CERN-LHCC-2018-012

17 April 2018

LHCC deliberation on Phase II upgrades

Summary of LHCC reports on the Phase II upgrade TDRs as documented in the minutes of the LHCC session from September 2017 to March 2018

1. Report on the LHCC review of the ATLAS Phase-II ITK Strip TDR

Review panel: Philip Burrows (chair), Alan Honma, Wolfgang Klempt, Fabienne Kunne, Steven Nahn, Paolo Petagna, Bill Wisniewski

LHCC 130, 10 - 11 May 2017

The LHCC conducted an in-depth review of the TDR for the ATLAS ITk Strip tracker system. The LHCC review team was augmented for the review with three experts, Alan Honma, Steve Nahn, and Paolo Petagna. The review process and outcomes are summarised briefly below.

- 20/11/16: An internal ATLAS TDR draft version was shared with the LHCC ATLAS referee team. Though largely complete, several chapters were missing from the document at that stage.
- 29/11/16: The ATLAS referees provided informal feedback on the internal draft at their regular LHCC Week meeting with the ATLAS management.
- Several external experts were added to the LHCC ATLAS referee team for the purpose of reviewing the TDR. The LHCC is grateful to Alan Honma, Steve Nahn and Paolo Petagna for serving in this capacity. The LHCC Chair and UCG Chair were also included to complete the membership of the LHCC ITk Strip TDR Review Team (the 'Review Team').
- 16/12/16: An updated draft TDR version was submitted to the Review Team. This was complete in layout with the exception of the chapter on Performance & Physics.
- 20/12/16: The Review Team met to agree the timetable for the subsequent review and to assign responsibilities among the Team members.
- 20/1/17: A complete draft TDR version, including the chapter on Performance & Physics, was submitted to the Review Team.
- 30/1/17: The Review Team met to discuss the draft TDR and identify a first round of issues requiring clarification and/or discussion. A list of questions was subsequently supplied to ATLAS.
- 8/2/17: The Review Team met with ATLAS ITk system representatives and ATLAS management to discuss the issues raised and the ATLAS responses, and to identify further items requiring clarification. A subsequent list of topics and suggestions for the format and scope of the formal LHCC review, was sent to the ATLAS management.
- 21/2/17: The Review Team conducted a formal review of the draft TDR. Detailed presentations were received from ATLAS on: 1) overview and rationale for the Strips (and implications for the Pixels) system layout; 2) performance and physics; 3) sensors and modules; 4) mechanics and cooling; 5) electronics, power supplies and cables; 6) integration and installation; 7) [with the UCG] management, schedule, risks, and finance.
- 23/2/17: The Review Team findings were presented to the LHCC in closed session. It was found that the TDR is a monumental document that contains a wealth of detail and represents the reference design for the ITk Strips system. The Strip tracker as proposed was found to be of a sound design. In conjunction with the proposed Pixel system the

complete tracker will address the tracking performance required to do physics in the high-luminosity LHC era. The design will maintain the current tracker performance levels in an environment with event-pileup values as large as 200, as well as extending tracking coverage into the forward regions. While there are many technical issues and associated risks to be overcome, no 'show-stoppers' were identified.

- However, a number of presentational issues were identified and ATLAS was requested to make corresponding improvements for incorporation into the final TDR. The most important of these was a request for a clearer presentation of the performance in terms of measurement capability in benchmark physics channels and in the context of representative models of Beyond-SM physics.
- LHCC gave its provisional approval of the draft TDR and recommended that the UCG review should proceed. It was agreed that, subject to satisfactory completion of the LHCC's requests, and subject to the findings of the UCG, the final TDR would be considered for approval at the May LHCC meeting.
- 7/4/17: The final version of the Strip TDR was made publicly available by ATLAS.
- 14/4/17: A package of additional materials to support the UCG review was made available by ATLAS to the UCG review team.
- 24/4/17: The UCG review team met with ATLAS ITk system representatives and ATLAS management for first-round discussions. Questions and comments were fed back to ATLAS in preparation for the formal review at the May LHCC week.
- 8-9/5/17: The UCG review team held a formal review of the Strip TDR. They concluded that the cost estimate, resources, schedule, and risk level are reasonable for the current stage of the project. They recommended Step 2 approval by the RB and RRB to allow resources to become available and MOUs to be signed. They recommended that, to ensure success, ATLAS, the LHCC and CERN management must closely monitor the funding situation and technical progress of this extremely complex project.
- 11/5/17: The LHCC, having satisfied itself that its requests for clarifications had been incorporated into the final TDR version, and noting that the UCG review had not identified any additional issues beyond those normal for a large project at this stage, formally recommended the Strip TDR for approval. The LHCC thanked and congratulated ATLAS for their achievement and for their prompt and constructive engagement with the review process.

2. Report on the LHCC review of the ATLAS Phase-II Muon Spectrometer TDR

Review panel: Philip Burrows, Paul Karchin, Pierluigi Paolucci, Blair Ratcliff, Rob Roser (chair), Concettina Sfienti, William Wisniewski, Darian Wood

LHCC 131, 13-14 September 2017

The LHCC reviewed the Technical Design Report for the ATLAS Muon Spectrometer Phase-II Upgrade required for high luminosity running. The TDR document detailed the physics motivation for such an upgrade, the electronics modifications to all three subsystems (RPC, MDT and TGC), as well as the addition of a fourth layer to the RPC system. Furthermore, included is a description of the power systems, impact of a potential shift to an environmentally friendly gas mixture, as well as the installation plan and description of the project management.

