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# ECFA High Luminosity LHC Experiments Workshop: Physics and Technology Developments

## Summary submitted to ECFA

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## 1. Introduction

The 2014 ECFA High Luminosity LHC Experiments Workshop[1] was a second meeting of the four LHC experiments with the accelerator and theory communities. The meeting was held in Aix-les-Bains, from 21st to 23rd October and attracted 250 participants.

This report follows on from the one published after the 2013 workshop[2] (ECFA-13-284, see Ref. (1)) that outlined the major physics goals and the projected performance reach for the High Luminosity LHC (HL-LHC) along with the research and development for upgrading the accelerator and experiments.

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[1] https://indico.cern.ch/event/315626/

[2] https://indico.cern.ch/event/252045/

Since last year, the Particle Physics Project Prioritization Panel (P5) has reported to the USA High Energy Physics Advisory Panel that "*The HL-LHC is strongly supported and is the first high-priority large-category project in our recommended program*" (2), in line with the earlier European Strategy report (3).

In this context, the HL-LHC project is evolving to prepare funding for its execution and to complete the required research on the planned technical solutions, leading to the development of prototype systems. The workshop was naturally focused on this latter aspect, building on the healthy communication established at the first meeting between the different experiments and the theory and accelerator communities. Preparatory groups again put together the material for the workshop main sessions, helping foster further interactions which have led to a much greater uniformity of understanding and approach across the LHC experiments.

The overall strategies of the four experiments remain broadly those described in (1) so these will not be repeated here, but instead the report will focus on new developments in physics and performance studies, accelerator preparations, detector research and development, electronics, online and offline requirements.

Following the 2013 workshop and further discussions at the RLIUP meeting[3], the planning for the HL-LHC programme after the current long shutdown (LS1) has become much firmer, with the next long shutdown (LS2) starting July 2018 and lasting 18 months. During LS2, major modifications to the LHC injector complex are envisaged along with the main ALICE and LHCb upgrades and the completion of the Phase-I upgrade programmes of ATLAS and CMS. After LS2 the LHC is expected to achieve a peak instantaneous luminosity of around $1.8 \times 10^{34}$ $\mathrm{cm}^{-2}\mathrm{s}^{-1}$ limited by the triplet magnet cooling[4]. In addition, a significant fraction of the work needed by the accelerator for HL-LHC operation will be anticipated during LS2. By the end of 2022, ~300$\mathrm{fb}^{-1}$ of integrated luminosity each should have been collected by ATLAS and CMS, while the peak doses to the interaction point triplets are expected to reach tens of MGy. At such doses mechanical failure of insulating materials are anticipated[5] leading to the need to replace these magnets. This will also be the stage at which several major components of the ATLAS and CMS experiments would also require replacement and so the third shutdown (LS3) is anticipated to run from the end of 2022 for a period of at least 30 months. During this time both machine and experiments will be upgraded to cope with a nominal levelled instantaneous luminosity of $5\times10^{34}$ $\mathrm{cm}^{-2}\mathrm{s}^{-1}$ and an "ultimate" design levelled luminosity up to $7.5\times10^{34}$ $\mathrm{cm}^{-2}\mathrm{s}^{-1}$. The accelerator complex will be configured to provide a virtual luminosity of around $20\times10^{34}$ $\mathrm{cm}^{-2}\mathrm{s}^{-1}$ to be able to deliver sufficient duration for the levelled fills to allow annual integrated luminosities in the range 250-300$\mathrm{fb}^{-1}$ during HL-LHC (Phase-II) operation[6] leading to an overall design goal of 3000 $\mathrm{fb}^{-1}$ by the mid-2030s. The implications for ATLAS and CMS in terms of radiation doses to central tracking and forward calorimetry necessitate major upgrades, as do the particle track densities and data rates in an environment

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[3] https://cds.cern.ch/record/1629486?ln=en

[4] https://indico.cern.ch/event/260492/session/0/contribution/1/material/paper/0.pdf

[5] https://indico.cern.ch/event/260492/session/0/contribution/3/material/slides/1.pdf

[6] http://indico.cern.ch/event/315626/session/1/contribution/2/material/slides/1.pdf

where the mean number of proton-proton inelastic interactions per 25ns beam crossing, <μ>, will be around 140 with the ultimate instantaneous levelled luminosity implying <μ> values of order 200.

Both the theory and experiment communities have made considerable progress in understanding the significantly improved physics reach with the increased integrated luminosities planned for all four experiments. Further studies, including full GEANT simulations of the ATLAS and CMS detectors, have also been performed to better optimize the experiment layouts to mitigate the sensitivity to pile-up. This is particularly important in the forward regions of these detectors that will play a key role in identifying the rare VBF, VBS and boosted physics signals.

There has been substantial progress on optimizing the designs of solid state tracking detectors, benefiting particularly from the work of the RD50 collaboration. Radiation tolerant solutions have been identified and the R&D programme evolves to qualify cost effective production process at potential vendors. This is particularly important for the large areas required for the outer strip trackers of ATLAS and CMS. Studies by RD42 have also progressed to develop diamond detectors suitable for beam luminosity monitoring.

More radiation tolerant scintillator based detector systems are also being proposed for calorimeter and tracker applications, with the added potential to deliver very fast signals of possible use in pile-up suppression. This covers development of plastic, liquid and crystal devices, both in plate and fiber configurations, as well as wavelength shifting capability. This is complemented by a vigorous programme to develop novel photo-sensors, either based on new materials, smaller pixels or both, to improve radiation hardness.

The work on micro-pattern gas detectors of RD51 informs a number of developments in gaseous detectors, while other activities in this area include improvements in lifetime and rate capabilities of wire based systems. The former devices have now reached sufficient maturity for large-scale production. There are also many new ideas being investigated to improve the rate capabilities of other technologies, particularly Resistive Plate Chambers. In addition, first candidates for eco-friendly gas mixtures are being identified.

There are many challenges in terms of electronics for the HL-LHC environment, not least those of addressing the radiation-hardness and channel density requirements of the layers closest to the beam, where RD53 allows shared resources for developing 65nm technology between experiments. Where 130nm or other technologies are sufficient, many prototypes of the required chip sets now already exist for the four experiments. There are also joint programmes for radiation-hard, low power and high bandwidth opto-electronics (GBT and VTT) coordinated through CERN and discussions on common standards for online systems.

For 2014, the workshop provided a forum for sharing ideas and experience on mechanics and cooling between the experiments. $CO_2$ cooling is becoming a standard with common developments now aiming at producing reliable large-scale systems. Developing ultra-light assemblies is another common trend, where much progress has been reported on new components and techniques, including micro-channel cooling.

The areas of online and offline data processing will require a radical change in paradigm within the particle physics community over the coming decade. The many opportunities for computing improvements and the first steps towards evolving to multi-threading programming where presented.

Finally, the topics at the experiment-accelerator interface include the severe requirements imposed by the high activation levels, which greatly limit access and impose detailed safety procedures and use of radiation protection technologies. Substantial progress was presented on understanding and modeling the activation levels in the experimental areas, with good convergence between ATLAS, CMS and accelerator estimates.

## 2. Theoretical and Experimental Developments on Physics Reach and Performance Studies

The first studies of the HL-LHC physics programme and the performance of the upgraded LHC detectors were documented for the European strategy meeting in Cracow (3), the Snowmass workshop in the US (4), and the first ECFA HL-LHC workshop in 2013 (1).

The second ECFA HL-LHC workshop was a significant step forward in developing improved understanding of the performance of the upgraded detectors in the harsh HL-LHC environment. The studies were organized to motivate a number of specific performance related detector upgrades and to address points raised during the first ECFA HL-LHC workshop.

Below only some key aspects of the programme are discussed. This section will present progress and prospects regarding Higgs and BSM physics analyses at the general purpose detectors, continue with a discussion of several detector performance aspects and close with heavy-flavour and heavy-ion prospects.

An important component of the HL-LHC programme is to carry out studies involving the recently discovered 125 GeV Higgs boson. One aspect is precision measurements of the properties of this scalar particle, in order to test the Standard Model pattern of couplings to elementary particles. Additionally, because of the hierarchy problem with quantum instability of the Higgs sector, many models of new physics affect precision Higgs observables, even in cases where the corresponding new particles are hard to discover experimentally.

The ATLAS and CMS experiments expect comparable precision, with an estimated uncertainty of 2-5% for many of the investigated Higgs boson couplings to elementary fermions and bosons, demonstrating that with an integrated luminosity of 3000 $\mathrm{fb}^{-1}$ the HL-LHC is a very capable precision Higgs physics facility. Figure 1 illustrates the improvements in coupling measurements expected for weak bosons and fermions with 3000 $\mathrm{fb}^{-1}$ of data (5), (6).

To fully benefit from the higher experimental precision in the Higgs sector it will be necessary to reduce theoretical uncertainties relative to today's state-of-the-art. Progress is currently being made on many fronts. Examples include steps towards a NNNLO computation of the Higgs-boson cross section in gluon fusion (7) and various NNLO computations for more exclusive final states (e.g. Higgs+jet (8), (9)), both of which can affect Higgs parameter extraction. A reduction in the uncertainty of parton distribution functions (PDFs) will also be needed, and here too the advent of new calculations at NNLO (10), (11) should help, as could detailed studies of the origins of systematic differences between different PDF sets (see e.g. Ref. (12)). Other progress that will be relevant includes higher order merging of parton showers and fixed-order calculations (see e.g. Refs. (13), (14)) as well improvements in methods to estimate higher-order uncertainties such as those discussed in Ref. (15).

Along with improving the precision of Higgs-sector measurements, the substantial luminosity of HL-LHC will make it possible to probe important rare processes involving the Higgs boson. Some examples involve rare decays, such as $H \rightarrow Z\gamma$, or those involving second generation fermion couplings, which can open a novel window on the problem of flavour (16). Off-shell and high transverse momentum Higgs production allows access to new physics near the TeV scale that may otherwise be hidden, only partially overlapping with the sensitivity to BSM (and SM) physics coming from precision Higgs measurements and providing complementary information (see (17), (18) and references therein).

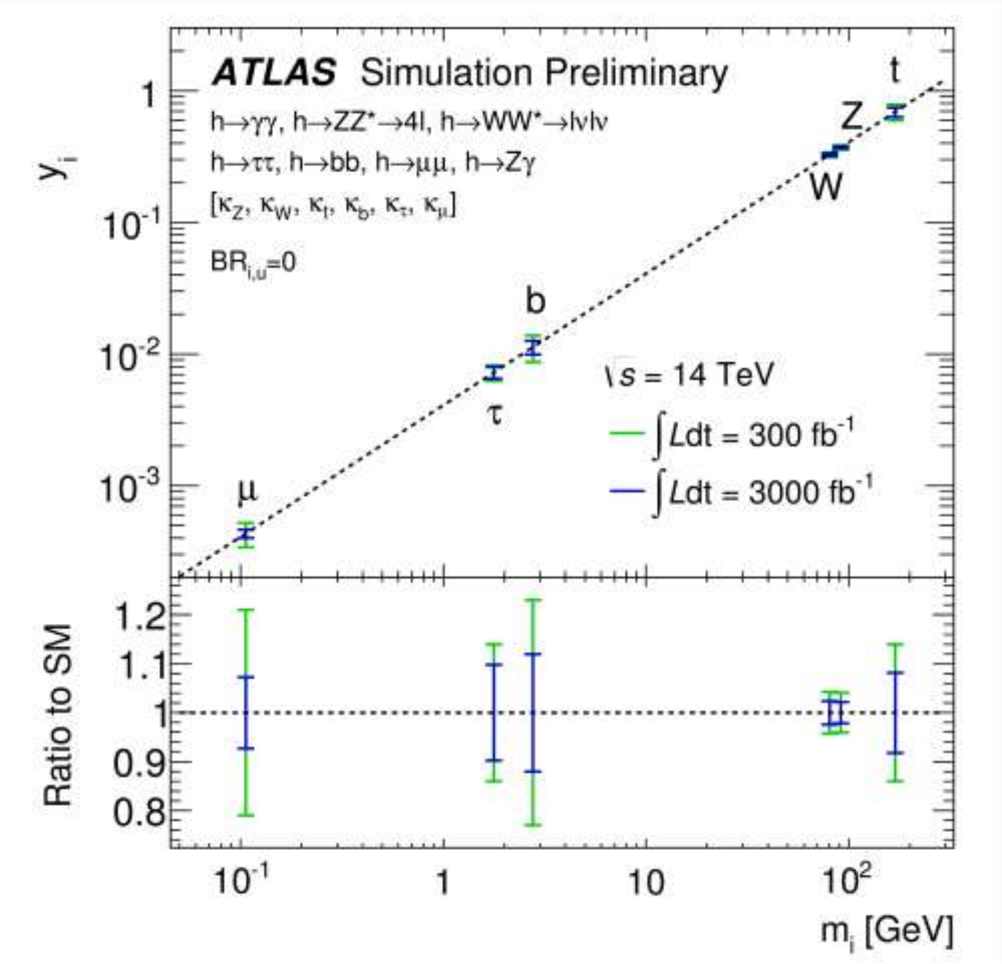

**Figure 1 Results for the reduced coupling scale factors for weak bosons and fermions as a function of the particle mass, assuming a data set of 300 fb or 3000 fb and a SM Higgs boson with a mass of 125 GeV.**

Finally, the HL-LHC may have the potential to study di-Higgs production. In the Standard Model, with the Higgs boson mass and the Higgs-field (φ) vacuum expectation value now both known, the structure of the Higgs potential is fully predicted. This is because the potential involves just two terms, proportional to $\varphi^2$ and $\varphi^4$. An elementary field potential of this kind has never been seen before in nature and it is crucial to test whether it is indeed the potential associated with the actual vacuum. A study of the Higgs boson self-coupling provides one such test, because the self-coupling is related to the third derivative of the Higgs potential at its minimum, uniquely predicted in the Standard Model. One main avenue for studying the self-coupling is through di-Higgs production, which is sensitive to the (off-shell) $H^* \rightarrow HH$ process. It should be noted, however, that this interferes with other mechanisms for the production of two Higgs bosons, which complicates the determination of the self-coupling. Furthermore, new-physics can modify the relation between the Higgs potential and di-Higgs production; for example di-Higgs production can be greatly enhanced in cases where the Higgs is composite rather than elementary (19), (20).

