Status of the LHCb upgrade

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1 Introduction

The upgraded LHCb detector will be able to read out all sub-detectors at 40 MHz and to select physics events of interest by means of a pure software trigger at the bunch crossing rate of the LHC.

The upgrade as described in the Letter of Intent [1] and Framework TDR [2] has been progressing towards submission of Technical Design Reports (TDRs) of all sub-detectors according to schedule. The TDRs for the Vertex Locator (VELO) [3] as well as for the Particle Identification (PID) detectors [4] have been reviewed by the LHCC and by the Upgrade Cost Group, and subsequently approved by the Research Board in March 2014. The LHCb Tracker TDR [5] for the Upstream Tracker (UT) and Scintillating Fibre Tracker (SFT) has been submitted to the LHCC in February 2014. The last TDR describing the Trigger & Online is in preparation and will be submitted to the committee in May. Thus, now the detailed cost breakdown for all detector components as well as the sharing of responsibilities among the involved institutes is available.

Negotiations with the funding agencies, for covering the expected CORE contributions to the various sub-detector components to which the participating institutes have committed, have been progressing well. We expect to submit the corresponding Addenda to the MoU for all sub-systems by the end of this year, and thus ensure timely construction of the upgrade detector within the cost envelope given in the TDRs, to be ready for installation during the 18 month long shutdown 2 of the LHC (LS2).

Now that the technology choices have been made, we are further optimizing the detailed layout of the detector using a small subset of the key physics channels for the upgrade. The decays under study are $B_s^0 \to \phi\phi$, $B_s^0 \to \phi\gamma$, prompt $D^{*+} \to D^0(K_S^0\pi^+\pi^-)\pi^+$ and $B^0 \to K^{*0}\mu^+\mu^-$. There are obviously many other important decays that are not included in this set, which is intended to be minimal, while allowing the full performance of the detector to be tested. A document with the relevant details will be released shortly.

In the following we give a brief update on the status for the tracking system and its expected performance as well as the particle identification detectors. We further review the status of the data processing as well as the progress in preparing for the LHCb upgrade in terms of interaction with the LHC machine groups, infrastructure, schedule and funding.

2 Tracking system upgrade

Since October 2013, several important decisions were taken, most notably the decision to use a full fibre tracker as the baseline solution for the three tracking stations behind the magnet. In addition, several important reviews were held, for the Upstream Tracker (UT) and the Scintillating Fibre Tracker (SFT), which shortly afterwards resulted in the submission of the LHCb Upgrade Tracker TDR [5]. The LHCb Upgrade VELO TDR [3] was already submitted at the end of 2013 and the VELO group is now proceeding to finalize the design for production. We detail here for each of the three sub-detectors of the tracking system the recent progress and expectations for the next half year.

2.1 Vertex Locator

Following the VELO silicon sensor and cooling technology decisions, further R&D was performed and a full software optimization was carried out in order to finalize the design for the preparation of the VELO TDR [3], submitted at the end of November. A detailed description of the L-shaped RF foil was implemented and the number of stations and their layout was optimized using minimum bias events passed through the full simulation in order to achieve full track reconstruction efficiency and optimum impact parameter resolution. The design was shown to be robust against radiation damage for the anticipated lifetime of the upgrade.

The geometry of the sensors, hybrids and modules was fixed and work has been ongoing to finalize the characteristics of the microchannel substrate. A design has been finalized which allows two plates to fit on a single 8-inch silicon wafer. There is a small increase in complexity with respect to the prototyped design, with the addition of a double etch to allow square input restrictions, through hole drilling, and the requirement for inner corner dicing. Before placing the final order a prototype has been produced at the EPFL clean-rooms to validate the performance. The R&D is now focusing on the vacuum soldering step to attach the fluidic connector to the microchannel substrate, and the long-term temperature and pressure cycling of the samples. For the pixel sensors themselves, following the initial prototyping the decision has been taken to pursue the final R&D step with two independent vendors which are qualified to produce radiation hard pixel sensors and orders were submitted for the final sensor design in February, with expected delivery in the Summer. The Timepix3 ASIC is continuing to be tested using the dedicated SPIDR readout system and has shown very satisfactory results, including the reconstruction of first tracks with a 2 GeV electron beam and a Micromegas detector. Wafer level probing has been completed and the first wafers are currently undergoing metallization, bumping, and thinning at one vendor. The first Single Event Upset (SEU) tests of the Medipix3 have been completed and have shown SEU sensitivity of the CERN HD cell library comparable to a standard cell library. The VeloPix design is progressing well, with the detailed layout of the pixel cell due to start shortly. The dedicated GWT serialiser design, which is expected to optimize power and bandwidth for the Velopix was finalized and a test chip submitted in February. Work is ongoing to layout a hybrid for the pixel Module-0, which will be constructed with Timepix3 ASICs. Detailed preparation work is ongoing for the forthcoming test-beams which will characterize the sensor and ASIC prototypes with a dedicated high speed telescope. In common with other upgrade elements the VELO faces a potential reorganization of the electronics milestones due to the recent decision of IBM to sell the chip fabrication foundry. The impact of this can be minimized, for instance by using alternative technology, and will be better known in the course of the next few months.