The goal of this upgrade is to preserve the ability of the muon system to trigger at current thresholds in a much higher luminosity environment and maintain muon acceptance at today's values. We concluded that the muon upgrade is well motived as an appropriate response to the challenges of running at the HL-LHC, and is properly matched to the physics goals.

The committee felt that at this stage, we can only provide conditional approval. The TDR, as presented, identified a number of R&D efforts underway that can impact final design. Thus, it is unclear to the reader what is the “baseline” system that is being proposed for approval.

For final approval, please identify clearly what is the baseline plan. The R&D described should be presented as possible options. If this R&D is successful and can be adopted, describe what the impact to the overall project would be in shifting the baseline.

LHCC 132, 30 November - 1 December 2017

A revised version of the Muon TDR was approved by the LHCC to proceed to the UCG review on November 28th with the following report added to the minutes of the November/December session of the LHCC:

The LHCC reviewed the ATLAS Muon Spectrometer Phase-II Upgrade Technical Design Report required for high luminosity running for the second time. At the last meeting, the committee granted conditional approval for this upgrade but asked for increased clarity in several areas. Namely, the proponents needed to identify clearly what is the baseline plan for the muon upgrade. The R&D described should be presented as possible options. Finally, if this R&D effort is successful and can be adopted, to describe what the impact to the overall project would be in shifting the baseline.

Based on the committee’s guidance, the ATLAS muon group produced an updated version of the TDR with several improvements for LHCC review. They provided updated performance plots and improved clarity on how simulation was used for physics prospects. A detailed discussion on greenhouse gas impact and plans was added. A refined RPC discussion clarifying what is in the baseline design and R+D opportunities to improve performance was also added. The power supply chapter was modified to include more modules than was originally described. Finally, the management chapter was significantly updated with much more detail than the original version.

The committee was pleased with added clarity provided in the updated version of the TDR and fully approve this version. The committee was also quite impressed with the latest round of presentations and information. In a few short months, it seemed that this upgrade project is functioning much more like a coherent team with significantly improved communications and ownership of the project that did not come across in the first review.

3. Report on the LHCC review of the ATLAS Phase-II LAr Calorimeter TDR

Review panel: Philip Burrows, Claudia Cecchi (chair), Mauro Donega, Jean-Louis Faure, Peter Krizan, Fabienne Kunne, Martijn Mulders, Bob Tschirhart, Bill Wisniewski

LHCC 132, 30 November - 1 December 2017

The TDR for the Phase-II upgrade of the Liquid Argon calorimeter has been submitted in September, and over a period of two months, the Liquid Argon Phase-II Calorimeter Upgrade Review Panel evaluated the scope of the upgrade project for the HL-LHC versus scientific reach and technical choices employed for the optimization of the design.

The electronic upgrade of the detector is well justified in view of the High Luminosity running. The motivations of the upgrade have been clearly presented going from pile-up mitigation, to radiation tolerance issues and compatibility with the Phase-I Trigger upgrade. The necessity for the LAr upgrade is well defined, even if many design choices have to be finalized. Some parts of the upgrade have, from the technical point of view, stringent requirements, but they have been shown to be feasible on the proper time scale.

Going into more details:

- Preamplifier and Shaping boards have been tested for two of the proposed technologies (65 nm and 130 nm ASICS). Some noise issues have been detected.
- ADC ASICS is the area presenting more difficulties. The baseline option, based on a custom 65 nm ADC, has been presented. A first version of the board has been tested, with some problems related to the loss of ENOB (equivalent number of bits) under investigation.
- The full prototype for the integrated Preamplifier/Shaper + ADC + optics is foreseen for 2021/2022.
- The HEC (Hadronic Endcap Calorimeter) needs a dedicated preamplifier/shaper board due to the opposite polarity signal and because of a different gain stage needed in one section.
- A new possible location for the LVPSs (Low Voltage Power Supply) has been discussed. The baseline option is at PP2 inside the toroid, where radiation is not an issue, but where a larger magnetic field is present, and longer cables are necessary.
- The off-detector electronics main board LASP (Liquid Argon Signal Processing), based on a monolithic blade ATCA (Advanced Technology Computing Architecture), shows a power requirement exceeding the specified upper limit of 400W/slot, this problem is under investigation.

Detector performances have been discussed starting from the assumption of reaching, with the upgraded calorimeter, the same performance as in the run 2 data taking. The optimistic performance scenario, which assumes the constant term and the pileup noise can be significantly reduced, is able to achieve this goal, but the reconstruction algorithms available today have not yet demonstrated this performance. The review panel asked to explicitly highlight and quantify in the TDR the benefits arising from the availability of the full granularity and history of energy deposits in a bunch crossing for triggering and PU (pile-up) filtering.

Based on the technical and scientific review, approval is given for the project to proceed to the UCG review.