Preliminary studies of the rare di-Higgs process, only accessible at the HL-LHC, have been performed by the ATLAS and CMS experiments, considering $HH \rightarrow bb\gamma\gamma$ and $bbWW$ final states. The findings of these analyses show the challenge that this physics process represents, where high performance on mass resolution, primary vertex measurement, b-tagging and photon identification efficiencies, as well as mitigation of the event pile-up effects, are crucial to the success of this measurement (21), (22). As an example, CMS presented the relative uncertainty on the di-Higgs boson production cross section measurement as a function of the b-tagging efficiency. Studies of other di-Higgs final states, such as $bb\tau\tau$ and $bbbb$, would be needed to improve the accuracy of such analyses (23).

As well as exploring the Higgs sector, with its corresponding scope for sensitivity to BSM physics, the HL-LHC also presents opportunities for direct discovery of new particles. The HL-LHC will extend the discovery reach of the LHC for a wide range of new phenomena from modified Higgs sectors to searches for dark matter candidates and for new resonances. The sensitivity to BSM models is significantly enhanced at the HL-LHC compared to the corresponding sensitivities at lower integrated luminosities.

One class of particles whose discovery potential benefits especially from the extra factor of ten in luminosity provided by the HL-LHC is that of new states with production rates that are suppressed, for example by small couplings. The electroweak production of neutralino-chargino pairs provides one such striking example. Both ATLAS and CMS studied the production of $\chi_1^+ \chi_2^0$ with decay to $WZ$ and $WH$ final states in the context of a simplified SUSY model. In the case of the $WZ$ final state, the mass reach increases by approximately 50% from Run 3 at the LHC to the HL-LHC, while the reach about doubles in the $WH(bb)$ final state.

Other scenarios with suppressed rates to conventional final states include models such as supersymmetry and compositeness with a split spectrum (24), (25) (see recent searches based on charm-tagging (26)) or models with compressed spectra and/or kinematic degeneracies in the decays.

The ATLAS and CMS Collaborations have also shown that the mass reach for the discovery of new heavy states like gluinos/squarks in standard supersymmetric scenarios or new gauge bosons ($W'$ or $Z'$) typically increases by about 20% at the HL-LHC. In a detailed study of five full-spectrum SUSY models, CMS showed that a combination of nine different experimental signatures is able to establish discovery with differing amounts of integrated luminosity but only the HL-LHC is capable of discovering the physics nature of all five models (27).

In the event of a discovery with the Run 2 or Run 2+3 datasets, it is likely to be difficult to distinguish between different new physics interpretations. For example, the CMS Collaboration has shown that a spin-1 dilepton resonance with a mass of 4 TeV could be discovered at the LHC but spin-0 or spin-2 interpretations could only be discriminated against at the 0.5 to 2 standard deviations level with 300 $\text{fb}^{-1}$ of data using both angular and rapidity distributions of the dilepton system. The level of discrimination reaches 2 to 5 standard deviations with the data set of the HL-LHC.

The mitigation of pile-up at the HL-LHC is of fundamental importance to be able to deliver the physics goals of the LHC luminosity upgrade. An instantaneous luminosity of $5\times10^{34}\text{cm}^{-2}\text{s}^{-1}$ is assumed to correspond to an average number of proton-proton interactions per bunch crossing (pile-up), $\mu$, of 140 events. The ATLAS performance has been evaluated using the baseline Phase-II central tracker in full detector simulation. CMS has shown the impact of aging on the detector after 1000 $\mathrm{fb}^{-1}$ data and then compared this to their Phase-II detector performance. In both experiments at Phase-II the efficiency for finding the primary vertex in top-pair events with pile-up is expected to be around 96%.

The b-tagging performance of the Phase-II detectors with $\mu$=140 is close to or better than that of the Phase-I detectors with $\mu$=50. ATLAS has studied the performance up to $\mu$=300. Without any retuning of algorithms, the light jet rejection for a given b-tag efficiency degrades by up to a factor of 3 between $\mu$=140 and $\mu$=200, and this grows to nearly a factor of 10 between $\mu$=140 and $\mu$=300. An extended beam-spot with lower pile-up density along the beam direction may help primary vertex finding, particularly when the vertex has low charged particle multiplicity; but once the correct primary vertex is identified, the long-flat beam-spot option seemed to offer little further improvement for b-tagging. The Phase-II tracking detectors bring an improvement for both experiments in muon resolution compared to Run 1. The Phase-II algorithms for $e$, $\gamma$, and $\tau$-lepton identification, however, still need more development work by both collaborations. CMS has shown that the Puppi algorithm to reject pile-up (28) is particularly effective for jet reconstruction, giving the best jet energy resolution of the algorithms studied, and eliminating jets from pile-up. Puppi weights reconstructed particles according to their likelihood to originate from pile-up before the particles are used in the jet reconstruction. ATLAS has also used track and vertex matching algorithms to reject pile-up jets. In addition, ATLAS has demonstrated that jet substructure identification algorithms continue to be effective at large pile-up. A jet mass algorithm for large radius jets allows the identification of top-quark jets. The efficiency and resolution only degrade gradually as $\mu$ increases from 140 to 300. Although most of the studies have still been performed with Run 1 algorithms, a range of further methods is considered, some of which were discussed at a recent dedicated pile-up workshop[7].

The ATLAS and CMS collaborations are studying upgrades of forward tracking and calorimetry by understanding their piecewise impact on physics analysis, leading to an optimized set of upgrades for each detector. Primary upgrades for both experiments towards exploiting the forward region include proposed extensions to the pseudo-rapidity ($\eta$) coverage of the tracking detectors.

The ATLAS collaboration is studying multiple forward tracker upgrade options varying the gross detector geometry as well as sensor granularity. Moreover, the ATLAS tracking extension studies demonstrate a 90% selection efficiency of forward jets from the primary vertex with a background rejection factor of 500 until an $\eta$ of 3.2, and 100 in the region $3.2<|\eta|<4.0$, showing that jets can be purely selected by exploiting forward tracking. The impact of the forward tracker extensions on physics analysis is demonstrated in a vector boson fusion (VBF) Higgs study, with a reduction factor of up to 3 in the expected signal strength uncertainty assuming a 90 % rejection of jets from pile-up collisions.

ATLAS also showed preliminary results on the impact of extensions to the muon spectrometer, including the addition of a new warm toroid at large pseudo-rapidity. Improvements to the muon momentum resolution are typically dominated by the contribution of the extended inner tracker at small values of muon transverse momentum. However, when using the fully proposed set of upgrades there is significant improvement to the

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[7] https://indico.cern.ch/event/306155/

muon transverse momentum resolution at high energies from the increased lever arm. The impact of this upgrade is shown in an analysis studying the $H \rightarrow ZZ \rightarrow llll$ final state, where the acceptance is increased by 35% from extending the tracking coverage to $|\eta|= 4.0$.

The CMS collaboration is pursuing a similar tracking extension in pseudo-rapidity up to $|\eta| = 4.0$ and also extending the muon coverage up to $|\eta| = 4.0$. The new tracker being proposed makes it possible to maintain the Phase-I tracking fake rate and track momentum resolution. These improvements are critical to the performance of *particle flow* reconstruction in the Phase-II upgrades, which attempts to reconstruct with best precision all charged and neutral particle content in the event. CMS is investigating two end-cap calorimeter designs. At present, both calorimeters are being studied for their performance benefits on their own and within the context of global event reconstruction.

Updated results for the HL-LHC from both experiments will be presented after evaluating the physics impact of each of the proposed upgrades, finalizing the physics simulation studies whose preliminary results have been presented in the ECFA Workshops of this and last year.

Study of the heavy flavour sector represents one of the most interesting domains for indirect searches for new physics. Substantial progress is expected in the next two decades, both from the experimental and theoretical side (with anticipated progress in lattice QCD calculations). The main experimental advances should come from the LHC experiments, thanks to the planned luminosity increases concluding with the HL-LHC upgrade, and from the BELLE-II experiment in Japan.

Analyses from Run 1 data have firmly established the major impact of the LHC experiments. LHCb has produced a plethora of results on a broad range of flavour observables in the charm and beauty sectors, and ATLAS and CMS have given significant contributions to the beauty sector, mainly using final states containing muon pairs due to constraints dictated by their triggers. One of the most striking results of Run 1 is the observation of the $B_s \rightarrow \mu^+\mu^-$ decay, through the combined analysis of CMS and LHCb data. CP violation induced by $B_s$ mixing has been measured with astonishing precision by LHCb, with relevant contributions also from ATLAS and CMS. The measurement of the $\gamma$ angle performed by LHCb is now dominating the world average, and further improvements are expected in Run 2 and beyond. The aforementioned observables are particularly interesting at HL-LHC as they are sensitive to new physics while not being dominated by theoretical uncertainties. Selected observables associated to the $B \rightarrow K^{(*)}\mu^+\mu^-$ decay channels, and observables sensitive to CP-violation (CPV) in the charm sector are also promising probes of new physics. For example, in the context of supersymmetry with a non-trivial squark spectrum and a light, natural third generation, flavour physics plays a key role: effects of the order of 5−20% are expected in CPV in the $B_{s,d}$ mixing, $B_s \rightarrow \mu^+\mu^-$, and $B_s \rightarrow K^*\mu^+\mu^-$ (29). The large number of top pairs expected at the HL-LHC further opens the possibility of new studies in $B$ physics, especially in the case of CPV, using “top-tagged $b$ decays" (30).

By incorporating knowledge emerging from the analyses of Run 1 data sets, sensitivity projections for HL-LHC operation have been updated. These show that improvements in sensitivity will come not only from increased data samples, but also from improved detection capabilities. This will lead to results of fundamental importance in the search for physics beyond the Standard Model (BSM). In the case that BSM particles are seen to be produced in LHC collisions, results in the flavour sector will provide crucial information to determine the couplings and the flavour structure of the new physics. If new particles are not observed, higher mass scales can be probed through quantum effects, giving a complementary approach to discover BSM physics.

Finally, studies of the heavy ion physics possible at the HL-LHC enriches and completes the physics programme of this machine and detector upgrades. The goal of the experiments ALICE, ATLAS and CMS is to integrate, for Pb-Pb collisions at $\sqrt{s_{NN}}$ = 5.5TeV, a luminosity of more than 10 $nb^{-1}$ after LS2. This represents an increase by an order of magnitude with respect to the expectation for Run 2. In the case of the ALICE experiment, the upgrade of the detector read-out capabilities will allow for the recording of all interactions, increasing the minimum-bias statistics by two orders of magnitude. The experiments stress the importance of a proton-proton reference sample at the same energy as Pb-Pb collisions. The ALICE requirement, driven by low-$p_T$ measurements, is for 6 $pb^{-1}$; the ATLAS and CMS requirement, driven by high-$p_T$ measurements, is for 300 $pb^{-1}$.

After LS2, the study of the Quark-Gluon Plasma formed in nucleus-nucleus collisions will focus on rare probes, on their coupling with the medium and hadronization processes. These include but are not limited to heavy-flavour particles, quarkonium states, real and virtual photons, jets and their correlations with other probes (1). New studies are now available, for example for low- $p_T$ heavy-flavour and charmonium measurements at forward rapidity in ALICE.

High-luminosity p-Pb collisions will be an essential part of the heavy-ion programme after LS2. The LHCb experiment will also contribute to this part of the programme, as demonstrated by its excellent performance during the 2013 p-Pb run. Proton-nucleus collisions allow, on the one hand, exploration of initial-state effects and low Bjorken-x gluon dynamics; and, on the other hand, study of the interplay between the initial conditions and the development of collective effects in the final state of high particle density collisions. In order to fully exploit this potential, the ALICE Collaboration is considering the technical feasibility and the physics case for a high-granularity calorimeter in the forward region ($\eta \sim 3-5$), to be installed during LS3. This detector would give access to forward-rapidity photons and neutral pions, which are predicted to be very sensitive to small-x gluon dynamics and the possible onset of gluon saturation.

