extrapolated up to $10^{15}$ cm$^{-2}$ seem to be adequate for the strip systems in the tracker upgrade. It will be important to measure the radiation hardness up to the fluences required for the SLHC. The largest area in the SLHC tracker will be made of long strips like the SCT, so SiGe could give an advantage through much lower power, especially for short shaping times.
5.2.5.3 **Single-Bucket Timing**

If the luminosity increase for the SLHC is achieved by shortening the bunch length, the occupancy from minimum bias events can be reduced by a significant factor if the hits and tracks can be associated with a single bunch crossing. If the signal rise-time falls within the clock cycle, single-bunch timing is possible in a straight-forward way. For longer shaping time the association depends on the signal-to-noise that is achieved. The pulse rise time depends on both charge collection and shaping times. For the LHC where the detectors are normally biased at about 100V, the holes (electrons) are collected in 14 (5) ns. Increasing the bias to 300V, the collection time are reduced to 7 ns for holes and 2.5 ns for electrons. These numbers should allow single bucket timing for machine frequencies larger than 40 MHz.

5.2.6 **On-detector Buffer Size and Data Link**

From simulation results, the occupancy of the two R/O data links of the Pixel b-layer, at LHC nominal luminosity and 100 kHz L1 trigger rate is of the order of 30%. With this level of occupancy the induced inefficiency due to limited size of event buffers, is negligible at LHC. For the operation at SLHC the R/O bandwidth must be reconsidered and linearly scaled with event size and L1 trigger rate. For the system architecture of the Pixels is preferable to have smaller event size for the same trigger rate; the 75 ns bunch length option will have the biggest impact in data link bandwidth and event buffer dimension. Optimization of both must be done once the machine scenario is chosen.

5.2.7 **Pixel B-layer Upgrade**

The innermost layer of the ATLAS pixel detector, known as b-layer, is located at a radius of 5 cm. It will be subject to a harsh environment at LHC design luminosity, in which it is expected to receive a lifetime dose in a period of 3-4 years. A replacement of the b-layer (see Ref. 8.13) is expected to happen by the year 2011-12. The new b-layer will provide an occasion to study and develop FE chips and sensors, contributing to the full upgrade of the tracker that will happen a few years later.

5.3 **Calorimetry**

5.3.1 **LAr**

The Liquid Argon Calorimeter will be affected by a higher luminosity in different ways:

- Increased radiation leads to a possible break down of the charge collection in the argon itself
- Radiation induced poisoning of the LAr can lead to a reduced signal collection efficiency
- Due to the long drift time of the signals, additional pile up will degrade the performance of the detector
- A higher occupancy requires substantial changes in the electronics read-out chain
- Radiation problems of the Front-End Electronics

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5.3.1.1 Detector

5.3.1.1.1 Ar$^+$ mobility and space charge effects
The signal in a liquid argon calorimeter is produced by the ionization of the argon and a subsequent collection of the liberated electrons in a strong electric field (10kV/cm). The drift velocity of the electrons is of the order 4mm/µsec, which gives a drift time of 450nsec for the ATLAS calorimeter. The positively charged ions are moving very slow in the field and do not contribute to the signal. In a high radiation environment the charge produced in a given LAr gap could be higher than the ions actually reaching an electrode. This leads to a build-up of a space charge in the gap, which reduces the electric field strength and eventually reduces the signal significantly. Such an effect has already been envisioned during the design of the FCAL and this is reflected in the very small gap sizes (down to 250µm). A reduced gap size leads to a shorter drift time of the ions, hence lead to a reduced ion build-up effect.

5.3.1.1.2 Layer Build-up effect
At what level this effect will be a problem is currently under investigation by a group at the University of Arizona. Here a strong $^{90}$Sr source (5mCi) is used to mimic the beam induced ionization level in a single cell. During the first measurements a strange effect has been observed: an insulating layer is building up on both electrodes of the cell, which acts like a zener-diode (breaks down at a few 10 Volts). The layer is sticking to the electrodes even after the electric field has been switched off. The layer can be removed mechanically. One explanation, currently under investigation, of this effect could be kind of a “Getter effect”, which would collect impurities in the liquid argon.

5.3.1.1.3 Poisoning of the Liquid Argon
Another effect which would lead to a reduced signal in the liquid argon is the poisoning of the argon with electro-negative molecules, which capture the electrons from the ionization process. Radiation can produce radicals in the calorimeter materials, which can be dissolved in the argon. Since a wide variety of materials are used in the calorimeter, it is very difficult to estimate the actual effect as a function of the radiation level. All materials have been pre-tested for radiation hardness, but these tests were performed in view of the envisioned radiation level for 10 years operation at nominal luminosity. This ensures that the requirement on the purity of the liquid argon of approx. 0.5ppm O$_2$-equivalent is met, including the assumed radiation safety factors. The effect of the poisoning of argon could be amplified by the above mentioned Getter-effect.