4. Report on the LHCC review of the ATLAS Phase-II Tile Calorimeter TDR

Review panel: Philip Burrows, Claudia Cecchi (chair), Mauro Donega, Jean-Louis Faure, Peter Krizan, Fabienne Kunne, Martijn Mulders, Bob Tschirhart, Bill Wisniewski

LHCC 132, 30 November - 1 December 2017

The TDR for the Phase-II Upgrade of the TileCal calorimeter has been submitted in September, and over a period of two months, the TileCal Phase-II Calorimeter Upgrade Review Panel evaluated the scope of the upgrade project for the HL-LHC versus scientific reach and technical choices employed for the optimization of the design. TileCal is the ATLAS Central Hadronic calorimeter made of scintillator tiles, read out by PMTs using Wavelength-shifting fibers (WLS).

Motivations of the electronic upgrades, very well justified, are mainly based on the new ATLAS trigger and readout architecture (higher latency and trigger rates), radiation tolerances, and improvements of the reliability of the system by implementing redundancies on the new electronic boards.

Some topics have been deeply investigated as they have been recognized to be the weaker points of the complete upgrade chain.

- The scintillators will not be replaced, and radiation damage could affect the performance of the detector. Starting from integrated doses over the 2016 data taking of ATLAS and from previous irradiation campaigns, an extrapolation of the dose at the end of HL-LHC has been presented. A 10% light loss has been estimated, but due to large systematic uncertainties, and because of differences in the material of the tiles placed in different regions of the detector, the review panel has asked for more studies in this respect. In particular a simulation of the detector response in the most exposed regions has been requested for an extreme aging scenario.
- The PMT response and absolute gain is continuously monitored by the laser system and can vary due to change in gain, opacity of the window, or variation in the quantum efficiency. Changes of the response as a function of integrated charge deposited has led to the decision of replacing only PMTs whose expected response loss will be greater than 20% at the end of HL-LHC. This amounts to a total of about 800 PMTs. In this context, the calibration system is crucial and new electronic control and a new hydraulic system are necessary for the upgrade.
- The Low Voltage Power Supplies (LVPS) are custom made devices with stringent size requirements due to the limited available space. The reliability of these devices is of fundamental importance, because they can only be accessed during longer breaks in LHC operations. Its operation relies on the ELMB++ interface, for which only a conceptual design is available at the moment. This currently represents the biggest uncertainty in the design of the device.
- The High Voltage Power Supplies (HVPS) positioning has been thoroughly discussed. The possibility to install them in a not irradiated and accessible environment is very appealing, but 10000 pairs of 100 m long cables would be required. At present only one company is able to supply the necessary multi-core cables and connectors for 32/48 pairs are not available. This baseline solution is therefore still under investigation and a backup solution is available.

Although the detector performance has been presented for $\mu = 200$, some of the physics results were only presented with a μ value of 40, and a trigger result demonstrating upgrade trigger performance was shown for $\mu = 50$. In addition, many of the performance plots include results only for the central barrel, and do not include the extended barrel. The review panel has requested to see all performance and physics plots for $\mu = 200$ and including the extended barrel.

Based on the technical and scientific review, approval is given for the project to proceed to the UCG review.

LHCC 133, 1 - 2 March 2018

Final LHCC recommendation for approval of the Phase-II Tile TDR had been deferred in the previous session of the LHCC to January 2018, pending more information on scintillator degradation and on detector performance at nominal pile-up values, as well as personnel shortages in the senior project management. The responses, including a progress report on renewing the management, were presented to the LHCC on 25-26 January and deemed sufficient for the LHCC to recommend approval.

5. Report on the LHCC review of the ATLAS Phase-II TDAQ TDR

Review panel: Volker Beckmann, Ulf Behrens, Amber Boehnlein, Vladimir Gilgorov, Michael Huffer, Thomas Kuhr, Rainer Mankel (chair), Dave Newbold, Pierre Vande Vyvre

LHCC 133, 1 - 2 March 2018

The TDR for the Phase-II upgrade of the ATLAS Trigger and Data Acquisition system has been submitted in December, and over a period of more than two months the panel has reviewed this proposed upgrade. The main goal is to accommodate the ultimate HL-LHC data-taking conditions at a mean pileup of 200 interactions per bunch crossing, and to enable a broad and challenging physics program. The TDAQ system consists of a hardware-based Level-0 trigger, designed for 1 MHz of trigger rate and a maximum latency of 10 μs, a Data Acquisition system for an input bandwidth of 5.2 TB/s and an Event Filter with a maximum output event rate of 10 kHz.

The Level-0 calorimeter and muon triggers are logical evolvements of the systems that will be used in Run 3. Enhancements of the readout electronics remove latency constraints and allow operation at the required trigger rate and latency. The hardware implementations rely strongly on FPGAs and the ATCA standard; the whole project thus depends on the sustained availability of ATCA as a viable standard over the following decades. The Global Trigger is a powerful system allowing for detailed topological selections already at L0 level; it strongly depends on very substantial firmware developments. The Central Trigger System is largely based on conservative extrapolations of the Phase-I components, and thus considered to be of at most limited risk.

The Data Acquisition system uses commodity hardware and software wherever possible. Its readout system is based on one type of board (FELIX), which greatly homogenizes development and management. In comparison to today's high end HPC installations or large computing centers, the overall throughput, storage capacity, storage throughput and overall number of computers seem within bounds of feasibility. The network architecture features sufficient redundancy.