## 3. Solid State Tracking Devices

The different solid state tracking detectors for the HL-LHC experiment upgrades and their associated timeline were discussed in detail in (1). The ALICE and LHCb tracking detectors will be replaced in LS2 while ATLAS and CMS will replace these detectors in LS3 with TDRs expected in 2016-17. Technical solutions for ALICE, LHCb and the outer radius (strips/strixel) of ATLAS and CMS have been established and R&D efforts are in advanced stages, while R&D for the pixel detectors is still intensive with several solutions on the horizon. In addition, a High Granularity Calorimeter (HGC) using silicon sensors has been proposed as one option to replace the CMS forward calorimeters and it will be introduced here.

The following paragraphs will concentrate on the challenges and synergies between the experiments focusing on progress in sensor development and pixel electronics design. The clear focus is on radiation tolerance, channel granularity, low mass, read-out bandwidth and trigger rate.

While the R&D on silicon sensors for all HL-LHC detectors continued to greatly benefit from the RD50 collaboration, the pixel electronics development is another common ATLAS and CMS endeavour which is now embedded in RD53.

## Sensors

The R&D for the ATLAS and CMS strip sensors, which are intended to be used to cover the outer radii of the Inner Detectors, is basically finishing and has converged on the use planar n-in-p sensor technology. A common CERN Market Survey (MS) is in preparation to identify potential suppliers. The following table gives an overview of the current options for all HL-LHC tracker sensor technologies. Only ALICE, with a reduced requirement on radiation tolerance, will use Monolithic Active Pixel (MAPS) in CMOS technology for the whole tracking system (~10m$^2$). This system is very advanced and full-scale prototypes exist. The MISTRAL and ALPIDE chips/sensors show excellent behaviour in beam tests. Optimization of charge over capacitance to minimize analogue power has been completed.

| | **Strips/Strixel baseline / options** | **Pixel outer layers baseline / options** | **Pixel inner layers baseline / options** | **Special** |
|---|---|---|---|---|
| ALICE | MAPS (Monolithic Active Pixels) | | | |
| ATLAS | **n-in-p planar**<br>FZ 300µm thick<br>AC-coupled<br>and/or HV/HR-CMOS | **n-in-p/n planar**<br>and/or HV/HR-CMOS | **n-in-n planar**<br>100-200µm active thickness<br>and/or HV/HR-CMOS<br>and/or **3D**<br>and/or diamond | |
| CMS | **n-in-p planar**<br>FZ 200µm *active* thickness AC- and DC-coupled<br>and/or MCz (pref)<br>and/or 300µm | **n-in-p planar** 100-200µm active thickness | **n-in-p planar**<br>100-200µm active thickness<br>and/or **3D** sensors | **HGCAL**<br>p-in-n planar<br>DC-coupled large PAD sensors 100-300µm active thickness (deep diffused) or n-in-p (also deep diffused) |
| LHCb | UT **planar n-in-p**<br>or p-in-n | VELO **planar n-in-p**<br>or n-in-n | | |

Optimisation of the innermost pixel sensors provides an area with further opportunities to exploit synergies between experiments. LHCb is fairly advanced, needing to have a detector ready by LS2. A variant of the MEDIPIX chip, the VELOPIX, will be used with an n-in-p or n-in-n 55x55μm cell sensor technology while reading the whole detector at 40MHz. For ATLAS and CMS, the current technology options under study for the inner pixel sensors are diamond, planar silicon or 3D silicon sensors, where trapping will be the largest challenge. The outer pixels layers could be equipped using planar silicon technology. For all regions, ATLAS is also evaluating sensors based on HV/HR-CMOS processes. Convergence on technology choices is expected in the next 18 months.

The critical R&D topics, where good communication between the different experiments is highly beneficial, will be described here. The sensor pitch option of 25μm is a new challenge where cell isolation and breakdown voltage have to be proven. Biasing options will be evaluated, but it now looks possible that the need for a bias grid could be avoided. Bump bonding techniques seem established, as long as the bump pitch remains around 50μm. The pitch however is a challenge for 3D sensors due to the aspect ratio of pitch over column width. A smaller pitch results in thinner 3D electrode columns for which the maximum etching depth needs evaluation. This depth defines the volume for the charge collection, which is the advantage of 3D over planar sensors. Common ATLAS/CMS R&D sensor submissions are ongoing. At high bias voltages, n-in-p sensors are subject to sparking and a reliable solution – industrially applicable – has to be found. Sensors processed on 8” wafers are also explored together with thinning these sensors – bowing will be an interesting challenge and as will the need to explore the limits with respect to bump bonding.

### HV/HR-CMOS Sensors

Monolithic active pixel sensors (MAPS) are used in the ALICE upgrade, but until recently did not seem radiation tolerant enough for use in ATLAS or CMS. This improved when processes referred as high-voltage (HV) and high-resistivity substrate (HR) allowed for drift-based rather than diffusion-based charge collection. Potential improvements with respect to the passive hybrid sensor baselines are cost reduction, improved resolution and material minimisation. In spite of the tight timescale until production start, the ATLAS collaboration has decided to explore a variety of processes as candidates for both strip and pixel sensors. Due to truly monolithic chips being too complex, it has been decided to target “hybrid” detectors first, with a separate read-out chip (e.g. FE-I4 for prototyping and then RD53-P1) for the trigger handling and data storage – while the amplification and partially also the discrimination functions are built into the active “sensor”. ATLAS aims at producing a representative size “demonstrator” by the end of 2015. This must provide the necessary input to decide by the time of the TDRs (2016-2017) whether HV/HR-CMOS sensors could be a viable solution.

Recent prototype results show promising efficiency and charge collection values also after irradiation and a significant improvement on noise and achievable minimum threshold compared to earlier test chips. Capacitive coupling to FE-I4 and CLICPix by means of gluing has proved successful with glue layers of only a few μm thickness. Together with industrially available chip thinning, this would allow creation of very thin (50 μm sensor + 50 μm ROC) bare modules at reduced interconnect cost. A first strip-like prototype has demonstrated that on-sensor address encoding can enable reaching pixel-like resolution with strip-like read-out without the need for full-area read-out chip coverage. A remaining issue concerns the ability and the yield to produce larger size sensors and in particular for large area usage in the strip region, the cost benefit of a hybrid system remains to be established.

Other topics requiring enhanced attention are system aspects, e.g. due to the power dissipation being significantly higher than that of passive sensors leading to new conditions for the cooling system. In general, the impact on the detector configuration is considered to be substantial and it is being actively investigated.

In addition to the ATLAS efforts, work starts also to be coordinated within RD50 and synergies exist with CLIC and mu3e detector R&D. The timescale for the demonstration of successful operation under HL-LHC conditions appears still extremely tight.

## Electronics

Electronics for the future pixel system pose new and so far still unaddressed issues. The different challenges and synergies can be seen in the table below. Radiation tolerance of the proposed 65nm architecture has still to be demonstrated; first results are encouraging, but also point to potential issues. The RD53 collaboration here is key to success. Bump bonding should be feasible in industry with a common pixel chip cell of $50x50\mu m^2$ serving $50x50\mu m^2$ or $25x100\mu m^2$ sensor cells. Buffering (latency) and high read-out rate are definitely challenging. Buffering and logic will be implemented locally (clusters of pixel cells). The chips will be more and more digital-like with isolated islands of analogue circuits. A good balance of the read-out capability and the necessary services (~material budget) has to be sought, and data compression is an R&D topic. Targeted R&D efforts on lightweight and high data transfer cables should be strengthened. This is particularly true for the development of electrical links driving the signals from the pixel chips to the optical transmitter placed further out in the tracking volume. Single event effects for the control parts have to be taken into account although experts agree that a triple redundancy is not necessary for the read-out out cells per se and solutions in 65nm exist.

Another very important aspect to minimise the tracker material, is the development of pixel electronics powering (multi-stage DC-DC or serial powering). This is motivated by the increase in power consumption due to the larger area of the detectors and the much larger number of channels.

| | **Bump pitch µm** | **Pixel size µm** | **Trigger rate** | **Read-out** | **Mass / layer % X0** |
|---|---|---|---|---|---|
| **ALICE** | Monolithic | 30 x 30 | 1/30 µs | All data w/rolling shutter or priority encoder | ~0.3 (*) |
| **LHCb** | 55 x 55 | 55 x 55 | 40 MHz | All data | ~0.5 (*) |
| **ATLAS** | 50 x 50<br>50 x 100 | 50 x 50<br>or 25 x 100<br>50 x 100 | 1 MHz | Triggered time stamp | ~1.0 |
| **CMS** | 50 x 50<br>100 x 100 | 50 x 50<br>or 25 x 100<br>100 x 100 | 1 MHz | Triggered time stamp | ~1.0 |

### High-granularity Calorimeter HGCal

CMS is evaluating the possibility of building a forward high granularity calorimeter with hexagonal silicon pad sensors. Hexagonal sensors versus rectangular have the advantage to maximize the use of wafer surface necessary for a system planned to span ~760m$^2$ of active area. Pad sizes would be around 0.5-1 cm$^2$ with sensor active thicknesses of 100-300µm realized using deep diffusion technology on FZ wafer material depending on the radius and radiation environment. Unprecedented levels of predominantly neutron radiation will be encountered and the impact of this is currently under evaluation. The sensors will be operated at a temperature of -30$^o$C and cell sensitivity from 1 to about 5000 minimum ionising particles is necessary.

Also ALICE is investigating a silicon based very forward calorimeter smaller in area but even larger in numbers of channels.

## 4. Scintillator-based Detector Developments

Scintillator-based detectors are planned for use in both tracking and calorimeter systems at the HL-LHC. In LHCb an upgrade to the tracking system based on scintillating fibres is moving into construction. ATLAS and CMS are evaluating the performance of their existing calorimeters and, in the case of CMS, investigating new scintillator-based calorimeter systems for future operations at the HL-LHC. We present here a brief summary of progress in two areas: radiation damage effects to calorimeters and the implications for calorimeter performance at the HL-LHC; the use of small diameter scintillating fibres in a large area tracking system for the LHCb upgrade.

### Scintillator-based Calorimetry

The preparatory group reviewed the progress made in understanding the current performance of scintillator calorimeters and the expected performance at the HL-LHC for the calorimeter systems proposed for use in that environment. Particularly, the CMS electromagnetic and hadronic calorimeters in the end-cap regions will need to be replaced due to radiation damage and vigorous R&D to identify suitable radiation-tolerant technologies is continuing. For plastic scintillator, the effect of radiation damage on the sampling systems which form the hadronic calorimeters in ATLAS and CMS has been a main focus of discussion in the context of the HL-LHC. Both ATLAS and CMS have detailed predictions for absorbed dose and expected light losses in their calorimeters based on gamma and hadron irradiations. A dose/damage curve, which is representative of the expected radiation damage in ATLAS can be found in the SDC Technical Report (31). The damage shows a reduction in signal of a few % for doses lower than about 50 krad, with an expected maximum light reduction at HL-LHC of 15%. The dose/damage curve for CMS (32) can be compared to the ATLAS curve for doses greater than 0.1 Mrad where both experiments observe similar loss of response as a function of absorbed dose. This degradation is monitored by calibration systems based on radioactive sources that allow corrections to be implemented. These calibrations are taken at a frequency of 1 per month to 1 per few months and therefore provide information largely on permanent damage.

At the end of Run 1, ATLAS measured a radiation-induced signal loss of ~2% for an absorbed dose of 2.2 krad in the most irradiated cell. CMS measured a similar signal loss of ~5% for an absorbed dose of 3 krad in the barrel hadron calorimeter.

A major difference of the two experiments is the pseudo-rapidity coverage and geometry of the scintillator calorimeter systems. ATLAS extends to $|\eta|=1.6$, while CMS extends to $|\eta|=2.8$, and the inner radius of the hadron calorimeter ($R_{inner}$) in ATLAS is 2.2 m, while for CMS the inner radius of the scintillator tile closest to the beampipe ($R_{inner}$) is 0.40 m. Consequently the maximum doses seen in the ATLAS hadron Tile calorimeter are ~100 times smaller than those in the CMS hadron scintillator calorimeter. For CMS, the absorbed dose in the highest $\eta$ cells is 0.1-0.2 Mrad for the 25 $fb^{-1}$ of delivered luminosity in Run 1. The cells in this region showed a 30% loss of signal, about three times higher than predicted. After 3000 $fb^{-1}$ at the HL-LHC, the highest dose in the ATLAS Tile Calorimeter is expected to be 0.2 - 0.3 Mrad. Although the measured loss of signal for this dose in CMS is larger than the ATLAS expectation (30% measured by CMS compared to 15% expected by ATLAS), the light output of the ATLAS Tile Calorimeter (33) is sufficient that, even for this increased level of damage, there should be no impact on the calorimeter performance through HL-LHC operation.

Initial radiation damage can be recovered with time as discussed in many references in the literature. However, no significant recovery was observed by CMS, even in cells with the largest signal loss. The situation is inconclusive in ATLAS due to the small dose levels, and therefore small levels of loss observed. The radiation dose at the end of Run 2 will likely allow a first statement by ATLAS on this question. Overall, the major source of changes in cell response in ATLAS is due to the photomultiplier gain variations, which are corrected with a laser calibration system.