5.3.1.1.4 Direct Activation of the LAr
A safety concern for the operation of the LAr-calorimeter could be the direct activation of the argon with radioactive argon ($^{41}$Ar, $^{39}$Ar and $^{37}$Ar) and other radioactive isotopes (Cl, S, Si, Mg, Al, Na). The argon isotopes will stay within the liquid phase whereas some of the others will attach to the surfaces of the calorimeter. A test has been performed at BNL to study this effect. The result shows a wide admixture of radioactive isotopes (most abundant $^{35}$Cl, $^{38}$Cl, $^{18}$F and $^{31}$Si). At extremely high radiation levels these isotopes produced could generate themselves a significant signal, leading to an enhanced noise level. An additional issue is the activation of the actual detector material which could lead, in addition to safety concerns, to an increased noise level in the calorimeter.
5.3.1.1.5  **High Voltage**

The electric field in all the LAr gaps is a prerequisite for the operation of the calorimeter. The electric field generated is essential for the charge collection. A high ionization rate in the LAr will not only lead to a shielding of the field (via the space charge), but will result in a significant current drawn by the calorimeter. What level of current is tolerable for the individual calorimeters has to be studied. This might require in addition a replacement of the High Voltage supplies as well as a re-design of High Voltage filters. Effects on the performance of the calorimeter, due to a break down of the field in individual gaps, field fluctuations and induced noise have to be studied.

5.3.1.2  **Readout Electronics**

5.3.1.2.1  **Architectural limits of the current LAr Readout**

The current readout is based on a complex architecture with 13 different technology ICs (COTS, DMILL, DMS and AMS) and a total of 20 different regulators. Analog pipelines are implemented to sample and store the signal processed by the Front-End preamplifiers and shapers and several ICs handle the dataflow, the L1 logic and the configuration of the board. Figure 5- represents schematically such an architecture.

![On-detector analog architecture](image)

**Figure 5-4: On-detector analog architecture**

There are several factors that may limit the current readout capability of the detector. One of the main limitations is due to the readout sampling rate:

Current readout is based on a 40MHz clock distribution (TTC). A major upgrade of the FEB may be required if TTC signals are distributed at a different frequency. In case would be possible to keep the readout functionality for sampling rates @40MHz even in shorter bunch-crossing scenarios implications in particular for the ROD have to be further investigated (Multiple sets of Optimal Filter coefficients [OFC] should be used).

In case of need to operate the readout at higher sampling rates some questions naturally arise, such as the pipeline depth required or the optimal number of samples. A possible advantage would be that anti-aliasing is improved being part of the calorimeter response spectrum beyond the Nyquist frequency.
5.3.1.2.2 Detector performances vs. pile-up/shaping

The energy reconstruction in a calorimeter cell is made through sampling the shaper output signals at every bunching crossing and calculating a weighted sums of the digitized samples. Pileup events from minimum bias are traditionally treated as an additional source of noise that scales approximately with $\sqrt{L}$ (see Ref. 8.18). The optimal filtering coefficients [OFC] used to reconstruct the cell energy optimize the energy resolution and compensate partially for a given pileup noise rate. It should be investigated to what extent the OFC compensate for a non-optimal shaping (at $10^{35}$ cm$^{-2}$ s$^{-1}$ the optimal peaking time would be 28 ns instead of 40 ns for the current readout).

![Figure 5-5: LAr calorimeter signals (left). Total and pileup noise as a function of the shaper peaking time (right) for different peak luminosities.](image)

5.3.1.2.3 Radiation tolerance

Components on the Front-End Electronics were all qualified for 10 years of LHC operation at nominal luminosity. Some components will be not likely qualified for 10 years of operation at SLHC. For many of them that the limits on radiation doses have not been determined making even uncertain what would be the expected lifetime at SLHC. For some even technology will be no longer available.

5.3.2 Tilecal

The main Tilecal limitations to operate within the previously listed SLHC scenarios come from:

- the increase of radiation levels
- increase of pile-up
- possible LHC operation with bunch spacing less than 25ns
- occupancy, possible increase of event size

A summary of the major issues for the TILECAL detector to operate at SLHC is given below. Details can be found in Ref. 8.4.
5.3.2.1 Detector

Radiation levels can affect the performance of the calorimeter over the long period of running due to the degradation in the light production and transmission in the scintillating tiles and fibres. The dominant source of radiation comes from the pp interaction rate \((10^9\text{ interactions/s}; \sigma_{\text{tot}} = 80 \text{ mb})\). The total dose level in the Tilecal per year for all scenarios can be roughly predicted by scaling from anticipated doses at the nominal scenario (from 4.2 to 50.5 Gy/Yr for sampling 1, from 0.1 to 11.3 Gy/Yr for sampling 2 and less than 2.5 Gy/Yr for the last sampling).

The relative light output loss as a function of the radiation dose has been deduced from irradiation studies performed on tile+ fibre system and from other measurements. The maximum anticipated light loss is about 18% (in sampling 1) for 5 years of running at a luminosity of \(9 \times 10^{34} \text{ cm}^{-2} \text{s}^{-1}\).

In addition to the radiation doses, natural tile+fiber ageing has to be taken into account to evaluate the total light loss. The effect from ageing has been evaluated in 1995 to be less than 1% per year.