The Event Filter consists of a processor farm (EFPU) and a hardware-based track trigger (HTT). The processor farm uses vertices and tracks to mitigate effects of pile-up. In order to benefit as much as possible from the evolution of technology, the paths for different solutions must be kept open, and the selection of hardware can only be made at a later point in time.

The hardware-based track trigger (HTT) performs the track reconstruction tasks of the event filter. It is based on Associative Memory ASICs for pattern recognition using an exhaustive road search, and FPGAs which are responsible for the track fit. Offloading this task to the HTT is estimated to save a factor 10 in terms of farm node CPU for the Event Filter. The panel considers the HTT a very complex project. Very substantial engineering tasks on ASICs, firmware and system integration are needed, as well as significant technical developments before the final ASIC is available. Commissioning is also very challenging and there may be only limited time available. There is no firm basis of practical experience from the FTK yet, from which the performance and resource needs could be extrapolated towards Run 3 and Phase-II. It will be important to validate and if necessary update the HTT strategy with the experience of the FTK operation as soon as possible. The lessons from the FTK development and implementation should be closely evaluated for the full benefit of the HTT project. Also the possibility of a "Plan B" should be kept in mind.

In many areas the project relies critically on timely development of the firmware. The amount and difficulty of the required firmware, as well as the organization of the inevitable, geographically distributed development process, and the large-scale configuration and management of the various firmware blocks are formidable challenges. Advance evaluation of performance and resource usage is of high importance.

Motivated by uncertainties of predicting trigger rates for hadronic objects and occupancy of inner pixel layers, the design of the TDAQ system foresees the optional evolution to a scenario in which the Level-0 trigger is split into two levels, referred to as Level-0 and Level-1. The Level-0 rate is increased to 2-4 MHz with a latency of 10 µs. Upon a Level-0 accept, a region-of-interest based readout of the strip tracker and full readout of the outer pixel tracker is initiated, and a new system named L1Track performs regional tracking with the technology as used in the HTT. These tracks are used for pileup mitigation, resulting in a Level-1 rate of 600-800 kHz at a latency of 30-35 µs. The earlier availability of tracks in the trigger decision is clearly an advantage, and opens attractive additional physics options, which could e.g. permit lower thresholds for important Higgs pair production channels. Challenges are the very high readout rate of the inner tracking system, and the difficult commissioning of the L1Track system, which makes this not a desirable option for the HL-LHC startup. Significant additional resources would be required to implement this evolved scenario.

In summary, the review panel is satisfied with the findings concerning the ATLAS TDAQ Phase II Upgrade TDR. Both scientifically and technically, the TDR is a sound document. The design is well motivated and driven by physics goals, and suitable to keep the thresholds for key physics processes reasonably low even under HL-LHC pileup conditions. The panel recommends for the TDR to proceed to the UCG review.

6. Report on the LHCC review of the ATLAS Phase-II ITK Pixel TDR

Review panel: Roberto Calabrese, Alan Honma, Katja Krüger, Luciano Musa, Steven Nahn, Paolo Petagna, Rob Roser (chair), Jeff Spalding

LHCC 133, 1 - 2 March 2018

The TDR for the Phase-II upgrade of the ATLAS Inner Tracker Pixel Detector has been submitted in December, and over a period of two months, the Pixel Detector Upgrade Review Panel evaluated the scope of the upgrade project for the HL-LHC versus scientific reach and technical choices employed for the optimization of the design.

The primary motivation of this detector upgrade is to preserve the physics performance of the current Run 2 detector in an environment where much higher data rates, interactions per crossing, and radiation dose are expected. The primary metrics for design include tracking robustness against detector failures, minimizing the total cost and minimizing the CPU required for track reconstruction.

The experiment presented a design to meet these requirements. They refer to the design as an "inclined duals" layout. It uses a combination of "planar" and "3D" silicon sensor technologies. The 3D is used in layer 0 where one needs maximal radiation hardness. With this design, there is a possibility of 13 hits on a track in the barrel and 9 hits in the forward region. This design significantly reduces the amount of silicon in the detector, allows for high tracking efficiency even if the hit efficiency is less than ideal, and appears to perform well with today's software and 200 pile-up events.

The committee believes that the design described in the TDR meets the performance goals with appropriate robustness against operational failure of individual components, and feels that this is a solid baseline approach even if there are design choices that still must be finalized.

At a high level, some of the design decisions that still need to be made include:

- Pixel shape (50x50 µm2 vs 25x100 µm2), optimizing track pT and position resolution, as well as two-track separation.

- Services and support design is less advanced, especially layer 0 and 1.
- The possibility to use passive pixel sensors using standard CMOS processes.
- Biasing structure (or no biasing structure) for sensors.
- Whether to use a monolithic CMOS modules (drop-in replacement of the hybrid module, with similar performance) in the outer barrel layer. This is a potential cost saving, but relies on significant R&D in the next two years.
- Details of the serial powering scheme are still to be developed and decided.
- Outer barrel: exploring possibility to use quad modules in the inclined section, to reduce number of modules (-1000) and simplify loading.