For what concerns the electromagnetic calorimeter, CMS will be replacing its end caps. The present lead tungstate crystals are expected to suffer a progressive loss of transmission due to the exposure to the large hadron fluences that will be accumulated over the years of HL-LHC running. A scintillator-based calorimeter is being developed for this upgrade, in a Shashlik geometry, with alternating plates of tungsten absorber and inorganic scintillator, light being extracted by wavelength-shifting fibres or capillaries running either through holes or along the chamfers of each cell. At this time, two inorganic scintillators are being considered: LYSO:Ce and $CeF_3$. The major advantages of LYSO are brightness and density. The merits of $CeF_3$ include its spontaneous recovery of damage from ionizing radiation and hadron exposure, while in LYSO the latter is cumulative, but a factor 5 smaller than for lead tungstate. The Shashlik geometry also helps reducing the effect of damage through a light path which is shorter by a factor ~10 with respect to a homogeneous crystal calorimeter. The scintillation decay time constant is ~ 30 ns in $CeF_3$ versus 40 ns for LYSO. The peak emission is at 430 nm for LYSO and in the ultraviolet (310-340 nm) for $CeF_3$ so different wavelength-shifting materials are needed depending on the scintillator adopted. Present R&D concerns the development of WLS material, mainly Ce-doped quartz to be used with $CeF_3$, and capillaries filled with liquid WLS for LYSO. Physics performance is being studied on prototypes that already went through a first test beam campaign in 2014.

## Scintillating Fibre Tracking

Scintillating plastic fibres (SciFi) as active elements in tracking systems have been exploited for more than 30 years (34). They allow building intrinsically fast and particularly low mass detectors with a high degree of geometrical adaptability. On the other hand, the achievable spatial resolution is correlated with the fibre diameter and hence with the light yield, unless one conceives staggered multi-layer fibre arrangements which come at a cost in terms of number of read-out channels and material budget. A further limitation is the moderate radiation hardness of plastic scintillators which prevent their use in very harsh environments. The dramatic evolution of photo-detection technology, currently culminating with the SiPM devices, has revived the interest in the SciFi technology and opens up new fields of application. The intrinsic properties of the SiPM, in particular the combination of high sensitivity, high gain and fast response, implemented in a solid-state sensor of sub-mm$^2$ size, allow designing large-scale high-resolution SciFi detectors that can be read out at LHC speeds.

LHCb is developing a large planar SciFi tracker that will, from LHC Run 3 onwards, replace the current Outer Tracker (gas straw tubes) and Inner Tracker (Silicon microstrips) by a single detector technology (35). The detector consists of blue emitting scintillating plastic fibres of 250 µm diameter, 2.5 m long and mirror coated at one end. The scintillation light exiting at the other end is detected by linear arrays of SiPM detectors (128 channels of 0.25 x 1.6 mm$^2$ size). The hit efficiency is directly linked to the amplitude of the signals (measured in photoelectrons) and the minimum threshold at which the photodetector can be operated. The ghost rate is related to the noise cluster rate, which depends again (but not only) on the threshold applied to the photodetector. In a harsh radiation environment, as expected at LHCb, the operation and the achievable performance of the detector are fully governed by radiation related effects. The ionising dose (up to 35 kGy in the inner region close to the LHCb beampipe) degrades the transparency of the scintillating fibre and hence the amplitude of the detectable signal. The SiPMs, located more than 2.5 m above and below the beampipe, are exposed only to small ionizing doses, however they suffer from a neutron fluence of up to $1.2 \cdot 10^{12}$ cm$^{-2}$ (1 MeV equivalent). Proportional to the neutron fluence, the leakage current (or, equivalently, the dark noise rate) of the SiPMs rises to values which de facto makes them unusable. ‘Normal’ operation can be restored by cooling the SiPMs, which suppresses the noise rate by a factor of about $2^{\Delta T/10}$. The SiPMs in the LHCb SciFi Tracker are therefore foreseen to operate at -40°C.

Technology has been developed to allow cost-effective winding of large area fibre mats together with instrumentation to measure and control fibre location in a semi-automatic fashion. In many tracker designs, the performance is still limited by moderate scintillation yield, optical attenuation length and radiation hardness. Recently a Russian group developed a novel type of plastic scintillator, in which Nanostructured Organosilicon Luminophores (NOL) are admixed to the polystyrene (PS) matrix (36). The NOL approach couples activator and wavelength shifters via bridges of Silicon nanoparticles to dendritic antenna structures. These authors report that different NOL formulations give up to 49% higher light yield and at the same time reduced decay time constants compared to standard scintillator formulations. Further measurements need to be performed with minimum ionising particles and the radiation tolerance needs to be established. If NOL material is found to maintain its appealing properties also in fibre form, this would be an attractive option for the LHCb SciFi tracker.

## 5. Timing Devices

At the High-Luminosity-LHC (HL-LHC), about 140-200 concurrent collisions per beam crossing will take place with vertex densities along the beam axis above 1 mm$^{-1}$. At these densities, some vertices and their associated particles will be merged forming fake jets of high transverse momentum. Moreover, the random overlap of energy deposits from neutral particles (mainly photons), that cannot be tied to any vertex, will deteriorate the calorimeter performance in terms of energy measurement and particle identification, as particles appear to be less isolated. On the other hand, collision vertices also have a time spread of order

200 ps due to the length of the colliding bunches (37). The addition of timing measurements, with a resolution of order 10 ps, for the energy deposits in the calorimeters and of the vertex times, from the that of the associated charged particles, could thus reduce the ‘effective multiplicity’ of concurrent collisions down to a level comparable to current LHC operation.

This measurement is being considered as an addition to the upgrade programme of the ATLAS and CMS detectors. Where the calorimeters will be replaced, the option for accurate time measurement could be embedded in the new design (38) (e.g. a fast-timing layer, or dedicated timing electronics). Alternatively a designated pre-shower could be added in front of the calorimeters. The typical size of these detectors in the end-cap regions, where the impact of pile-up is more severe, would be of order 10 $m^2$, with read-out granularities of 1 $cm^2$. Several devices with fast-time response are being studied in R&D programmes, and several options exist, including micro-channel plate (MCP) devices (39), fast-avalanche silicon detectors (40), (41) and micro-megas devices (41). Similarly, read-out approaches − either based on analogue time-pickoff circuits coupled to time-to digital converters or on fast analogue-to-digital samplers followed by a digital time-pickoff method − exist with time performance matched to the requirements at the HL-LHC.

Preliminary studies of the performance gain offered by precise timing have started (42), and should be finalized in the course of 2015 by ATLAS and CMS. Full qualification for the high radiation environment of the devices and electronics read-out options should follow, as well as designated studies of system aspects, including time calibration, and clock distribution and channel response jitter, that should be kept to the level of 10 ps.

Detectors with excellent timing capabilities have been exploited in experiments at colliders for particle identification with time-of-flight systems. One notable example at the LHC is the ALICE-TOF (43), which has set a reference for large-area timing detectors with a per-track resolution of 80 ps over 140 $m^2$ and about $10^5$ read-out channels. The per-track resolution − limited only by system aspects –achieved *in-situ* is better than the target design and no upgrade is planned. A new TOF station, aiming at a per-track resolution of 15 ps, is instead being considered for the upgrade of the LHCb experiment. The proposed detector, TORCH (44), makes use of Cerenkov emission in quartz bars, read-out at one end through internal reflection. At the read-out end, a pixelated MCP phototube is expected to provide a per-track resolution of 15 ps by combining the measurement from about 30 photoelectrons per track. To achieve this goal on about $10^5$ channels, system aspects should be controlled to a comparable precision. The TORCH R&D programme, in addition to being relevant on its own, will therefore provide valuable inputs to other fast-timing based upgrade plans towards HL-LHC.

## 6. Calorimetry with Liquified Noble Gases

Ionization sampling calorimeters, with a sensitive medium such as liquid argon, have good energy resolution and excellent stability.  Many have been deployed in major high energy physics detectors since Willis and Radeka introduced them in 1974 (45).  Under normal operating conditions the current pulse at the electrodes, plotted versus time, is a triangle with a sharp rise followed by a fall which reflects the time for an ionization electron in the applied electric field to drift across the electrode gap.  The pulse shape is invariant and the pulse amplitude is proportional to the energy deposited in the calorimeter.

During LHC Run 1 the ATLAS liquid argon calorimeters were observed to be stable below the 0.05% level up to instantaneous luminosities of about 70% of the design value and up to an integrated luminosity of about 20 $fb^{-1}$. As the LHC luminosity improves, with expectations to exceed the design value by almost an order of magnitude within the next decade, the detector builders are asking to what degree the various detector elements will degrade with accumulated exposure and will be impaired due to the higher rates.

Two R&D projects have probed the behaviour of liquid argon at ionization rates in excess of those experienced so far. The Positive Ion Buildup (PIB) project uses high activity beta sources to ionize the liquid argon at rate densities above that at the worst location in the ATLAS calorimeter, i.e. in that part of the forward calorimeter closest to the beam line. In a test run in a small cryostat lasting more than 10 months, an ATLAS-style electrode measured the ionization current which was stable at the 0.1% level, after correcting for the decaying activity of the source (half-life of 29 years), for an equivalent exposure of 330 $fb^{-1}$.

In the HiLum project, conducted at the IHEP U70 synchrotron in Protvino, an intense extracted proton beam was sent into successive layers of absorbers and calorimeter mock-ups, equivalent to instantaneous ionization rates well in excess of that expected at any time during the lifetime of the ATLAS detector. After several days at the highest rates the Electromagnetic End-cap (EMEC) calorimeter mock-up received an exposure equivalent to about 1000 $fb^{-1}$. While analysis is not complete, so far there is no indication of degradation.

These two R&D projects also investigated the only known impairment the ATLAS calorimeters might experience at the HL-LHC, i.e. space-charge effects. By varying the potential across the liquid argon gap, the PIB project was able to determine the threshold for entering the space-charge regime to good accuracy. This threshold is parameterized by the positive Argon ion mobility which was found to be $\mu_+ = 0.08 \pm 0.02$ $mm^2/Vs$. A paper describing these PIB results has been submitted to Nucl. Instrum. and Methods A.

The HiLum project measured the amplitude and shape of the calorimeter pulses while in the space-charge limited regime. Here the pulse shapes vary markedly from the clean triangle shape observed below the space-charge threshold. The pulse amplitude is no longer proportional to the energy deposited in the calorimeter, the main part of the pulse shortens, and a tail develops which is longer than the invariant triangle pulse. It is, however, possible to increase the space-charge threshold above any ionization rate that will ever be seen in ATLAS running. Decreasing the liquid argon gap is the most practical method.

In conclusion, liquid argon calorimetry is well suited to high luminosity operation. The performance does not degrade up to exposures tested so far. Also the performance is not impaired at the highest instantaneous luminosities, tested well above the range expected in ATLAS, as long as space-charge effects are avoided by choosing a suitable gap width. If the space-charge regime cannot be avoided, then the pulse amplitude is no longer proportional to the energy deposit and the pulse shapes are distorted. Corrections for this behaviour will depend on the location in the calorimeter and on the short-term history of the ionization rate.

## 7. Progress with Gaseous Detector Systems

Gaseous detectors are widely used at the LHC experiments, especially for the large areas needed for the muon detection. Most of these systems belong to one of the three following configurations:

- Drift tubes (DTs) employed in the muon systems of ATLAS and CMS, in the ATLAS Transition Radiation Tracker and in the LHCb Outer Tracker;

- Multi-Wire Proportional Counters used in the ATLAS and CMS Cathode Strip Chambers for tracking, in the LHCb Muon System and in the ALICE Time Projection Chamber, Transition Radiation Detector, RICH detector and Muon Tracking Chambers;
- Resistive Plate Chambers (RPCs) installed in the large Muon Systems of ATLAS, CMS and ALICE for Triggering, and in the ALICE Time Of Flight system (TOF).

An exception to this picture is the innermost region of the first station of the LHCb Muon System, where, due to the high particle rates, it was decided to install Micro-Pattern Gas Detectors (MPGDs), in this case based on Gas Electron Multiplier technology. Another impressive application is the ALICE Time Projection Chamber (TPC), which is a very performant device for heavy ion physics.

All these devices have of the order of 100k to 1M read-out channels and are operating with high efficiency at the LHC. However, since their installation, several technology aspects have substantially improved. These are in particular:

- The read-out electronics (integration, radiation resistance).
- The understanding and optimization of the detector configurations based on performant simulation tools such as Magboltz, HEED and Garfield.
- The improvement in ageing characteristics due to the development of special gas mixtures.

Gaseous detectors have also regained territory that was occupied by other technologies, for instance RPCs are now used to replace scintillators for triggering and time of flight measurements in large area systems.

After LS2 and LS3 the currently installed gaseous detectors may run into limitations at the increased luminosities, such as those due to occupancy, space charge effects (for wire chambers) and voltage drops (for RPCs), and ageing and drift distortions due to ion backflow. Three options exist to overcome these limitations:

- Upgrade of the read-out electronics with improved performance (ALICE TRD and Muon System), better trigger capabilities (CMS DTs) or lower noise (RPCs operation at low gas gain and thus higher rates).
- Use of finer granularity detectors to cope with the higher rates (ATLAS reduced diameter MDTs for higher occupancy regions of the current spectrometer and small strip TGCs for the New Small Wheels) or RPCs with thinner or lower resistivity electrodes.
- Introduction of Micro-Pattern Gas Detectors (MPGDs) as in the ATLAS New Small Wheels (MicroMegas), ALICE TPC (GEM), CMS forward Muon system (GEM) and LHCb Muon System (GEM).