20 pe/GeV are enough to achieve the required TILECAL energy resolution. Then, to be able to detect the muon signal in each sampling, 40 pe/GeV are required. TILECAL set a minimum requirement of \(~50\) pe/GeV, adding a safety margin of 20% for light loss during LHC operation. The mean light yield for TILECAL modules tested in 2002, 2003 and 2004 is about 65 pe/GeV, taking into account natural tile ageing prior to 2002. The light loss budget could be evaluated as 65-40= 25 pe/GeV, allowing an overall decrease of the light yield of about 40% during LHC operation.

Some nice features of the Tile calorimeter help to reduce the impact of light losses on the detector performances. Tiles can be calibrated using the Cesium system, and the HV of the PMTs can be tuned to uniformize to first order the light loss in the optics. The voltage system is able to handle calibration variations of at least a factor 2. So, the anticipated decrease of jet energy measurement due to the light yield degradation could be fully recovered. Nevertheless the light loss will be different from tile to tile connected to the same PMT, due to radiation effects decreasing as a function of the radial depth. The applied average Cs calibration factors will recover only partially the spread of the light loss.

The energy resolution depends on the photo statistic contribution. For light output losses of 10, 20 and 50%, the relative degradation of the resolution is found to be resp. about 0.6, 1.4 and 5.4%.

The anticipated light losses induced by radiation doses and ageing at SLHC will have no effect on the measurement of the jet energy, and a marginal effect on the jet energy resolution for the measurements made with the TILECAL.

5.3.2.2 Electronics

Radiation affects also the electronics located inside the girder as well as the power supply located in the fingers. Numerous aspects have been studied (TID, NIEL, SEE...) on CMOS and bipolar components. All active components have been tested above expected doses (with

\[^8\text{TID} : \text{Total ionizing Dose}
\]^NIEL : \text{Non Ionizing Energy Loss}
\]^SEE : \text{Single Even Effects}
appropriate safety factors\(^9\) after 10 years at nominal luminosity; the worst location with respect to radiation levels being kept as baseline. TID, NIEL doses and SEE rate for all Luminosity scenarios could be scaled from the nominal scenario luminosity. All components have been irradiated above radiation levels expected for a SLHC operating at a luminosity of \(9 \times 10^{34} \text{ cm}^{-2} \text{s}^{-1}\) for 5 years. Nevertheless, if current safety factors have to be applied, some components are below the requirements. The SEE rate will induce only marginal failures on TILECAL electronics, and in order to asses the TILECAL electronic capabilities at SLHC from the radiation point of view, a global estimator \(R\) has been defined:

\[
R_i = \min\left(\frac{SFD_i^k}{SFR_i^k}\right);
\]

SFD being the safety factor deduced from qualification tests on TID and NIEL for component \(k\) and scenario \(i\), and SFR the required safety factor for a component \(k\). The estimator \(R\) has been computed assuming 5 years of running at scenario \(i\). Values are summarized in Table 5-2. 7/20 for the IR-Upgrade scenario indicates that the safety factor reached from various radiation tests is 7 at minimum, while the required safety factor is 20.

This table demonstrates that the TILECAL electronics have been sufficiently tested for doses expected for an Ultimate scenario operating at a luminosity of \(2.3 \times 10^{34} \text{ cm}^{-2} \text{s}^{-1}\) during 5 years. TILECAL electronics can maybe operate safely in other higher luminosity scenarios (still a factor 3 of safety for the highest luminosity scenario), but additional radiation tests are needed to reach the required factors, particularly on the mother board and interface cards. Finally, experience gained during the first years of LHC running will allow a better knowledge of the radiations doses, and hopefully a reduction of the required safety factors (factor 3.5 applied for simulation uncertainty on TID and 5 for NIEL rates).

It should be noticed that prior to any upgrade, ATLAS will run a certain time at luminosities between \(10^{33}\) and \(10^{34} \text{ cm}^{-2} \text{s}^{-1}\). Doses integrated over this first period of LHC running will have to be counted also.

<table>
<thead>
<tr>
<th>Scenario</th>
<th>Luminosity ((10^{34} \text{ cm}^{-2} \text{s}^{-1}))</th>
<th>(R)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nominal</td>
<td>1.0</td>
<td>30/20</td>
</tr>
<tr>
<td>Ultimate</td>
<td>2.3</td>
<td>13/20</td>
</tr>
<tr>
<td>Piwinski-2</td>
<td>3.2</td>
<td>9/20</td>
</tr>
<tr>
<td>Piwinski-1</td>
<td>3.6</td>
<td>8/20</td>
</tr>
<tr>
<td>IR-Upgrade</td>
<td>4.6</td>
<td>7/20</td>
</tr>
<tr>
<td>Piwinski-IR upgrade</td>
<td>6.3</td>
<td>5/20</td>
</tr>
<tr>
<td>Superbunch</td>
<td>9.0</td>
<td>3/20</td>
</tr>
</tbody>
</table>

### 5.3.3 Combined performance

Pile-up noise is by far more critical for the accuracy on the jet energy measurements at SLHC than the light yield loss due to radiations in TILECAL. The main contribution comes from

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\(^9\) Safety factors applied for TID/NIEL/SEE:
- a factor 3.5/5/5 for simulation uncertainty
- a factor 4/4/4 for inhomogeneous batches
- a factor 5/1/1 for bipolar components
pile-up in the LAr calorimeters. Apart from the OFC, nothing on the detector can be done to fight against the pile-up. Some algorithms can be foreseen to reduce the pile up effect at the reconstruction level (as an example: jet defined in a smaller \( \Delta R \) cone, \( E_T \) cuts on cells).