The review committee expressed some concerns to ATLAS management based on the current level of maturity of the design and encouraged the collaboration to make decisions as soon as it is sensible to do so and establish milestones for when decisions could be made. The collaboration has launched a "Layout Task Force" to further optimize the layout with conclusions expected by July 2018. The review committee questions whether this is sufficient time to make both the high-level optimization design decisions and then understanding all the implications on mechanical supports, services and cooling budget. The committee asked for a few modifications to the TDR to document improved knowledge transmitted in this week's presentations.

The review panel finds physics goals and technical implementation of the Phase-II ATLAS Inner Tracker Pixel Detector well matching with the HL-LHC programme and recommends the TDR to proceed to the UCG review of the project.

7. Report on the LHCC review of the CMS Phase-II Tracker TDR

Review panel: Gianluigi Casse, Marcel Demarteau (chair), Dmitri Denisov, Claudia Gemme, Eric Kajfasz, Masahiro Kuze, Petra Riedler, Marcel Stanitzki

LHCC 131, 13 - 14 September 2017

Over a period of about two months the CMS Phase-II Tracker Upgrade Review Panel evaluated the scope of the Tracker Upgrade project for the HL-LHC versus scientific reach and the methodology employed for the optimization of the design. The panel also concentrated on identifying key technical risks and assessed the technical readiness of the project. Early on the collaboration made a choice to implement a L1 track-trigger based on track vectors (stubs) rather than hits, which required two closely spaced silicon sensors (pT-modules). Given the boundary conditions on pile-up and occupancy, this has led to a tracker design of three distinct systems: a Pixel detector at the innermost radii, hybrid Macro-Pixel-Strip modules at intermediate radii, followed by Strip-Strip modules at the outer radii. The collaboration has completed a thorough evaluation of scope versus cost versus performance by studying the effects of parameters that can be varied progressively with gradual impact (such as strip pitch and pixel size) and discrete steps that have large impact (such as the number of layers). This optimization process has led to a reduction in silicon area by nearly 25 m2, with a commensurate reduction in cost, compared to the design proposed in the Technical Proposal. The design compromises on a couple of performance parameters, but good use has been made of technology improvements and the design is overall robust. The extended pseudorapidity coverage provides for extended physics reach and better missing transverse energy resolution, which enhances physics sensitivity across the board.

The availability of the RD53-A chip, which is behind schedule, is critical to underpin and validate the design of the pixel detector. Minor schedule delays are proposed to be mitigated through use of schedule contingency or a compressed production schedule, but the project is fully exposed to significant delays in the availability of the RD53 chip. Besides the RD53 chip, the project is further dependent on three additional common chips that are not under the control of the project. Additional readout chips in similarly demanding technology, one of which is behind schedule, are required for the outer tracker and there is limited time for long-term, full-scale prototype testing with final versions of all components.

Sensors for the inner tracker have not been tested to the full radiation dose. It is also noted that there still is a large parameter space in sensor specifications that is still being researched. Expeditious convergence and decisions on all open issues should be pursued. In fact, the combined delays in the availability of all components will be reflected in shorter time for appropriately testing larger sections of the detector. If in the outer tracker the individual module is being powered relatively independently through a dedicated DC-DC converter, the inner tracker presents more delicate system aspects, like serial powering among others.

The hybrids for the outer tracker are demanding and form a most critical link in the construction of the silicon modules. The acquisition strategy for the hybrids calls for qualifying three vendors, which is strongly encouraged. Strong quality control and oversight is required to ensure satisfactory production. Vendors should be evaluated for single-point failures.

Due in part to the high voltage requirements and trigger implications requiring precision alignment, the module production has to meet highly demanding quality assurance specifications, with limited time for testing with final components. Implementation of rigorous on-site quality control at production and vendor sites is required and the software tools to track and monitor the quality assurance should be setup immediately and integrated in the procedures of the R&D phase. The decision to base the Level 1 Track Trigger on the FPGA approach is fully supported.

In summary, the Tracker Upgrade Project pushes tracker designs into a new paradigm with a scope that is justified in terms of technical realization as well as physics performance. The design is bold, but no technical showstoppers have been identified. It is critical that the remaining R&D be supported as strongly as possible and that appropriate funding for the R&D efforts be provided. Strong oversight is required to keep the schedule. Based on the technical and scientific review, approval is given for the project to proceed with the UCG review.

8. Report on the LHCC review of the CMS Phase-II Barrel calorimeter TDR

Review panel: Franco Bedeschi (chair), Marco Delmastro, Dmitri Denisov, Doug Glenzinski, Gerald Eigen, Alex Kluge, Alex Kuzmin, Francesco Lanni

LHCC 132, 30 November - 1 December 2017

Over a period of about two months the CMS Phase II Barrel Calorimeter review panel has evaluated the proposed upgrade of the CMS barrel calorimeter. The main motivations for the upgrade are the need to significantly reduce the noise in the APDs and their rate of "spikes", and to make the calorimeter compatible with the higher Level 1 trigger rates and increased trigger complexity demanded by the high luminosity operation. The panel found these motivations very solid. Additional findings are that the project appears to be in a very good stage of advancement for the TDR phase and is well organized and managed by a competent and experienced team. Moreover, most studies done in the TDR cover a range of integrated luminosity up to 4500 fb^{-1}, in excess of the 3000 fb^{-1} planned for the whole HL-LHC running period. This demonstrates that the proposed upgrades have adequate performance margins.