### Development of a New Generation of Resistive Plate Chambers for High Radiation Environments

The RPC is a unique gaseous detector due to the absence of any drift time and, therefore, an ideal detector for fast decisions and for very high time resolutions. Moreover, the simple structure and low material cost make it suitable for very large area applications. A new generation of RPCs is in preparation to face the requirements of the HL-LHC concerning rate capability, space and time resolution. The RPC rate capability is mainly limited by the current that can be driven by the high resistivity electrodes. It can be improved with lower resistivity and thinner electrodes, and with lower liberated charge. With lower bulk resistivity the detectors can operate at higher current. However this may increase the detector aging. A new robust ageing test is required to qualify RPCs for a high current working mode. Reducing the electrode thickness has in principle a similar effect as reducing the resistivity, with the advantage of increasing the induced signal. Smaller average charge allows increasing the rate capability at constant current thus avoiding ageing enhancement. This requires the front-end electronics to have an excellent sensitivity and signal to noise ratio. Moreover a very careful optimization of the chamber structure as a Faraday cage is needed to shield external noise sources. Thinner gaps can reduce the delivered charge and at the same time improve the timing. The lower charge can be compensated by a multiple gap structures.

The RPCs that ATLAS and CMS are envisaging for the Phase-II of LHC will have an overall structure similar to the present ones but with gas volumes of: thinner gaps, thinner electrodes and also, possibly, a multi-gap structure if required to achieve good detection efficiency. A RPC of 1+1 mm bi-gap, and sensitive area of 18x18 cm$^2$, built with HPL phenolic electrodes from residual ATLAS plates and equipped with a new front end circuit was installed at about 40 cm distance from the gamma source at the GIF facility and tested for several weeks. The rate measured at full efficiency was about 20 kHz/cm$^2$, which is a major improvement with respect to the RPCs presently operating in ATLAS and CMS. A similar test was carried out by CMS by modifying its standard “two parallel gaps” structure. Each gap was split into two gaps of 0.8 mm thickness; the prototype, of active area 45 x 45 cm$^2$, was built with standard HPL and front-end electronics. It showed an efficiency plateau of ~ 1 kV with streamer probability < 2 % in the middle of the efficiency plateau and a rate capability of 3 kHz/cm$^2$.

CMS is also investigating RPCs produced using semi-conductive silicate glass with a $10^{10}$ Ωcm resistivity, significantly lower that for standard borosilicate (float) glass and essentially comparable to the value for HPL. Tests performed with a localized beam have shown promising results with, for the multi-gap configuration, a rate capability exceeding 10 kHz/cm$^2$ and a time resolution better than 100 ps. Tests to measure their performance in conditions of uniform irradiation are foreseen in the coming year.

The RPC tracking capability achievable with the charge centroid method was also measured at a muon beam. A quadruplet of small chambers with 8 mm pitch strips, 1 mm gap and 1.8 mm thick ATLAS standard electrodes was used in the test. The track residuals distribution gives a spatial resolution of $\sigma = 132$ μm for a single chamber. The time resolution of the same chambers, measured in a high irradiation environment, was $\sigma_t = 420$ ps at 3 kHz/cm$^2$, consistent with the value measured with cosmic rays. These results should be easily extended to large area chambers and it is expected that the time resolution can be improved by a factor 2-3 using 0.5+0.5 mm bi-gaps, while much higher resolutions typically of 20 ps, have been achievable with very thin multi-gaps. To pursue this R&D line would, however, require, clearly establishing the expected benefits.

A new front-end electronics, with an excellent signal to noise ratio, is crucial and a new family of components, based on Silicon-Germanium technology, is presently available and seems very promising. A full custom Si-Ge integrated circuit, optimized for RPC read-out, is under development.

Finally the search for new working gases with high performance and low environment impact has already been started and looks very promising.

### Precision Micro-Pattern Gaseous Detectors (MPGD) for Large Areas

For the LHC upgrades, MPGDs are proposed for the regions exposed to the highest rates and/or where high spatial resolution is needed. Out of the many different types of MPGD available, Gas Electron Multipliers

(GEM) have been proposed to be used in ALICE and CMS and exploited already in LHCb; while the Micro-Megas (MM) technology has been chosen for ATLAS.

In ATLAS, the New Small Wheels (NSW) will be equipped with both sTGC and MM detectors to offer excellent robustness under HL-LHC operating conditions. The MM detectors combine precision tracking functionality with trigger capability in a single device. In total, 512 Micro-Megas chambers, each with a surface area up to 3.1 $m^2$, will be built, corresponding to a total detection area of around 1200 $m^2$, with ~ 450 µm strip pitch and 2.1 M channels overall. The main issue to be addressed for using MM detectors in high energy experiments, like ATLAS, is sparks. Sparks or discharges lead to HV breakdown with relatively long recovery times and sometimes damage to the detectors themselves. The final approach chosen to overcome this problem is based on resistive strip layer techniques to AC couple the read-out strips. In ATLAS, MMs will be operated with the µ-TPC schema, i.e. using the arrival times of the ionized electrons to reconstruct the position of the primary ionizations and thus the particle track in the drift gap of the detector. This improves the spatial resolution, in particular for tracks incidence above 10°. ATLAS has also developed the floating-mesh production technique which successfully overcomes a number of previously encountered problems and allows an easy reopening of the detector, if required.

GEMs are characterized by spatial resolution of order 100 µm, time resolution of a few ns, and detection efficiency more than 95 % even for rates exceeding a few $MHz/cm^2$. In order to make GEM detectors suitable for HL-LHC and particularly for the CMS Upgrade, many technology breakthroughs have had to be achieved, for instance the production of large-area GEMs with a single-mask technique has been demonstrated. A novel spacer-less and stretching technique has also been developed that allows production of large-area triple-GEM detectors without any gluing. Furthermore using these techniques allows reducing the production time to a few hours and permits easy reopening of a chamber if necessary.

In CMS, GEM detectors (double stations) have been proposed in yet un-instrumented locations in the end-caps, to cover the pseudo-rapidity range $1.5 < \eta < 2.2$, for robust tracking and triggering with improved muon momentum resolution in order to restore redundancy in the muon system. Also, an additional six-layer station is foreseen to be installed in a space of around 30 cm freed behind the new end-cap calorimeters, providing coverage up to $\eta = 3$ or more. Several test beam campaigns have now demonstrated that GEMs are suitable for these applications and long term tests corroborate earlier measurements.

In LHCb, GEMs have already been operating, with twenty-four triple-GEM detectors with a 24x20 $cm^2$ active area, in the inner region of the first station of the Muon System, with an excellent and stable performance during the whole of Run 1. The plan is to install new GEM detectors in the second station of the same Muon System, replacing part of the forward MWPC inner layer. Particular care will also be required in studying possible replacements of the $CF_4$, currently used in these detectors, which might be progressively phased out by the European Community regulations, and tests have already started.

In ALICE, GEMs will not be installed in the Muon System, but will replace the MWPC based read-out chambers for the Time Projection Chamber. The goal is to reach 50 kHz operation in Pb-Pb collision. The GEM detectors have to be optimized for low Ion Back Flow (IBF < 1%), and therefore the interplay between geometry, fields and diffusion must be carefully optimized. In addition, GEMs in the ALICE TPC will have to provide an energy resolution better than 12%, to maintain the dE/dx resolution for charged particle tracks in the detector. The baseline solution is detectors based on quadruple stacks of GEM foils with different hole pitch.

In conclusion, MPGDs have reached full maturity and are now ready to be exploited for the HL-LHC upgrades.

## Wire Detectors for Triggering and Tracking at HL-LHC

Operating wire detectors at the upgrade luminosities poses concerns in terms of rate capability and ageing properties. However, the main reason for upgrading wire detectors is the need for improved granularity to avoid the saturation of channel occupancy and, in ATLAS and CMS, also to allow for a more selective muon trigger through a better $p_T$ resolution and a better ability to reject fake muon candidates. In two cases, barrel Monitored Drift Tubes and end-cap Thin Gap Chambers in ATLAS, it was decided to redesign part of the detector with increased granularity. This has the advantage that the existing service and software infrastructure can be easily re-used. Moreover, thanks to the experience gained with the current MDTs and TGCs, it was possible to optimize the detector design towards a more robust and cost-effective production process. Improved mechanical accuracy needed to achieve the required higher granularity has been demonstrated on prototypes. The sMDT detectors needed for Phase-I upgrades to the current system require 12 middle layer and 32 inner layer chambers, which are in construction, while the mass production of the sTGC needed to instrument the new ATLAS Small Wheel is already starting.

Extensive studies have and are being carried out to validate the operation of the wire detectors that will not be replaced for the HL-LHC operation. So far, space charge effects are proven to be under control for detectors with small drift volume. The LHCb MWPCs will experience the highest particle rates for wire chamber detectors at the LHC. During tests performed on the current detectors in 2012 at 1 x $10^{33}$ $cm^{-2}$ $s^{-1}$ (half the maximum upgrade luminosity) these chambers were operated with rates up to 200 kHz/$cm^2$, and the efficiency drop due to space charge effects was measured to be only 2%. On the other hand, in most cases, to increase the rate capability will require an upgrade of the read-out electronics.

Detector operation is not expected to be affected by ageing effects for the integrated charge foreseen at HL-LHC. However for some detectors further irradiation tests are being performed to assess safety margins. Prototypes of the new ATLAS sTGC and sMDT were recently exposed to an integrated charge of 6 C/$cm^2$, five times more than that expected for 20 years of HL-LHC, without discernible performance degradation. The CMS CSC group is starting a new irradiation campaign at GIF++ during 2015. Similarly to the studies being carried out for the GEMs, the goal is also to test possible replacements of the $CF_4$ gas, which can drastically improve ageing properties, but whose use could be limited in the future due to new eco-safety regulations.

## Trends and Synergies in Gaseous Detectors R&D

For HL-LHC operation, the development of a new generation of gaseous detectors with improved performance has been made easier thanks to proper environments where groups performing R&D on various detectors can meet and exchange ideas; an example being the RD51 collaboration in the field of MPGDs. A similar collaboration is being proposed for RPCs, in addition to the already existing biennial RPC workshops. Of course, the ECFA meetings and the preparatory groups have also provided an excellent opportunity for exchanging ideas and exploring such synergies.

Particularly important is the new Gamma Irradiation Facility in preparation at CERN (GIF++), foreseen to be operational from 2015. Setting-up a common facility to test the novel or existing detectors in conditions close to those expected at HL-LHC is a great success. This will be a natural place to share experience across experiments.

Another common issue is the quest for new eco-friendly gas mixtures. Investigating new possible candidates which will replace $C_2H_2F_4$ (for RPCs) and $CF_4$ (for GEMs and Wire Chambers) will require a long R&D, since many gases and gas mixtures should be tested. Complementary tests have already started in various laboratories around the world (CERN, Frascati, Ghent, Rome) and have brought the first fruitful results. For instance, the ATLAS groups presented tests on mixtures containing tetra-fluoropropane, which are already quite promising.

## 8. Summary on Electronics

The demands on the upgraded experiments in terms of impact parameter resolution, channel count, hermeticity, tracker mass, timing resolution, trigger and data read-out rates, radiation hardness etc, will place severe constraints on the required electronics. This will necessitate the design of detector specific read-out ASICs and systems, as well as specific R&D activities on electronics in the following fields:

i) Very deep sub-micron technologies (e.g 65 nm and lower)
ii) High density, low mass interconnect and hybrid technologies
iii) Radiation hardness
iv) High reliability design and qualification
v) Efficient power distribution systems and low power design techniques
vi) Low power, high speed electrical and optical links
vii) Modular electronics standards for high speed data back-end processing

The material on these topics is organised first to cover the progress made for trackers, calorimeters and muon detectors. Then progress on IC design and technologies, and the high-speed optical and electrical links is described including a discussion on use of FPGAs in the experimental caverns.

### Electronics for Outer Trackers

The 2013 report included comprehensive coverage on the upgrade electronics for all the silicon detectors, so this report presents an overview of more recent progress. Note, however, that electronics for the pixel detectors is described above in the solid-state detector section. Developments described below include those on-going for the Phase-I upgrades of the ALICE TPC and the LHCb Upstream Tracking (UT) and scintillating fibres detector and for the Phase-II upgrades of the higher radius ATLAS and CMS trackers.

The ALICE TPC upgrade aiming at a continuous or triggered sampling at 10 MHz is based on a new front-end ASIC and the extensive use of the GBT and the versatile link components. The front-end chip, called SAMPA, is a 130 nm CMOS ASIC. It handles 32 channels, each of them containing an amplifier-shaper followed by a 10–20 Msps ADC. The read-out is serial (4 320 Mbps links).

Two developments in 130 nm CMOS technology are on-going for the LHCb UT and scintillating fibre trackers: the SALT (128 channels) and PACIFIC (64 channels) chips. The GBT and the Versatile Link components transfer the large amount of data from the detector to the counting room, while radiation-hard DC-DC converters (FEAST2) power the front-end modules.