The spread of the deposited energy by minimum bias (MB) events increases as the square root of the number of interaction per bunch crossing (BX). Therefore the pile-up contribution for each scenario can be scaled from the contribution evaluated for the Nominal scenario with a scale factor \( SF = \sqrt{N_i/23} \) where \( N_i \) is the number of interactions/BX for scenario \( i \). The jet energy resolution for each scenario can be predicted using a standard parameterization with a noise term \( c \) expressed in function of the SF factor, the electronic noise \( (c_1) \) and pile-noise \( (c_2) \) contributions for the calorimeters at nominal luminosity scenario:

\[
\frac{\sigma E}{E} = \frac{a}{\sqrt{E}} \oplus b \oplus \frac{c}{E} \quad \text{with} \quad c = \sqrt{c_1^2 + (c_2 \times SF)^2}
\]

The jet energy resolution at various energies as function of the noise term value is shown in Figure 5-6. The ATLAS TDR values of \( a = 62.4\%/\text{GeV}^{1/2} \); \( b = 1.7\% \); \( c_1 = 3 \text{ GeV} \) and \( c_2 = 9.6 \text{ GeV} \) (for a cone \( \Delta R = 0.4 \) at \( \eta = 0 \), no digital filtering applied and jets calibrated to the Hadronic scale) have been taken.

As expected, the pile-up increase affects more low energetic jets, and has little impact on high energetic jets (see Figure 5-6). An energy resolution curve has been established for all scenarios (see Figure 5-7, except for the Superbunch scenario where the energy of jets is not measurable.)
Typically, for 100 GeV jets at $\eta=0$, the energy resolution is about 12% for the Nominal scenario, and increases up to 40% for the Piwinski-IR upgrade scenario (435 MB interactions/bunch crossing).

5.4 Muons

5.4.1 Introduction (Intensity consideration on the Muon spectrometer)

The expected particle rate and its effect on detector performance system have been one of the most relevant issues in the design of the Muon spectrometer and in the specification of the requirements placed on the detectors.

Studies of particle fluence and detection rates have been repeated over the years, following modifications and different options in shielding design. The most recent analysis is reported in Ref. 8.5.

The particle fluence is dominated by low energy (<100 keV) neutrons, high energy neutrons and photons (with typically energy < 1 MeV), each of them ranging up to nearly $10^5$ cm$^{-2}$s$^{-1}$ in the highest $|\eta|$ region, at LHC conditions. The detection efficiency for these particles is in the range of 0.1-1%. The rate for charged particles (hadrons, muons, isolated electrons) is relevant only in the forward region ($|\eta|>1.5$). The detector rate is expected to exceed 300 Hz/cm$^2$ in the inner End Cap station, for $|\eta|>2$, while it is limited to ~20 Hz/cm$^2$ over large regions of the Barrel and the outer End Cap station.

Given the uncertainties in the values of the fluence and of the detection efficiency, a conservative factor of 5 (as safety margin) was applied in the requirements placed on the detectors, covering both detector performance (resolution, pattern recognition, read-out requirements) and long term effects (ageing), see Ref. 8.16. Despite modification in the shielding and updates in detection efficiency for neutrons and photons, the overall picture has not changed significantly over the years, and the Muon system is still expected to be able to

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\(^{10}\) T. Kawamoto and S. Palestini
handle background rates up to about 5 times the LHC expectations with minor degradation of performance\textsuperscript{11}.

For operation in the SLHC scenario, with intensities up to 10 times the LHC values, the demands on the Muon system are increased. The effects on the detectors components are discussed in the following sections. Different configurations of shielding and beam pipes have been considered. The modification with the most significant impact would be the use of a beam-pipe made of Beryllium (for 4.5<z<16 m, with reduction of rates by a factor of 2 to 3). Increasing the shielding is not expected to be so effective.

The rate dependence on $\eta$ is such that the maximum value would be reduced by a factor of 2 (5) if the acceptance in the inner End Cap station would be limited to $|\eta|<2.1$ (< 1.8) (currently it extends to $|\eta|=2.7$, with trigger coverage up to $|\eta|=2.4$)

5.4.2 Particle rates and performance of MDT chambers

MDT chambers have been repeatedly tested under high radiation in the X5/GIF facility at CERN. As an example (see Ref. 8.17), Figure 5-8 shows the measured single-tube resolution vs. impact radius under different background rates. Space charge due to positive ions (actually, fluctuation in the space charge) causes degradation of the resolution, in particular at large radii. The largest intensity (1 kHz/cm\textsuperscript{2}) corresponds to the maximum rate (largest $|\eta|$ in the inner End Cap station) expected – with significant uncertainty - for a luminosity of $10^{35}$ cm\textsuperscript{-2}s\textsuperscript{-1} (without safety margin), and provides an indication of the degradation in performance by a factor 1.5-2 in space resolution in the region of highest intensity. Most of the spectrometer would operate at ~100 Hz/cm\textsuperscript{2}, where the effect on resolution is limited.