The radiation models used in the TDR are accurately tuned on the data and show that radiation damage to the $PbWO_4$ crystals has acceptable effects on the energy resolution, but the dark current and corresponding noise increase of the APDs is a serious problem. This is solved by reducing the APD operating temperature from 18 to 9 degrees C. Remarkably this is achieved retaining most of the current cooling system. The hadron barrel calorimeter scintillator is also degraded by radiation, but the corresponding light loss most likely will not be a problem, considering the higher quantum efficiency of the SiPM readout that will be implemented during the Phase-I upgrade. More studies are needed to reach a final decision on the need to replace the inner scintillator layers. The review panel recommends that this decision be made before the January 2018 UCG meeting.

The two ASICs of this upgrade are the amplifier with fast shaping time (CATIA) and the ADC with 160 MHz sampling frequency (LiTE-DTU) to tag APD spikes. The development of CATIA is advanced. Successful prototypes have been produced and all major decisions on the chip design have been taken. The simulation of the signal output reproduces very well the observations, thus giving confidence on the performance estimates. The LiTE-DTU chip is still being designed. The ADC cell is already well specified and will be bought from an external company. The remaining part of the chip still needs substantial work. The review panel recommends completing as soon as possible the studies needed to determine the specification of the functionality of this chip (size of the buffer FIFO, latency to deliver to BCP, compression scheme and BW contingency), preferably before the first submission. The power distribution board is based on the FEASTMP_CLP radiation hard DC-DC converter developed at CERN. This unit has wide use in the LHC experiment upgrades, but has shown problems recently in a specific application, so attention should be paid to the DC-DC converter tests.

The new back-end boards, BCP, are critical to reach the latency and rate requirements of the upgraded Level 1 trigger. These boards are common to the EM and hadronic part of the barrel calorimeter and appear to satisfy the requirements, however the review panel recommends completing the study of the total latency achievable, in particular considering the inter-board communication and front-end data distribution latency. The details of the clock distribution system needed to achieve the planned 30 ps timing resolution are not available yet and should also be defined soon. In any case it is understood that a minor degradation of the timing resolution is not critical for the final detector performance.

The time needed to rework and install super-modules is derived from experience, making the schedule realistic, but supervision and coordination with other systems needs to be better clarified.

The review panel finds physics goals and technical implementation of the CMS barrel calorimeter upgrade well matching with the HL-LHC programme and recommends the TDR to proceed to the UCG review of the project.

9. Report on the LHCC review of the CMS Phase-II Muon TDR

Review panel: Florian Bauer, Alessandro Cardini, Silvia Dalla Torre, Dmitri Denisov, Hubert Kroha, Paul Newman, Mario Martinez-Perez (chair), Alessandro Polini, Osamu Sasaki, David Waters

LHCC 132, 30 November - 1 December 2017

The committee reviewed the technical Design Report (TDR) of the CMS muon systems, which describes the foreseen detector upgrade in view of the HL-LHC period starting in 2026. Different elements of the read-out electronics for the muon chambers: Drift Tubes (DT), Cathode Strip Chambers (CSC) and Resistive Plate Chambers (RPC) need to be replaced in order to cope with the expected Level 1 trigger rate of 750 kHz and the Level 1 trigger latency of 12.5 microseconds. The better timing capabilities of the new trigger electronics allows moving the trigger primitive logic to the back-end electronics, leading to a more versatile trigger logic, also aiming for an increased background rejection rate. The TDR proposes the construction of new muon chambers in the forward region. This includes two new Gas Electron Multiplier (GEM) detector sets and two improved RPC chamber sets.

The CMS experiment carried out extensive longevity studies of the four different muon chamber technologies (DT, CSC, RPC, GEM), with the aim of determining whether their functionalities can be maintained up to the expected HL-LHC luminosity levels. Except for the DT chambers, the other three muon chamber technologies did not show to date any sign of ageing. The committee welcomes the mitigation measures taken by the experiment and notes that this deterioration will only have a mild effect in the muon reconstruction.

The proposed upgrade of the DT and CSC read-out electronics is mandatory, in order to maintain the detector performances over the entire HL-LHC period. The improved trigger capacities will preserve the physics program. For both, DT and CSC chambers, prototypes of upgrade read-out electronic cards either exist or are well advanced. The remaining R&D effort is small. In case of the DT, the experiment plans to instrument a whole sector with the new electronics already in 2019, which can be seen as the ultimate validation of the project. The proposed upgrade of the RPC's link system is well motivated to improve the timing resolution and to provide a higher bandwidth.

The construction of new chambers in the pseudorapidity region 1.8 – 2.8 promises to add redundancy to the muon reconstruction, to control the trigger rates at low pT, and to offer new functionality to trigger on exotic signals involving displaced muons, long-lived particles, and heavy charged particles. Altogether, the committee is convinced that these potential improvements are worthwhile enhancements of the trigger.

Two new sets of GEM chambers are proposed, ME0 and GE2/1, which will cover the pseudorapidity regions 2.0 – 2.8 and 1.6 – 2.4, respectively. The technology proposed follows closely that of the already constructed GE1/1 chambers. The layout of the new chambers and the number of layers proposed are well motivated by space constrains, signal efficiency and background rejection. No signal deterioration has been observed so far during the ME0 aging studies. Similarly, the committee takes note of the positive results obtained on the discharge probability measurements carried out by the experiment.