A global VELO electronics architecture review with external and internal reviewers took place in November, covering the entire signal chain from the ASIC outputs through to the TELL40 data processing. The conclusions of the review have been circulated and agreed by the VELO group and work is ongoing to address any areas of concern. In general the architecture was judged to be correct and compatible with the LHCb upgrade in general. The number of links will be optimized and the VELO team is actively developing code and evaluating the FPGA resources. The initial studies are extremely encouraging, showing that the LL1, Decoder and GWT protocol, together with the TELL40 VELO time reordering, will fit very well within the FPGA resources. At the same time improvements have been implemented in the software for clustering and tracking on the CPU. A VELO upgrade software review was organized in January, giving excellent feedback for the code design and next steps.

The effort to unify the different aspects of the VELO upgrade mechanical design has seen much recent progress. A kick-off meeting for the mechanical integration was held in March, with a follow up meeting shortly afterwards, and work is underway to organize a common repository for the designs and interfaces involving multiple institutes. The work on the RF foil thinning is also progressing well, with the studies of the chemical etching of the inner region showing a good performance with homogeneity at the level of approximately 15 μm. Work is ongoing to demonstrate the reliability and the application to the L-shaped foil.

2.2 Upstream Tracker

Since the last report, a conceptual design review of the Upstream Tracker and an electronics architecture review, with internal and external reviewers, took place in November 2013. Following these successful reviews, the UT group proceeded to write the UT chapter of the LHCb Upgrade Tracker TDR [5] which was submitted in February 2014.

The Upstream Tracker (UT) design is based on the "stave" concept described in the Tracker TDR. Active cooling is embedded in a carbon foam support structure, hosting hybrid circuits providing the electrical connectivity of the silicon front-end electronics elements to the back-end electronics.

Work on sensor prototyping focused on the test of ten Hamamatsu Atlas07 detectors and on custom-designed sensors with different detector technologies (n-in-p and p-in-n) being developed by Micron Semiconductor Limited. The Atlas07 detectors were characterized by measuring their capacitance and current versus applied voltage. It was verified that the maximum leakage current at 600 V is of the order of 1 μA and that the detector capacitance for a 10 cm strip detector is of the order of 12 pF or below, validating the specifications for the front-end electronics. Similar tests are ongoing on the first Micron Semiconductor Limited prototypes. Different irradiation facilities have been approached to proceed with irradiation of the various detector types. A laser test of small test detectors is ongoing, and a board to interface prototype full-size detectors with the Alibava read-out system is being designed.

The development of the FE chip (SALT) is progressing. A MOSIS MPW run was submitted in February 2014 which contains the following elements: a final version of the ADC, a preamplifier-shaper with a modified baseline stabilization, a new channel pitch, an increased gain, and additional DACs. A converter from single-ended shaper to differential input ADC will be added in the next submission. Further developments are now ongoing, such as the refinement of a very low power PLL exactly matching LHCb requests (in particular radiation resistance), a DLL for tuning of the sampling phase, a first version of the data serializer and dedicated digital logic to quantify the importance of single-event effects. The algorithms of DSP processing have been fixed and high level emulation software has been completed. The low level (ASIC) implementation is currently ongoing. The preparation for the irradiation test of the existing ADC is in an advanced stage, with measurements planned for late Spring 2014. Two front-end prototypes have been characterized and are performing according to specifications. In addition, extensive measurements on the ADC have proven excellent performance of this component. An important test planned for late Spring is the study of the ADC performance in a radiation environment.

The design of the UT system-electronics has started. Two options for readout architecture are being considered, one of which involves some data concentration in the balcony electronics. Progress has been made towards the choice of a final readout architecture. A conceptual design of a general test board has been developed and is being reviewed to make sure that it accomplishes all the testing needs of the R&D phase. Issues related to mechanics and cooling of these electronics are being addressed.