The response at high rate has been studied, with satisfactory results, also for the other detectors used in the Muon spectrometer. Ageing tests for up to 10 ATLAS years (with safety margin of 5) have been performed.

![Figure 5-8: Space resolution for single MDT tubes vs. impact radius for different background rates.](image)

\textsuperscript{11}This refers mainly to Muon as a standalone system. The combined performance for muons with $p_T$ below ~150 GeV/c might be more significantly affected by rate effects on other systems.
5.4.3 Bunch crossing rate and detectors intrinsic response

The MDT chambers have a maximum drift time of about 700 ns, and the detector performance would not be affected by changing the bunch crossing rate to 80 MHz or 13.3 MHz, as considered for different SLHC options. A superbunch configuration, with separation between bunches larger than the maximum drift time, would increase the effective detector occupancy and reduce the efficiency in pattern recognition and tracking. The detector read-out, for this and as well for the other Muon subsystems, was not designed to operate above 40 MHz.

The CSC chambers (|η|>2, End Cap inner station) have been designed for a charge collection time matching 40 MHz bunch crossing rate, and the assessment of their performance for higher luminosity and faster crossing rate needs additional study.

The RPC chambers (trigger chambers in the Barrel) have a fast response (avalanche signal ~5 ns long) and are intrinsically capable of being operated with a crossing rate above 40 MHz. The TGC chambers (trigger chambers in the End Cap) have a speed of response matching the LHC bunch crossing rate. The maximum collection time depends on the incidence angle (or on η) and varies between 10 and 16 ns for 97 % collection efficiency, for 1<|η|<2.4.

5.4.4 Muon trigger

Under a preliminary analysis, the Level-1 trigger should be able to cope with a factor 10 increase in the luminosity, under the assumptions that:

a) the safety factors of 5 assumed in the background rate will be approximately confirmed at LHC (and improvements in shielding/beam pipe would keep the occupation ratio comparable to the values considered in past simulations),

b) the current bunch crossing rate of 40 MHz in maintained. The total trigger rate would still be mainly due to muons below threshold rather than accidental trigger rate.

For a slower crossing rate (as the 13.3 MHz which was considered) the fraction of accidental trigger would be higher.

At faster rates, issues of different kind would arise. For the TGCs, the current trigger electronics is designed to work with 40 MHz clock frequency. It could operate with bunch crossing of 20 or 13.3 MHz. With 80 MHz bunch crossing rate, it might be used to the cost of not resolving pairs of adjacent bunch crossings, and presumably with some increase in accidental triggers. In order to operate with faster clock rates, substantial replacement of trigger electronics would be needed. Furthermore, the limitation due to the signal collection time discussed above would prevent anyway an efficient bunch crossing identification.

For the RPCs, the detector response is faster, and the trigger electronics has an internal clock at 320 MHz. Nevertheless, the option of operating the trigger at frequency higher than 40 MHz requires additional studies, and would presumably imply the replacement of significant parts of the electronics.

5.5 TDAQ\textsuperscript{12}

The T/DAQ system of ATLAS for the initial design luminosity includes a hardware-based LVL1 trigger, providing fast synchronous decisions at the bunch crossing frequency of 40 MHz, as well as the Higher Level Trigger and DAQ system, operating asynchronously. In

\textsuperscript{12} S. Tapprogge.
general, the increase in luminosity should be compensated by more refined algorithms and/or increases in the $p_T$ thresholds for the selection of objects, in order to keep the LVL1 accept rate at similar values as foreseen presently (75 kHz, which are upgradeable to 100 kHz). Here the impact of more pile-up events on e.g. isolation criteria from calorimeter information and an increased background rate leading to a more frequent occurrence of accidental coincidences (muon system) needs to be considered. Furthermore it has to be taken into account that for a fixed LVL1 accept rate, the necessary readout bandwidth will increase due to the larger occupancies and the smaller granularities expected for an upgraded detector. Example signatures showing the necessary increase in $p_T$ thresholds for inclusive selections are shown in Table 5-3.