Two improved RPC chambers are proposed, RE3/1 and RE4/1, in the pseudorapidity region 1.8 – 2.4. The new chambers feature a smaller gap and different charge threshold and resistivity to better handle the HL-LHC rates. In addition, a new 2D scheme for the readout of the strips is considered to improve the position resolution and to reduce the number of read-out channels. The committee takes note of the fact that two prototypes of different sizes have already been tested successfully. The design and test of the front-end electronic boards, based on Si-Ge technology, is still in progress. However, the read-out scheme has been validated in a small prototype.

Concerning the strategy to reduce the emission of F-gases by CSC and RPC chambers, the CMS experiment presented a comprehensive plan. In addition, studies on alternate gas mixtures are progressing.

Finally, the experiment presented the physics motivation for the new upgraded chambers in terms of a variety of physics channels involving multi-leptons in the final state, for which the presence of extended muon coverage would be beneficial.

The LHCC panel would like to formulate the following recommendations:

- The committee considers that the DT ageing results are not completely understood and therefore recommends continuing the irradiation and the related studies.

- The DT project plans to instrument the detector with new electronics in 2019. This action is an example to be followed. The panel encourages the rest of the systems to do so wherever possible.
- The fact that both GE2/1 and ME0 use (as much as possible) solutions introduced for GE1/1 is a good conservative attitude. The panel observed that there is limited feedback from the slices already installed in CMS and therefore this test cannot guide the construction, which is starting now. However, the panel considers this is an important test for CMS GEMs. Any information from this test will provide an important guidance on the GEM operation for CMS.
- The panel encourages the project to continue the GEM discharge studies under "CMS" conditions. This will allow the collaboration to integrate enough discharges such that definitive conclusions can be drawn on the robustness of the holes and the chambers against shorts.
- The panel consider that the proposed strategy to reduce F-gases in order to be compatible with the CERN requirements on greenhouse gases is viable. In parallel, studies on alternate gases and gas mixtures should be pursued, but the final choices must take into account the detector performance and longevity.
- Altogether, the committee finds the improved RPC project convincing, given also the already acquired experience in the detector construction and tests. The committee recommends following in depth the validation of the choices for the Si-Ge front-end electronics in the improved RPCs and the challenging prospect of the 2D readout, which need to comprise comprehensive tests on real-size detector prototypes.
- The committee finds that the physics case was not presented in enough detail and, in particular, it is not completely clear what the gain of the additional pseudorapidity coverage is in terms of physics output. We recommend CMS to continue to work on the physics motivation and provide clear evidence of the separate impact of each muon upgrade and not just the combined impact of all upgrades taken together.
- The review committee finds the CMS muon system TDR technically sound and satisfying the specifications of the HL-LHC programme. The committee therefore approves the TDR (pending information of the individual upgrades on the physics reach) to proceed to the UCG review of the project.

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In its previous session the LHCC had given provisional approval for the CMS Muon TDR to proceed to the UCG review, pending more information on the physics motivation of the upgrade, in particular the gain of the additional pseudorapidity coverage in terms of physics output, and clear evidence of the separate impact of each muon upgrade and not just the combined impact of all upgrades taken together. The CMS collaboration provided additional information to clarify the role played by each detector upgrade in boosting the performance of the detector. The information was presented in terms of the separate impact of the extended muon coverage in five relevant physics channels. The committee found that, after including this information in the TDR, the physics case for the muon detector upgrade is clearly demonstrated and in January recommended the definitive approval of the TDR to continue with the UCG review of the project.

10. Report on the LHCC review of the CMS Phase-II Endcap Calorimeter TDR

Review panel: Catarina Bloise, Marcel Demarteau, Dmitri Denisov (chair), James Dunlop, Howard Gordon, Beate Heinemann, Eric Kajfasz, Alex Kuzmin, Petra Riedler, Chiara Roda

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The committee received the final version of the TDR on December 21, 2017. Three Vidyo meetings with CMS took place between early January and late February to discuss the project. Culmination of the review was a full day session on February 26th, 2018, where the project and the remaining referee questions were discussed.

The existing CMS endcap calorimeter (based on crystals (electromagnetic) and scintillator/WLS (hadronic)) will not withstand HL-LHC radiation doses. This region of calorimetry (eta between ~1.5 and ~3.0) is critical for both missing energy and various physics objects reconstruction, including leptons, photons, and jets. As a result CMS had to develop a new design of the endcap calorimeter to provide adequate performance in the harsh radiation and pileup conditions of HL-LHC. CMS, internally, went over the comparison of various designs and selected the option which is documented in the TDR submitted to the LHCC. The proposed endcap calorimeter is a silicon sensor sampling calorimeter (absorber materials W, Pb and stainless steel), followed by plastic scintillator tiles with direct SiPM readout for the volume with lower radiation levels (absorber material is stainless steel). The electromagnetic calorimeter is fully based on silicon sensors while the hadronic calorimeter is a combination of silicon sensors and scintillating tiles.