The CMS outer tracker upgrade consists of two different types of modules: the “2S” modules of two back-to-back strip sensors at the largest radii and the “PS” modules of one strip sensor back-to-back with a macro pixel sensor at intermediate radii. Four separate ASICs are required: the CBC is the front-end for 2S modules (130 nm CMOS technology), the SSA for the strip sensors of PS modules (65 nm CMOS technology), the MPA for pixel sensor of PS modules (65 nm CMOS technology) and the CIC concentrator chip for both 2S and PS modules (65 nm CMOS technology). The three front-end chips include an analogue front-end, comparator and digital back-end but the CBC and MPA also include stub-finding logic (Track stubs formed by hits in top and bottom sensors are identified and only those with $p_T$ above a programmable threshold in the 4T field are kept). CMS relies on a low power, low mass version of the GBT and of the Versatile Link components as well as tuned radiation-hard DC-DC converters able to operate in an intense magnetic field.

Both barrel and end-cap modules of the ATLAS outer tracker upgrade use the same chip set: the ABC front-end ASIC and the hybrid controller chip (HCC), both of them being prototyped in 130 nm CMOS technology. The original architecture responded to a two level trigger (L0 and L1) and a region of interest based read-out at L0 rate for participating in the L1 track trigger. The possibility of reading out the full tracker at L0 rate (1 MHz) is now being considered. Similarly to CMS, ATLAS relies also on the low power GBT (although using its high speed version) and low mass Versatile Link components. Two versions of powering are being considered: serial power and the use of DC-DC converters. Both have been prototyped and proved to work.

The development work for upgrading the outer trackers in several different technologies is necessitated by the difficult requirements placed on the four experiments. Several prototype ASICs have already been tested and the overall development is progressing on schedule. There are many opportunities for common development and shared work such as the frame contracts between CERN and IC foundries (common access to technologies and design tools), shared work for radiation qualification and important components provided by the CERN electronics group (GBT and low power GBT, Versatile Link components and radiation and magnetic field hard DC-DC converters).

## Electronics for Calorimeters

The common goal for the read-out electronics of all the calorimeters is to meet the challenging pile-up conditions, the radiation environment (in particular the impact of single event effects) and the new requirements imposed by the upgrade of the trigger systems. All experiments plan to read out the calorimeters at 40 MHz in order to simplify the front-end design (no trigger pipeline, etc.) and to allow use of high granularity in the trigger algorithms. When needed (e.g. CMS end-cap calorimeter) replacement with a much higher granularity detector also offering better timing resolution is considered, putting very challenging constraints on the front-end electronics.

Analogue front-end designs optimised for high pile-up are required. Several detector specific ASICs are being designed in 130 nm and 65 nm CMOS technologies and in SiGe BiCMOS technologies. Many prototypes have already been tested.

All systems require a low power, high dynamic range (14–16-bits), high resolution (~11–12 effective number of bits) digitiser per channel at 40–80 Msps and high bandwidth optical links (at least 5–10Gbps) feeding a back-end electronics with embedded high density optical receivers and large high-end FPGAs.

There are certainly possible (and desirable) common developments across experiments in the domain of front-end ASIC designs, such as the development of IP blocks for ADCs, high-speed serialisers and front-end electro-optical devices. Each calorimeter could then develop their specific read-out ASIC integrating its specific analogue front-end and integrating some of the above common blocks. This would allow a simplification of the front-end board architectures, as well as a significant reduction in power and hence in the required services.

### Electronics for Muon Detectors

All muon systems will have some form of electronics upgrade, the main reasons being higher radiation levels, higher data volumes, higher trigger rates, longer level-1 trigger latencies, faster and smarter data processing or aging. Specific developments for the upgrades of the end-cap muon detectors of ATLAS and CMS, and the muon detectors of ALICE and LHCb are proceeding. Several ASICs are being designed for the front-end part in 130 nm CMOS technologies (VFAT3 for CMS, SAMPA for ALICE and VMM for ATLAS). Some prototypes already exist (SAMPA and VMM).

At the system level, the GBT and Versatile Link components are planned to be used as well as the radiation tolerant DC-DC converters. The back-end electronics is based on xTCA and/or PCIe.

### Using FPGAs in the Detector Cavern

The use of high-end FPGAs in the front-end electronics of some sub-detectors (those with the lowest radiation constraints) is very attractive as one can take advantage of powerful functions such as high-speed links for increased data read-out, PLLs for clock management related to synchronization with the accelerator clock or DSP blocks for data processing.

However their behaviour in radiation environments requires special care, especially the effect of single event upsets which are different for each technology (SRAM, anti-fuse and flash memory). Several mitigation techniques have been presented but it should also be noted that characterizing a device needs major effort and that the community would benefit a lot from some coordination. So far, collaboration across different projects has been rare and mainly based on the activities of interested individuals. Some initiatives have been put in place, such as the development of a web page for sharing information and the organization of a “Workshop on FPGAs for High-Energy Physics” at CERN on March 2014 (after ACES2014), but additional efforts are needed.

### Electrical and Optical Links

Optical links have been instrumental in building the LHC detectors and they will also be crucial at the HL-LHC. The LHC experiments deployed optical links to an unprecedented scale for their read-out systems. The lessons learned during the development, procurement, installation and commissioning of these systems have highlighted, among other issues, the need to increase link bandwidth (to better amortize system cost), to share R&D effort (to better use the limited resources available) and to enforce extensive and rigorous quality assurance programmes (to identify shortfalls as early as possible). The “Radiation Hard Optical Link” project was launched with the objective of developing a common and “universal” optical link for data read-out, trigger and control. A 5 Gbps radiation-hard bidirectional optical link is now available with the GBT chipset and the Versatile Link transceivers. The production phase is now launched and components for the Phase-I upgrades will be delivered in 2015.

A review of the requirements for the upgrades of the ATLAS and CMS trackers as well as the read-out of the calorimeters and muon detectors have shown the necessity of developing a lower power or a higher speed version of the link (about 10 Gbps) as well as a lower mass version of the optical transceivers. The so-called lpGBT and Versatile Link+ projects are now starting with the aim of delivering a link either running at about twice the speed of the current one with the same power budget or at the same speed with about a quarter of the current power budget. Collaborative efforts for these projects are welcome as the developments of the GBT chipset and of the Versatile Link have proven to be rather time and manpower consuming.

Very harsh radiation environments and/or stringent material budget constraints sometimes preclude the use of optical links. That is for instance the case in the inner layers of the pixel detectors. The use of high-speed electrical transmission on low mass cables can then be the only solution. Several developments (e.g. for the ALICE ITS or the LHCb Velo) are looking very promising.

*Silicon photonics* is a potential paradigm shifting technology, bringing the promise of tightly integrating opto-electronics and front-end electronics. Some components are being evaluated (in particular for their radiation hardness). An increased effort would be needed, should this technology prove promising.

### IC Design and Technologies

Radiation tolerant ASICs are one of the key enabling technologies of the LHC experiments. In particular, ASICs designed for radiation tolerance in 250 nm CMOS played a major role. ASICs will continue to be key components for HL-LHC, however, a number of challenges have to be faced when keeping up with the evolution of the technology: higher hit rates, higher radiation hardness, higher trigger rate or trigger-free operation, minimisation of material and power consumption, high dynamic range design in sub-100 nm processes, high pile-up which might require sub-ns time stamping.

Following Moore’s law for HL-LHC applications presents some practical challenges, either technical (large variety of transistor devices available, large choice of metal stacks, increased simulation/layout complexity, power density challenge, wafer diameter increases) or organisational (mask set costs in 65 nm are of the order of 1 MCHF).

From the first generation of LHC ASICs it has been learnt that the selection of a CMOS process must be based as much on its commercial viability as on the elegance of the technical solutions it offers, as this impacts yield (i.e. cost) and long term accessibility. It has also been learnt that collaboration between groups works best if based on a common technology platform and that duplication of design effort, while valuable for training purposes, is not optimal.

Common foundry access through CERN covers now 250 and 130 nm CMOS processes from the former IBM foundry (now Global Foundry) as well as 130 and 65 nm CMOS processes from TSMC. Radiation qualification of the latter two is on-going. In particular RD53 is performing extensive tests of the 65 nm process at the very high radiation doses required by the pixel detectors. Some not yet understood issues are observed after about 300 Mrad.

An effort for sharing designs is being put in place in the framework of RD53 for the pixel electronics development in 65 nm technology. Already a number of IP blocks are available, as well as a repository and a usage agreement between collaborating institutes. A similar effort is starting for the other technologies and shall be pursued in the coming years.

Interconnecting chips to sensors is also a key process. Although aluminium wire bonding remains the dominant means of I/O from chips, flip chip is now common on high volume consumer goods and is used in some of our applications. Through Silicon Vias (TSVs) are being used in some special applications (such as smartphone camera assemblies and DRAMs) but such processes are still difficult or impossible to access in smaller volumes. However TSV-last processing (i.e. the vias are drilled on finished wafers) starts to become viable, and has been demonstrated in the context of the Medipix collaboration.

# 9. Progress on Mechanics and Cooling

The high power dissipation in HL-LHC detectors makes the thermo-mechanical design challenging for the next generation of all LHC experiments. The technical issues are common for most detectors, although materials and solutions may slightly differ. A stronger collaboration among groups active on cooling has already shown relevant benefits, both in terms of technical achievement and resource optimization. The same approach is supported to share experience in the field of mechanical structures, whose design needs to be strongly coupled with the cooling system.

Silicon trackers (pixels and strips) are the detectors where the tensions from diverging requirements are strongest: low temperature; large thermal power; high stability; low material budget; use of state-of-the-art technologies; long-term reliability. For this reason, this section essentially focuses on engineering issues related to silicon tracking detectors.

**Lightweight Structures**

Based on the experience of the present LHC detectors, it looks indeed mandatory to tackle the issues of cooling and mechanics together at the very early stages of design. No matter which cooling configuration is chosen for the next generation of detectors (with pipes, micro-channels, or even air cooling), the design will need to cope with the on-detector cooling system as part of the structure. Moreover, in tracking detectors this feature requires particular care in the selection of materials, in order not to compromise the material budget. To achieve structural and thermal designs that are optimized, the known limits of the presently used carbon fibre technology need to be pushed and new materials like diamond, carbon nanotubes and graphene need to be carefully evaluated. Advanced production technologies, like additive manufacturing and micro-fabrication, need to be considered as concrete alternatives to standard processes.

The population of a material database with data on radiation hardness, mechanical and thermal properties for the possible materials is acknowledged as a common need across experiments. The database structure is being prepared, but data needs to be collected from the different sources and measured for new materials. It is recognized, as well, that unification of design criteria, production processes and procedures across experiments will be extremely beneficial in order to achieve the desired quality. This can be accomplished by maintaining frequent communication through specialized forums (like the Forum on Mechanics of Tracking Detectors) between engineers working on the different experiments.

## Cooling

For the next generation of detector cooling systems, the common trend is to further lower the operating temperature with coolants down to -40°C. This goes together with the need to reduce the radiation length of the thermo-mechanical structures. A standardization of the cooling systems turned out to be a very effective solution among collaborating groups from different experiments. Over the past few years, this has led to a baseline cooling technology for the HL-LHC detectors based on evaporative $CO_2$ systems. ATLAS IBL, CMS Phase-I Pixel, LHCb Velo and UT are or will be cooled by means of this technology. With the present design this covers cooling power ranges up to 15 kW with the lowest achievable temperature at the detector evaporators of -40°C.

$CO_2$ cooling has several advantages with respect to the previous evaporative system based on fluorocarbons:

- The latent heat is significantly higher and lower flow rates are required. The diameter of the boiling channel can be significantly reduced while the impact of the high evaporation pressure is mitigated. As a result, small pipe diameters with thin wall thickness have a direct beneficial impact on the overall detector system radiation length.
- Unlike fluorocarbons, $CO_2$ has no environmental restriction and its cost is significantly lower.

The system that has been successfully developed in the framework of the $CO_2$ cooling is the so-called 2PACL: 2-Phase Accumulator Controlled Loop. This system does not require compressors in the vapour phase and pumps on the liquid side to generate the flow. This solution avoids the complications related to the oil-free compressors that would have been required in a standard system. The common effort on the 2-PACL $CO_2$ cooling systems has developed and produced reliable cooling plants to be used as laboratory facilities or serving the actual LHC detectors. The more challenging requirements for the next detector generation necessitate further developments. In particular the cooling power of the units must be scaled up by a factor of 2 (or more) with respect to what has been achieved today. The process will not be as smooth as might be hoped. Increasing the unit power from the actual 15kW to 30-45kW implies that the technological limits of some of the key components for the 2-PACL system will be reached.

The roadmap to future upgrades requires not only more powerful cooling units. Many of them will be operating in parallel to meet the overall cooling capacity that, in some cases, can be up to 180kW. Summing up the needs of all the experiments it turns out that ~15 large cooling units must be delivered almost at the same time. Such an effort exceeds the present fabrication capability available in the participating particle physics laboratories. Possible industrial partnership must be investigated at a very early stage.