Table 5-3 Example trigger menu with inclusive signatures and expected rates, for LHC and an upgraded LHC (SLHC)

<table>
<thead>
<tr>
<th>Selection</th>
<th>LHC</th>
<th>SLHC</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Threshold (GeV)</td>
<td>Rate (kHz)</td>
</tr>
<tr>
<td>inclusive single muon</td>
<td>20</td>
<td>4</td>
</tr>
<tr>
<td>inclusive, isolated e/gamma</td>
<td>30</td>
<td>22</td>
</tr>
<tr>
<td>muon pair</td>
<td>6</td>
<td>1</td>
</tr>
<tr>
<td>isolated e/gamma pair</td>
<td>20</td>
<td>5</td>
</tr>
<tr>
<td>inclusive jet</td>
<td>290</td>
<td>0.2</td>
</tr>
<tr>
<td>jet + missing ET</td>
<td>100+100</td>
<td>0.5</td>
</tr>
<tr>
<td>inclusive ET</td>
<td></td>
<td>150</td>
</tr>
<tr>
<td>multi-jet triggers</td>
<td>various</td>
<td>0.4</td>
</tr>
</tbody>
</table>

For the LVL1 system, a major issue will be related to the value of the bunch crossing frequency of an upgraded LHC. Further issues can arise from an increase in the detector granularity or the use of additional components in the LVL1 decision process. The LVL1 muon trigger will also depend on the performance of the muon trigger chambers, as discussed in the section on the muon system upgrades.

The system being presently built already faces limitations from the data movement and fanout on e.g. the backplanes of various components, which would be even more challenging at reduced bunch spacing. Bunch spacing intervals above about 10 ns may allow assignment of the trigger decision to a unique bunch crossing as in the present design of the LVL1 trigger. Closer bunch spacing may require new approaches where detector signals and/or trigger decisions cannot be uniquely assigned. Clearly this could have implications for pileup and readout data volumes.

For the electronics situated on or very close to the detector, the increase in particle fluxes might impact (as for the detector front-end electronics) the requirements on radiation hardness and/or tolerance.

An aim would be to achieve at LVL1 a larger rejection power, possibly by using improved and refined algorithms – with possible impact on the required data volume and granularity. The very challenging idea of having a track based trigger at LVL1 should be contrasted to the capabilities expected from the RoI approach which should be available again for LVL2.
A final aspect concerns the TTC system, which would have to be upgraded as well if a shorter bunch spacing would be part of the machine upgrade. It should be investigated whether additional functionality would be beneficial.

An upgraded HLT/DAQ system could have a similar architecture as today. Again, one would aim to profit from technology advances, e.g. in the increases in bandwidth of networks and processing power in CPUs. The system would likely have to cope with an increased data transfer bandwidth and require more processing power. Details will depend on the granularity of the upgraded detector components. It should be noted that if LVL1 were to provide more rejection power, the task of the HLT will be more demanding and more complex and time/data-consuming algorithms would have to be deployed, in order to arrive at similar output rates to mass storage, as foreseen today. It is also expected that less inclusive selection criteria will form a larger fraction of the trigger menus.

6 Directions for R&D

In this section, the major lines of R&D for the various sub-components of an upgraded ATLAS detector are defined. These should serve as initial guidelines for possible R&D projects to be defined in the near future. As the resources available for R&D will be limited, it is important to focus R&D activities on the needs of an upgraded ATLAS detector.

6.1 Electronics

As mentioned in section 5.1, there are a few topics that obviously require some R&D work. The first one is the development of front-end ASICs in sufficiently radiation hard technology, one good candidate being the very deep sub-micron CMOS technologies (0.13 µm or below). These technologies have such characteristics that it is necessary to check the feasibility of performing analogue front-end designs. In order to both reduce the power consumption and the volume of data to be read-out some R&D concerning data compression and low power design need to be done. The thorough study of the radiation hardness of SiGe technologies should also be considered. The knowledge on the radiation tolerance limits of existing electronics must be improved. Already known devices with low safety margin factor such as the ELMB in some places and some low voltage power supplies will require R&D. Additional work on how to handle single event effects will also be necessary. The distribution of the power inside the detector requires a major effort in particular in the direction of radiation hard power converters. As the TTC system needs some modification (because of the very likely change in BC frequency), R&D in this field is very desirable.

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13 P. Farthouat
6.2 Tracking\textsuperscript{14}

- Performance: define initial proposal for layout and sensor structures, study pattern recognition capabilities and iterate. The goal will be to define a tracker system which has a minimum cost, a minimum of material, and provides adequate tracking performance, including vertexing, for an approximately five year period of data collection.
- Sensor: all Si, new materials (profit from e.g. RD50). The choice of sensor material (for example p-type substrates) can have a large influence on survivability of the individual silicon detectors: the total charge that can be collected, and the voltage required for good charge collection. This is already important in the present ATLAS detector and will become even more important as the fluence seen by the detector is required to increase. The inner radial region of the tracker will likely require a new detector configuration in order to have sufficient charge available, the other regions allow several options for which an optimal solution has to be chosen. The choice for the outer regions will have a large impact on the total cost and services.
- Electronics: DSM process, SiGe process. The pixel detector in an upgraded ATLAS will have to use the DSM CMOS available at the time of detector construction. We will have to design in this process and learn about the analog performance, fluence limits, and susceptibility to single event upset, in order to optimize performance. The outer parts of the detector, where the sensor element capacitance is largest, could profit from a BiCMOS solution, in order to minimize power. We will have to investigate whether the use of SiGe offers a viable option or whether we will use DSM CMOS everywhere in the detector. In either case, the front-end of the outer tracking elements will require a separate design and optimization from the inner pixel electronics.
- System: power management, data transmission, low mass supports. The system aspects of an upgraded tracker will require special attention in order for the services to fit into the existing ATLAS detector. In addition the expected low voltages for the front-end electronics pose safety concerns and will likely require better power management than with the present detector.
- Radiation hard opto-communication: drivers and receivers, local voltage control system. Radiation hardness will be an issue not only for the detector and front-end but also for all the circuits making up the data receiving and transmission system. In addition choices have to be made about how the data is transmitted, for example do we use slow or fast links, and do we transmit analog, digital, or binary information.