The proposed design is unprecedented in complexity, driven by the harsh radiation and pile-up requirements in the forward region of the LHC detectors: the largest number of calorimeter readout channels to date (6 million silicon high precision analog channels), a huge silicon area, integrated and un-accessible readout electronics, integrated and highly segmented CO2 cooling for the 100kWof heat in each endcap, large high speed data flow to the Level 1 trigger system and DAQ and many others. While challenging, the proposed design is expected to be able to operate in the harsh HL-LHC environment at a level similar to the endcap calorimeter performance during Run 2 and in some cases provide improvements in performance.

Silicon sensors are based on 8" wafers with ~1 cm2 and ~0.5 cm2 cell area (smaller and thinner sizes are closer to the beam). Silicon cell inter-calibration, performed using signals from MIP particles, is required to reach ~3% accuracy in order to keep the energy resolution constant term for electromagnetic showers below 0.5%. In the region of lower radiation doses suitable for scintillator/SiPM detection a less expensive design to cover the large area is selected. The size of the scintillating tiles varies from 2 x 2 cm2 to 5.5 x 5.5 cm2 with a total of 400k channels. Planes of silicon sensors and scintillator tiles are placed between calorimeter absorbers creating 28 longitudinal layers in the electromagnetic and 24 layers in the hadronic calorimeter. The committee notes that the inter-calibration procedure, which is among the drivers for the transverse calorimeter segmentation, has to be further developed using simulation and test beam data with the goals to estimate the systematic uncertainty affecting the procedure and to potentially simplify the calorimeter design and reduce its cost. The longitudinal calorimeter segmentation has to be optimized as well using benchmark physics processes instead of technical parameters (such as energy resolution). In particular the performance goals for the hadronic calorimeter should be clearly specified. Measurements and tests of sensors on 8” wafers are not yet available. The cost of the calorimeter will be affected in the case 8” wafers could not be used, it is therefore very important to monitor advances in this area.

Readout of the calorimeter sensors will be performed with a specially designed ASIC which is under active development. In addition to precise amplitude measurement, the time of each cell energy deposition will be recorded, providing an opportunity to reduce pile-up noise and to provide accurate time measurements of the electromagnetic and hadronic showers. CMS has to provide more details in the TDR on how timing measurements are going to be used and how they improve studies of the benchmark physics processes. The required high accuracy of the amplitude and time measurements make both the ASIC and the overall calorimeter electronics very demanding, including noise levels and reference timing distribution. CMS has to provide well defined specifications for the electronics components and proceed expeditiously to prototyping and full system tests, as issues with ASIC underperformance affected various LHC experiments.

The electromagnetic energy resolution of the calorimeter is $\sim 25\%/\sqrt{E}$, which is typical for sampling calorimetry. The single charged pion energy resolution is ~10% at transverse momentum of 100 GeV. Further improvements in the algorithms are expected to improve energy resolutions. Efforts in the algorithm development have to be increased to provide feedback on the calorimeter design.

The physics performance of the endcap calorimeter was studied using a set of physics processes, including Higgs boson studies and VBF jets processes. The expected calorimeter performance is compatible with Run 2 and in some cases even improved, for example, providing ~20% better Higgs to ZZ channel detection efficiency. It is important to continue developing a set of benchmark physics process simulations to be able to verify the performance of the selected calorimeter design.

CMS is progressing with prototyping of various elements of the detector, testing them in test beams, developing production sites as well as working on the engineering design and assembly procedures. Optimization of various elements of the detector is still in progress. The committee recommends to proceed expeditiously toward finalizing design choices, based on the required performance and cost/complexity of the system.

CMS proposed milestone plan aims to progress to the Engineering Design Review (EDR) for June 2020. This plan includes continuing developments of the silicon sensors, SiPMs and scintillator. In addition R&D and design plans are developed for the readout ASIC, silicon modules assembly, motherboards, tile boards, cassettes, system tests, mechanical engineering and integration, CO_2 cooling, back-end electronics, power and bias supplies. The committee finds the proposed plan overall appropriate, while intensive and challenging to be accomplished in the time available. CMS institutions involved in the project have to provide the required resources to finalize R&D by the time of EDR. CMS and the LHCC will have to closely monitor the progress of the project.

The committee provided a list of specific recommendations to CMS, in addition to those described above. These recommendations are expected to be addressed in the updated version of the TDR or on the way towards the EDR. Among these recommendations are specification/studies of the hadron calorimeter (including calibration procedure), system integration, as well as studies of the most probable failure modes in the fully assembled detector during long term operation. The results should then be used to optimize the design, including segmentation and various systems connections.

The committee observed that the endcap calorimeter upgrade team is strong, dedicated, with much experience and well organized. The team is actively engaged in addressing the remaining design and construction challenges of the endcap CMS calorimeter.

Review outcome: the proposed design of the high granularity endcap calorimeter for the CMS upgrade is challenging but is expected to satisfy requirements of the harsh HL-LHC running conditions. Continuing R&D and simulation studies are needed to verify and optimize the design choices. We recommend the TDR to proceed to the UCG review of the project.

References:

All documents are publicly available in CDS: http://cds.cern.ch

UCG Reports and TDRs

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   CERN-LHCC-2017-008 ; UCG-022
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8. CMS Phase-II Barrel calorimeter TDR
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9. CMS Phase-II Muon TDR
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10. CMS Phase-II Endcap Calorimeter TDR
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Minutes of the LHCC meetings

LHCC130 – CERN-LHCC-2017-007, 10-11 May 2017

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