The development of the cooling units is certainly a relevant issue, but it is by far not the only one. Once the cooling power is generated at the proper temperature in the plant, the coolant has to be efficiently transferred to the detector structures. In this type of system the transfer lines are cold and act as a heat exchanger. They are a rather complex component where inlet and outlet lines are arranged coaxially and surrounded by a vacuum insulation that can be both "passive" or "active"[8].

Much progress has been made up to now. Flexible triple coax lines are now installed in the ATLAS IBL, but significant improvements are mandatory to meet the requirements for the future. Finally the coolant reaches the structures of the detector where the heat is generated. Evaluating the boiling parameters in the channel becomes essential to predict the dynamical behaviour of the entire system. Two-phase flows undergo dramatic modifications influencing pressure drops and the heat transfer coefficient. $CO_2$ models for horizontal pipes down to ~1mm size have been implemented in a 1-D calculator. They must be refined and compiled into a user-friendly code, ideally coupled with standard FEA software.

New and interesting solutions have been developed on the evaporator side – i.e. on the local detector structures. They are based on the idea that the coolant evaporates in the part that generates the heat. This is the front-end electronics generally located in the proximity of the sensors.

The micro-channel cooling technique foresees to cut tiny channels on a substrate placed right underneath the chips requiring cooling. The coolant ($CO_2$ , fluorocarbons or another) evaporates in the immediate vicinity of the volume where the heat is generated. The temperature build-up becomes very low and the overall thermal figure of merit is excellent. The technology is mature. This solution has been adopted for the LHCb VELO and NA62. Other experiments, for example ALICE, have chosen it as a back-up option.

It should be mentioned that micro-channel cooling reveals some implementation difficulties when there are multiple devices to be cooled connected in series. In fact, the construction of a long daisy-chained micro-channel poses issues at the interconnections. This is the case, for example, for a long stave in a barrel detector. Typically the chips (or modules) are lined up parallel to the beam axis for a length that can significantly exceed one metre. Connecting in series a large number of micro-channel devices still needs significant R&D.

### Detector Integration and Environmental Issues

System integration includes a variety of engineering processes: from engineering of complex systems to Design for Assembly (DFA) that focuses the design to facilitate the assembly process. The current detectors were assembled adding small parts to a large structure. Electrical modules were tested standalone and mounted in layers with services. The sequence was serial. The foreseen detectors for the HL-LHC are larger with many more channels. There will be many more mechanical parts as well as electrical modules. The size of the integration work requires sharing among several sites where most of the available manpower resides. Moreover, the activation levels in the areas where the services of the new detectors will be installed lead to the need to minimize the work to be done in situ. The global dose delivered to the personnel must be "As Low As Reasonably Achievable" (ALARA). The experiments are therefore facing a tendency to increase the level of integration from the early stages of the construction sequence. An example of this approach is given by the

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[8] Active insulation generates the vacuum through continuous pumping. In a passive system, the vacuum is made once and for ever.

ATLAS strip local support for the HL-LHC upgrade tracker, which includes integrating the cooling and an electrical bus into the mechanical structure.

Increased integration does increase the risk, introducing single failure modes that could affect the functionality of a large part of the detector. It is a drawback of a higher integration approach, but there are professional engineering tools and methods for minimizing the risk. The most relevant of them is Quality Control (QC), which can be extremely effective in mitigating the risk if it starts at the early stage of the project when the design can still be corrected. Integration strategy has a direct impact on the environmental control, which includes the design of the services penetrating the detector volumes and the separation between cold and warm sections. For the present detectors, different solutions have been implemented, with CMS featuring one unique volume and ATLAS having eight different ones (which was certainly a further complication). The “single volume” approach selected by CMS, with all sub-detectors integrated on surface into a limited volume prior to installation in the experiment, allowed tightness requirements inside the Tracker volume to be met, while in ATLAS only the presence of a back-up auxiliary environmental volume for the whole Inner Detector implicitly solved the humidity issues. On the other hand, the early adoption in ATLAS of “engineered” solutions for the service distribution areas, allowed for a satisfactory environmental management of the external service volumes. In the case of CMS this problem was initially tackled through an “in-situ intervention” approach, which caused the need of important corrective interventions during LS1, involving the addition of thermal insulation and vapour barrier layers.

The lesson learned on this subject is clear: in the future the trackers should not be split into multiple volumes. Working temperatures are similar among sub-detectors that need to be more *integrated*, sharing more efficiently the internal structures. A clear design of cold/warm volume boundaries must be tackled from the early stages, considering the adequate volumes for insulation or external auxiliary environmental volumes.

## 10. Developments in Triggering, Online and Offline Computing

### Hardware Triggers

The LHC experiments face considerable challenges to exploit future increases in luminosity. After LS2, both ALICE and LHCb will adopt a “triggerless” architecture. This shifts the burden of triggering to farms of commodity processors steered by software developed in large collaborative projects and to the personnel who provide and maintain this software. ALICE will use continuously read out triggering detectors with different latencies, busy times and technologies, differently optimized for pp, pA and AA running scenarios. LHCb will run trigger-free in order to achieve a substantial increase in physics reach, reading every bunch crossing (46) .

Although technologies may at some point evolve sufficiently, present read-out links do not allow ATLAS and CMS to adopt “triggerless” architectures with acceptable detector power and material budgets for their tracking detectors. Therefore, at the HL-LHC, both ATLAS and CMS will retain their hardware Level 1 triggers. Three changes to these trigger systems are planned during LS3. The first is the addition of a L1 tracking trigger for the identification of tracks associated with calorimeter and muon trigger objects. The second is the utilization of finer granularity information from the calorimeter and muon trigger systems. The third is a combination of significant increases in L1 rate, L1 latency, and High-Level Trigger (HLT) output rate. All three changes are required in order to realize the physics potential of ATLAS and CMS at the HL-LHC.

The ATLAS experiment will divide its L1 trigger into two stages. The first stage is a L0 trigger with a rate of 1 MHz and latency of 6 μsec that will use more fine-grained calorimeter and muon information to produce seeds for a regional read-out of the tracker. The second stage L1 trigger will use this information to further reduce the rate to around 400 kHz with a total L0 and L1 latency of 30 μsec. The output of the L1 Trigger will be processed by the HLT with an output to storage rate of 5 to 10 kHz. The CMS L1 trigger will retain its present architecture but its latency will increase to 12.5 μsec with an output range of 500 to 750 kHz for pile-up ranging between 140 and 200. CMS will use an un-seeded L1 Track trigger at 40 MHz along with finer granularity calorimeter and muon triggers. The CMS HLT output rate to storage will range between 5 to 7.5 kHz for pile-up ranging between 140 and 200.

The L1 tracking triggers for ATLAS and CMS have been simulated to show that along with the higher L1 trigger rates, they enable thresholds at the HL-LHC comparable to those used in Run 1, allowing full usage of the statistical power of the HL-LHC data. For example, for a trigger menu with thresholds comparable to Run 1, a L1 Tracking trigger reduces the overall L1 rate by a factor of 5, and the rate of muon and electron triggers by a factor of 10. CMS has shown that a L1 track-based MET reduces the rate over calorimeter MET by 2 orders of magnitude. The L1 tracking triggers also require upgrades to the calorimeter and muon triggers that will provide sufficient granularity and other information for combination with the tracks in order to achieve the full benefit of this added capability. This additional information from the calorimeter and muon triggers will also enhance their stand-alone performance in the face of the additional pile-up. Nevertheless, in spite of the improvements with a L1 tracking trigger, the calculated rates for a L1 menu with Run 1 thresholds are at least 300 Hz for both ATLAS and CMS without any safety factor, necessitating the increase in L1 bandwidth beyond the present 100 kHz of the Phase-I ATLAS and CMS detector read-outs.

### DAQ and Software Triggers

The LHC beyond Run I foresees a steady increase in the fraction of collision data which is sent off-detector for processing by so-called “software triggers”, meaning any trigger stage or algorithm that is executed on commodity processors. Typically these have been CPUs, however there is an increasing amount of R&D into massively parallel GPU and FPGA “co-processors” to aid CPU farms with those tasks that can be naturally parallelized. It is important to note that even within CPUs, the technological trend is towards more cores and by the time of Run 4 a typical CPU may well have as many cores as one of today's smaller GPUs. For this reason, it is necessary to significantly rethink almost all aspects of event reconstruction and selection in order to fully exploit the power of the data processors anticipated for the HL-LHC era, a point discussed more fully below.

All collaborations assume a steady growth in the computing power available per CHF of between 25% and 35% per annum as part of what is needed to cope with the higher instantaneous luminosities and more complex events of the HL-LHC era. In addition to this, it will be necessary to find another factor of between two and five in performance, depending on the experiment in question, in order for software triggers to effectively reconstruct events. One increasingly important strategy will be to extend the latency of software triggers to fill as much of the machine idle time as possible by using massively parallel local storage buffers composed of hard-disks attached to the individual processing nodes of the software trigger farms. LHCb intends to test such a system during Run 2. Their software trigger will be split into two stages, and events buffered between the two in such a way as to keep the farm processors fully utilized between fills. Such approaches, if successful, may allow the doubling of online processing power per CHF in the HL-LHC era.

Data rates of around 40Tb/s going into the ATLAS, CMS, and LHCb software triggers imply an overall volume of around 60 exabytes of data to be processed per year of data taking, a volume comparable to the largest commercial data processing tasks. Such data rates will be especially challenging because the events will be packed with interesting physics that these state-of-the-art detectors should be able to study. For example, a bunch crossing at ATLAS and CMS during Run 4 will contain on average one bottom pair and twenty charm pairs, while the rate of fully reconstructed signal for certain key CP-violating observables will exceed 2 kHz at LHCb. In the case of ALICE, every single bunch crossing (50 kHz in Pb-Pb and 200 kHz in p-Pb collisions) is considered interesting and the role of the trigger system is to compress each bunch crossing by a factor 100, rather than rejecting any events. In such a signal-dominated environment it will become increasingly important to shift more of the final analysis burden from the offline processing to the software trigger, and to consider new data processing paradigms such as analysis using trigger-level objects, or saving only part of each event through suppression of raw data which is associated with pile-up vertices. While ATLAS and CMS aim to write out between 5 and 10 kHz of events for offline analysis, and LHCb between 20 and 100 kHz, these "events" will most likely no longer be the traditional full raw detector output, but rather a heterogeneous mixture of full events, trigger-level analysis objects, data mining events for long-term archival ("parking") and other compressed data formats. In addition, as the software triggers will increasingly discriminate between different signals rather than between signal and backgrounds, it may also be important to perform the detector alignment and calibration in real time, as well as developing multivariate analysis methods which are safe for online use.

## Software and Computing

Trends in hardware evolution have continued to demonstrate the validity of Moore's Law, viz. the density of transistors on CPUs doubles roughly every 24 months. However, whether this scaling holds, even for the next decade, remains a subject of intense research and a slow down to a doubling every 36 months is entirely possible. For the HL-LHC timescale this leaves some uncertainty over the "raw" computing power that might be available. The principle driver for computing hardware is now energy consumption, with the figure of merit being nanoJoule/instruction. Even if the more optimistic predictions are realised, it is already clear that modern computing hardware is becoming increasingly hard to exploit effectively. One of the most difficult areas to tackle, given the large amounts of legacy code in the experiments, is that of data layout. The performance gap between memory and CPU has been increasing and hundreds of cycles can be wasted while data and instructions are fetched from main memory. Here a paradigm shift from *object oriented design* to *data oriented design* will allow the knowledge of other communities to be applied to HEP. This re-design of in memory event storage and algorithms will be a fundamental part of preparing for HL-LHC and will be essential to move computations efficiently from CPUs to accelerators or FPGAs. The kernel code for core algorithms will need to be portable to many platforms as the era of an x86_64 mono-culture is almost certainly over.

In exploiting multi-core architectures the LHC experiments have now made significant progress. CMS have now demonstrated a multi-threaded version of their framework that scales well and saves huge amounts of memory. ATLAS and LHCb have collaborated on the GaudiHive, which is being developed aiming at Run 3 and has also shown good scaling, albeit in limited reconstruction cases. ALICE have an ambitious plan to develop a new framework, $O^2$, which unifies online and offline processing.

For costly algorithmic code, which must be adapted to make best use of parallelism and features like Single Instruction Multiple Data (SIMD), there are practical demonstrations that show significant progress. e.g., the Geant V project has successfully parallelised particle transport as well as implemented vectorized code for common geometry operations. Track triggers remain a challenge to simulate, as reproducing the logic of an associative memory on CPU devices is extremely slow and inefficient. Fast simulation strategies will be important to develop to keep up with event complexity and rate at HL-LHC.

For tracking, which dominates the reconstruction time at high pile-up, many parallel algorithms are available. However, realistic studies of likely physics performance are needed to balance cost of serial approaches (which can better reduce combinatorics) and parallelism (which can utilise more cores); the goal is overall improved throughput with robust physics performance. These same goals apply equally to other areas.

Once data have been reconstructed, offline computing will have to cope with roughly an order of magnitude larger raw data volume in the HL-LHC era. While the cost of archival tape storage is expected to be similar to today, disk storage at sites storing derived data copies, caches, etc., may fall short by a factor of 2-3, based on current extrapolations. As for online software triggers, the cost of CPU is expected to be 2-5 times more than flat budgets. Any shortfalls will need to be primarily addressed by better use of computing resources. In contrast, networking has seen a steady exponential growth and expected technology developments will likely see this continue, which should provide ample network capacity for HL-LHC. There also exist possibilities to use networks more extensively to offset disk requirements with fewer disk resident copies and more remote access to data to feed CPUs at different sites.