6.3 Calorimetry\textsuperscript{15}

6.3.1 LAr

6.3.1.1 Detector

The signal degradation due to radiation induced effects on the charge collection as well as pile-up induced problems will require further tests as well as extensive simulations. The effects on the charge collection in the LAr will require test beam setups as well as table top experiments.

\textsuperscript{14} G. Darbo and A. Seiden
\textsuperscript{15} F. Lanni, D. Pullin and C. Zeitnitz
6.3.1.1.1 Space charge effects, LAr poisoning and High Voltage

Detailed studies of the effects of the build-up of the space charge in the LAr-gap are necessary in order to determine the consequences for the charge collection efficiency, the high voltage system and the ultimate radiation limits for a reasonable operation of the calorimeter. Within the LAr community first plans have been made for a very high intensity beam test with a simplified small calorimeter module.

6.3.1.1.2 Layer Build-up Effect

This effect has to be understood in order to determine the operation parameters for the calorimeter at high radiation levels. If the “Getter effect” is real, an additional purification procedure might be needed in order to reach the required contamination level of the liquid argon. The University of Arizona continues to study this effect.

6.3.1.1.3 Contamination and activation

Further experiments and simulations (e.g. CINDER type activation calculations) will be required to understand the level of the contamination/activation as function of the radiation level in the different parts of the LAr calorimeter.

6.3.1.2 Readout Electronics

A LAr upgrade would have to be done adiabatically with the aim of minimal changes at the level of the subsystem interfaces. Changes in the LAr readout will likely imply changes in other subsystems breaking the above assumption of an adiabatic process. In particular the Level-1 (LVL1) trigger, HLT and even the Tile Calorimeter (the interface to LVL1 is similar) may be affected. A new design of the LAr readout must therefore address carefully the issues of interfaces and guarantee compatibility with designs and strategies adopted by the other subsystems.

Power constraints may limit technology choices for upgrading the readout-electronics. Power dissipation should be kept at least within the current limits simplifying wherever possible the power distribution on board.

In the LAr community some discussion and planning has already started on R&D programs for alternative readout schemes:

i. On-detector analog architecture like the current scheme based on upgraded analog pipelines that digitize signals only upon the arrival of a LVL1 trigger.

ii. On-detector digital architecture using radiation resistant ADCs and high bandwidth links to send all data off-detector and data compression mechanisms. In this case no more L1 pipeline and associated control logic are required on-detector gaining in flexibility, large reduction of COTS on board and therefore also of voltage regulators needed to be supplied to the board.

iii. Off-detector analog architecture. Aiming at minimizing the components on the front-end electronics, analog signals pre-shaped could be driven off-detector through analog optical links.

Possible implementations for which extensive research is required are here summarized:

- Interest in developing rad-hard ASICs in particular for the IBM .13um process (see Sec. 6.1) has been expressed to explore scheme ii, starting with the design of a Gain Selector and MUX ASICs (in combination with COTS to realize a first prototype).

- High bandwidth radiation hard optical links: VCSEL arrays (up to 80Gbps), laser drivers based on Silicone-on-Sapphire technology (.25um SoS drivers up to 10Gbps
will be soon available), grating-outcoupled Surface-Emitting (GSE) lasers with phase shift modulation (for operations in the 10-40 Gbps range), within scheme ii.

- VCSEL lasers to be used as analog drivers in scheme iii. The photon statistics may limit the dynamic range and has to be studied in detail.

The question of a revision of the preamplifier/shaper response should be also considered in view of optimizing detector performances in upgrade scenarios. As shown in Figure 5-5 the minimum ENI is achieved by shortening the shaping time as the pile-up noise increases. However a shortening of the shaping time will increase the sensitivity of the detector response to the parasitic in the detector (e.g. inductance of the connections) as well as the sensitivity to cross-talk between channels. Furthermore, current preamplifiers (based on bipolar discrete component hybrids) are sensitive to NIEL radiation damage and the possibility of using them for the lifetime of upgraded scenarios should be assessed.

### 6.3.2 TileCal

New tests are needed to qualify the TILECAL electronics for radiation levels expected in case of a SLHC operating during 5 years at a luminosity above $2.3 \times 10^{34}$ cm$^{-2}$s$^{-1}$.