Each of the experiments has embarked on a programme of upgrades that will evolve their computing systems into the future:

> The ALICE upgrade (for Run 3) foresees a break from the traditional online-offline separation in favor of a single processing system, $O^2$, performing reconstruction, calibration and data compression (quasi) online to better manage the expected data volume. A large fraction of the storage ALICE will need will be in the data buffer of this new $O^2$ system. The integration of General Purpose Graphics Processing Units (GPGPUs) and FPGA accelerators will be supported directly in the new framework
>
> ATLAS is currently commissioning a new data placement system and is gaining experience with hardware acceleration and multi-threading. New software approaches are being developed to work around expected hardware limitations (such as whole node scheduling at grid sites and using an event by event approach, the EventServer, at HPCs). Storage strategies are being reconsidered, with a new optimised storage format (xAOD) and a reduction of data duplication.
>
> CMS expects the computing needs to grow by a factor 65-200 with respect to Run 2. This means, given the expected technology evolution, a deficit of a factor 3-15 for the CPU needs and 4-5 in storage. Roughly 40% of the CMS processing capacity is devoted to reconstruction, 20% to data reduction, the remaining 40% is a mix of simulation, user analysis and smaller scale calibration and

monitoring activities. In addition to other options mentioned above, CMS plans to investigate the improvements in cost per capacity of using specialized computing centres for dedicated workflows.

LHCb expects an evolution rather than a revolution to cope with the 8-10 times increase of the HLT output to 100kHz. During Run 2 the idea will be investigated of performing full reconstruction and calibration online and writing only the reconstruction output in the form of a microDST instead of full RAW data to minimize the impact on offline storage and computing. LHCb offline CPU usage is dominated by simulation (>60% expected in 2016), efforts are underway to optimize the code, utilize more heterogeneous resources and tune the storage format.

Currently (and also in the foreseeable future) technology evolution is driven by the Big Data industry, where the prevailing computing model involves using specialized, large data centres providing services for smaller, energy efficient, end user devices. Utilizing spare resources of existing centres is under investigation. Developing a new software approach for utilizing this new emerging heterogeneous computing paradigm will require a significant effort and manpower.

As these software and computing problems are fundamentally shared by all the experiments, cross-experiment forums, such as the HEP Concurrency forum, are valuable mechanisms for sharing experience. The recent initiative to improve the management and community support of HEP software in the form of a HEP Software Foundation also increases the ability to share knowledge and focus efforts on common solutions to shared problems.

## 11. Accelerator & Experiment Interface, Activation & Mitigation

In the following the main challenges for upgrading the experiments, with one major issue being the increased radiation hazard due to activation, will be described and a summary of the baseline upgrade plan for the LHC will be given.

### Challenges for the Experiments in LS2 and LS3

For the ALICE and LHCb experiments, LS2 will be the major shutdown for upgrades, allowing them to make optimal use of the expected capabilities of the LHC. Both experiments will radically increase their trigger and data taking capabilities, with associated changes to the detectors as described in earlier sections. Because the current electronics cannot work with the new trigger and read-out requirements, these upgrades for both experiments have to be completed in a single shutdown. Central technical groups at CERN will be needed to help with installation of new computer farms and their infrastructure, the exchange of beam pipes and collimators, extensive cabling and fibre installation, and upgrades to cooling and gas systems. Many groups will be involved requiring early and detailed planning.

ATLAS and CMS plan their major upgrades for the HL-LHC era in LS3, but with many significant improvements planned well before then. CMS will exchange its silicon pixel detector in the extended Year-End-Technical Stop of 2016/17. In LS2, the photon detectors of the Hadron Barrel and Endcap calorimeters will be changed from HPDs to SiPMs and the beam pipe will be changed from stainless steel to Al2219 to reduce activation. ATLAS will see the installation of the New Small Wheel and both experiments expect major changes to electronics and triggering capabilities to cope with increased luminosity. ATLAS and CMS will therefore need to prepare resources for LS2 at least comparable with those for LS1.

Since the last workshop, major progress has been made in analysing the global infrastructure upgrades or replacements needed for reliable operation beyond LS3. A significant objective is to minimize the impact these upgrades have on parallel work for the experiments. As an example, a detailed schedule is in preparation for replacement of the elevators and studies for other installations are ongoing. It is clear that LS3 will be a shutdown of unprecedented work density and co-activity at CERN. Both experiments will be replacing their trackers and CMS will need to replace its forward calorimeters; with a decision on the ATLAS FCAL also expected this year. New muon chambers, particularly, but not necessarily only, at high $\eta$, are anticipated. New trigger capabilities also imply major upgrades to on and off detector electronics throughout the experiments, as also discussed in previous sections.

These intense programmes for both large experiments will be further complicated by the necessity to change the TAS collimators for the higher aperture of the new Triplet magnets. These collimators will be highly radioactive, therefore exchanging them will limit any parallel activities in the caverns. However, an engineering study to advance this exchange to LS2 showed that neither from the radiation protection point of view nor for scheduling would this offer any advantage. To be able to perform this dense programme within the foreseen time represents a major concern since the teams that successfully assembled the experiments and were present through LS1 will only be partly available for LS2 and gone by LS3. As a consequence, a succession policy for all relevant experts in the field and in the management must be developed now, as the complexity of the environment requires well-trained and experienced teams, which have to be formed years before this critical shutdown.

## Radiation Protection and the Challenge of Activation

In August 2014 the HL-LHC project responsible released an updated expectation for the luminosity profile during HL-LHC operation, changing the expected activation of detector components. As the impact of the luminosity profile changes are relevant essentially only for the ATLAS and CMS detectors, the investigations concentrated on these two experiments.

FLUKA Calculations were run for ATLAS and CMS detectors in order to have an updated estimation of the dose rates for LS2, LS3, LS4 and LS5. The dose estimations are performed using the most up to date detector configurations. Two different luminosity profiles are considered after LS3: one nominal profile with a levelled luminosity of $5\times10^{34}\mathrm{cm}^{-2}\mathrm{s}^{-1}$ giving an integrated luminosity of 250 $\mathrm{fb}^{-1}$ per year, running up to 3000 $\mathrm{fb}^{-1}$ and one maximal profile with integrated luminosity of 300 $\mathrm{fb}^{-1}$ per year, running up to 4000 $\mathrm{fb}^{-1}$. Scaling factors for ATLAS and CMS detectors have been determined comparing LS1 environmental dose rates values with those at future shutdowns, assuming a cooling period of 4 months (scaling factors increase for longer cooling times). For both experiments, the activation will be a factor 2.5 higher in LS2 with respect to LS1, a factor 4 higher in LS3 and a factor 20 for LS4 and beyond. For LS2, major parts of the experimental caverns of ATLAS and CMS (UX15 and UXC55) are expected to stay classified as Supervised Radiation areas. Only some regions like the Inner Detector or the forward shielding will become Limited Stay areas. In later shutdowns for these regions, environmental dose rates of hundreds of μSv/h with local peaks of mSv/h near the TAS can be expected.

To be able to face such high doses rates, the experiments, in collaboration with the CERN Radiation Protection (RP) group, are already engineering solutions to mitigate radiation effects on future shutdown work. The ALARA, "As Low As Reasonably Achievable" studies are acting on: shielding design, strict optimization of the working procedures, when possible motorization of some tasks or use of robots, radiation protection assisting devices like a new type of gamma imaging camera and an appropriate material choice for the experiment upgrades. In this latter context, the web based material selection tool, Actiwiz, is being developed.

A revision of the radioactive waste and operational zoning is also performed for ATLAS and CMS experiments taking into account the exemption limits currently under revision in Europe and the new HL-LHC luminosity profile. The possible impact of these new zonings on the waste management policy and on the need of new storage areas or radioactive workshops needs to be carefully assessed.

Finally, it is should be noted that for the ALICE and LHCb experiments, the dose rates are not expected to change significantly in the future, so they will be able to remain Supervised Radiation areas.

## HL-LHC Baseline Upgrade Plan

The first HL-LHC Baseline was presented in July 2014 (47) to the LHC Machine Committee. Together with the Baseline, were presented a series of options whose objective is to mitigate some of the risks already identified for the operation of LHC and in case of late delivery/failure of one of the baseline components. The complete description of the systems belonging to the baseline and to the options can be found in the HL-LHC conceptual specification (CS) series (48). The CSs provide the scope, benefit for the machine performance and equipment performance objective for all major components of the HL-LHC. The CSs contain also their preliminary technical parameters, configuration and installation constraints, interface parameters and schedule.

The work is structured in Work Packages (WPs). Each WP integrates components of the same nature. There are presently 18 WPs of which five give global support to the component driven WPs

A non-exhaustive list of key hardware included in the scope is enumerated here:

- WP3: Insertion region magnets including new inner triplet magnets and the redesign of D1 and D2 dipoles to increase the aperture and replace magnets not resistant to the future radiation levels.
- WP4: New superconducting deflecting cavities called Crab cavities to compensate for the geometric reduction factor.
- WP5: Improved collimation system to reduce impedance in case of beam instabilities and protect new elements installed such as the new inner triplet or the crab cavities
- WP6: Warm power converter system for new components and radiation resistant and superconducting links for remote powering of cold circuits to reduce/eliminate dose to personnel and to equipment.
- WP7: New quench and machine protection systems to increase redundancy and flexibility and to adapt to new fast events and to protect new hardware.
- WP8: Replacement of the present TAS and TAN in P1,P5 and TAN in P8 to reduce the maximum instantaneous power density transmitted from the interaction debris in the downstream elements.
- WP9: New cryogenic system for P4, P1 and P5 to increase flexibility and availability.
- WP10: Radiation-matter interaction simulations requiring detailed modelling of the whole areas of interest as well as the proper characterization of the relevant source terms.

- WP11: 11T dipole for the Dispersion Suppressor (DS) region to create space for the installation of collimators. Critical for reaching maximum ion luminosity
- WP12: Improved vacuum system elements such as non-shielded beam screens to screen cold bore from beam induced heating or shielded beam screens to protect from physics debris
- WP13: Improved beam instrumentation for more accurate beam size and position measurements, beam halo and intra-bunch position, beam size evolution.
- WP14: Improved Beam transfer and kickers systems to protect from increased energy deposition in case of impact and of increased radiation background.

The activities of the HL-LHC follow the HL-LHC life cycle (49). The first draft Master Schedule was prepared using the schedules prepared by the WP Leaders (WPL) during the preparation of the CSs to which was added the different constraints indicated in the CSs and on the System Architecture and interface identification documents (50). It also took into consideration the ALARA principle to minimize the exposure of workers during de-installation/installation tasks. The combination of the draft Master Schedule with the different constrains provided the first Installation and Commissioning schedule for the HL-LHC components.

## Radiation Protection Considerations

To optimize the design of new components, check the radiation resistance of those presently installed and minimize the doses to be taken by workers during the de-installation /installation tasks, the CERN RP group has produced three-dimensional residual dose rate maps. The maps cover the TAS to the D1 region and consider different cooling times ranging from 1 hour to 1 year after the beam stop for the long shutdowns and for both the nominal and the ultimate scenarios (Figure 2).

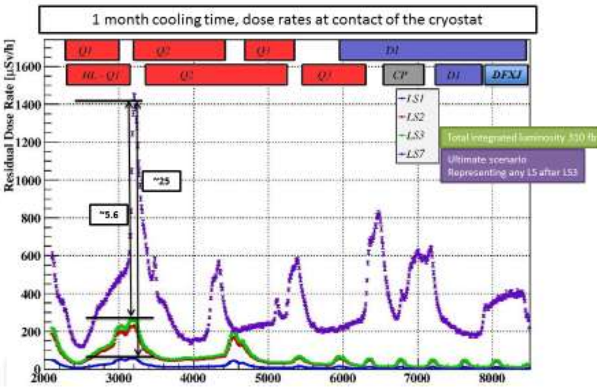

Figure 2 Ambience Dose Equivalent Rate – Time evolution

The maps show factors 4 to 6 for the increased ambient dose equivalent rates between LS3 and the first LS after the HL-LHC installation and a factor 15 to 30 increase compared to LS1. Comparing ultimate vs nominal shows a factor 1.2 to 1.5 increase, depending on the cooling time.

## 12. Conclusions

This report only touches on some of the many areas where impressive progress in preparation for the HL-LHC programme was presented at the 2014 ECFA High Luminosity LHC Experiments Workshop. Much more material can be found in the actual presentations from this intensive 3 day meeting[9]. The two ECFA workshops are widely agreed to have provided extremely valuable opportunities to discuss upgrade goals, key techniques and synergies across the experiments and with the theory and accelerator communities. However, 2015 will be very busy with Run 2, Phase-I upgrade construction and Phase-II upgrade optimisation. It is therefore proposed that the next workshop should be planned for spring of 2016, when ATLAS and CMS will be well advanced with their Phase-I programmes and approaching first Phase-II TDRs; while ALICE and LHCb will have already gained considerable experience in their full upgrade construction.

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