All components have been sufficiently tested for TID and NIEL doses expected for an Ultimate scenario operating at a luminosity of $2.3 \times 10^{34}$ cm$^{-2}$s$^{-1}$ during 5 years, safety factors included. To conclude positively up to an IR-Upgrade scenario operating at $4.6 \times 10^{34}$ during 5 years, further TID (NIEL) qualification tests are needed for mother board CMOS and bipolar components (interface, mother board and digitizer components), respectively at TID doses of 40 and 200 Gy (NIEL rates of $9 \times 10^{11}$, $10^{13}$ and $10^{15}$ MeV/cm$^2$). For completion, new TID (NIEL) qualification tests could be required for 3-in-1 and interface bipolar components (HV-micro, HV-opto, 3-in-1 and adder components), which have been tested successfully up to doses expected in the IR-Upgrade scenario, but on pre-production components only. For scenarios with foreseen luminosity above $4.6 \times 10^{34}$ cm$^{-2}$s$^{-1}$ new TID radiation tests above doses already applied are required in order to determine if TILECAL components are enough tolerant. This is particularly true for bipolar components which have safety factors set to 70.

Tests are also needed to determine if the TILECAL electronics is able to cope with a SLHC operation with bunch spacing less than 25ns, for example a bunch spacing of 15 ns with a front-end electronic frequency at 30ns. In this case, TILECAL will not be able to sample every event on the peak of the pulse. A new treatment of the signal at the level of the optimal filtering in the ROD has to be implemented. In addition it has to be proved that front-end electronics works fine at a 30ns frequency. One difficulty could come at the level of the interface where the G-link output for data is set to a fixed 25ns clock (no use of QPLL chip). It is not obvious to resynchronize to 30ns with the current interface design. Other difficulties like the ability to span the Deskew2 clock over the full clock period or related to the output buffer size have to be investigated. In the worse case interface cards would have to be redone, which would require R&D, the production of 270 cards, and 4 months of operations for the replacement of the cards on the detector.
6.4 Muons

The option of operating the Muon System at intensities significantly higher than LHC requires additional studies in several areas:

a) Long term stability. Ageing studies on detectors and on electronics have been performed under the assumption of 10 years at LHC luminosity, and applying a safety factor of 5 to the background rate obtained from simulation. The opportunity of additional studies, to be performed soon, should be considered. After LHC start-up, the measurement of actual rates will allow to assess the situation, and to specify the extent of the need of modifications to shielding and beam pipes.

b) Detector performance. Studies performed in the past have normally explored intensities up to 500 Hz/cm$^2$ (or higher for the innermost region of the first End Cap station), corresponding to LHC luminosity with background increased by the safety factor in order to account for uncertainties. Additional studies, in particular for pattern recognition, are needed in order to evaluate the complexity of operating at higher luminosity.

c) Due to the higher detector occupancy, the possibility of replacing the detectors in the areas of highest intensity (large $\eta$ regions in the Inner and Middle End Cap stations) should be studied. This covers both aspects of detector R&D and of resources and schedule.

d) The option of higher bunch crossing rate relates to different areas of study:
   - Understand the option of keeping the current electronics, with limited upgrades or no modifications at all. This study could be based on simulation or on test-beam data. The implication of an inefficient bunch-crossing identification should be understood in the contexts of Muon and combined detector performances.
   - The option of new trigger electronics should be explored. Planning of this requires the assessments on the availability of resources (human and financial), and on time needed for R&D, development ad construction. The issue of bunch crossing identification in the End Cap would not be fully solved on read-out and trigger electronics alone.
   - Faster detector response would be of large benefit in different areas (TGCs for triggering at higher bunch-crossing frequency, CSCs for detector occupancy; the MDTs would benefit from a more linear drift time in order to reduce the sensitivity to space charge). Changes in gas mixtures are constrained by the requirement on detector stability on short and long terms.

6.5 TDAQ

The following issues could form the main path of R&D activities for TDAQ. In some areas, there is clearly dependence on more precise specification for upgraded sub-detectors and some parameters will have to be yet calculated (e.g. expected occupancy and data volume due to the higher luminosity and more granular detector components):

- LVL1 trigger design for a higher bunch crossing frequency (e.g. 66/100 MHz)

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16 T. Kawamoto and S. Palestini
17 S. Tapprogge.
Design of a TTC system with enhanced capabilities (?) for a higher bunch crossing frequency

Increase in readout bandwidth (for fixed LVL1 accept rate)

Increase in HLT/DAQ capabilities and coping with further increase in complexity

Development of refined algorithms (both LVL1 and HLT) and assessment of achievable rejection power (for constant efficiency)

Increased use of data compression

7 Conclusions

The present version of the workplan document provides a rather comprehensive overview of the issues and ideas for an upgrade of ATLAS, to match a possible upgrade in luminosity of the LHC by up to one order of magnitude. Based on these assessments, a first attempt has been made by the High-Luminosity Upgrade Steering Group to indicate possible lines of R&D as a reference for the upcoming workshop in February 2005. The next steps to be taken after the workshop will include a more precise definition of concrete R&D activities for ATLAS, and the development of more refined plans (in follow-up meetings targeting more technical details for the various areas).
8 References


8.5 V. Hedberg and M. Shupe, *Radiation and induced activation at high luminosity*, ATLAS note ATL-TECH-2004-002


8.7 F. Zimmermann, private communication