A prototype CO_2 cooling system has been exercised with a realistic full size mock-up of the UT stave. The mechanical structure has undergone several thermal cycles. Prototypes of different sensor-hybrid modules are being built. All the test stands for different performance measurements are being commissioned for our application. An irradiation campaign and test-beam run are being planned. The design of the “end stave” structure has started, together with other aspects of the integration in the LHCb experiment.

2.3 Scintillating-Fibre Tracker

Significant progress has been made on the design of the tracking detector placed downstream of the LHCb magnet. A Technology Validation Review was held in November 2013 which allowed the LHCb Collaboration to decide upon the use of a scintillating fibre (SciFi) technology read out with multi-channel Silicon Photomultipliers (SiPM) for this tracker. The full description of the SciFi Tracker is part of the LHCb Tracker Upgrade TDR [5], submitted in February 2014.

In the past six months, the SciFi Tracker R&D programme brought new results in all aspects of the detector design. The technique for laying down scintillating fibres into 2.5 m × 0.135 m mats has been refined and high quality mats have been produced. The handling, cutting and casting of these fibre mats has developed into a well controlled procedure which can be adapted for production. The fibre mats are placed on rigid panels made of a sandwich of carbon fibre and honeycomb structure. The first panel prototypes were shown to have the required mechanical properties for the targeted alignment accuracy. The first 1 m long detector panel has been produced and it will undergo many tests in Spring 2014. The development of the SiPMs with two companies has continued, and photo-detectors with improved efficiency and noise performance are expected. The SiPMs must be operated at low temperature ($-40\,^{\circ}\mathrm{C}$) to compensate for the noise induced by radiation damage. A dedicated workshop with cooling experts resulted in the choice of a single-phase liquid cooling as the baseline solution. Detailed thermal simulations have been made, and are driving the design of the read-out box placed at the end of each detector module.

An electronics review was held in December 2013, after which it was decided to use a simple three-threshold digitisation scheme on the ASIC. This also reduces the complexity of the front-end board and the clustering algorithms. A single-channel prototype of the front-end ASIC was produced, and initial tests demonstrate the validity of the design. Multi-channel prototypes are now in preparation and will be available for testing later in 2014.

Finally, a detailed and realistic description of the SciFi Tracker has been implemented in the LHCb Monte-Carlo simulation, and was used to evaluate the detector performance under the LHCb upgrade running conditions. The results of these studies are presented in the LHCb Tracker Upgrade TDR.

The SciFi Tracker team consists of more than 20 collaborating institutes, and represents one of the major detector efforts for the LHCb upgrade. The work of the group is focused on finalizing the detector design and on the production of a first fully operational detector module (Module-0) by the end of 2014. Procurement of the scintillating fibres and SiPMs will start in 2015, in parallel with the preparation of the detector production equipment. This will be followed by the start of the fibre mat and module production in the second half of 2015.

3 Track Reconstruction

The focus of tracking efforts in the last six months has been to finalize the studies for the VELO and the Tracker TDR [5]. Additional progress was made in the following areas:

- **Robustness studies for the Fibre Tracker**
  The momentum resolution for low momentum tracks is limited by multiple scattering while for high momentum tracks the single hit resolution plays an important role as well. Due to the lower amount of material in the upgrade detector compared to the current detector the momentum resolution is expected to be about 10–20% better. It has been shown that degrading the expected (signal only) hit resolution in the Fibre Tracker from 60 μm to 100 μm has hardly any impact on the momentum resolution. Therefore even taking into account noise and misalignment, which both result in a worse single hit resolution, the expected momentum resolution will be better than in the current experiment. The occupancy in the outer half of the Fibre Tracker ($x \geq$1.5 m) is rather low, therefore several ideas are being considered to merge channels or increase the fibre diameter in this region. These changes would effectively result in a worse single hit resolution. It is therefore very encouraging to see the results of this initial momentum resolution study. Studies of the thermal noise indicate that the performance of the tracking in the Fibre Tracker is stable for temperatures up to $-30\,^{\circ}$C. Studies reducing the single hit efficiency showed that this has only a mild effect on the pattern recognition performance (a 1% reduction in single hit efficiency results in about a 1% drop of track reconstruction efficiency).

- **Reconstruction of long-lived particles**
  Long-lived particles such as K_S mesons and Λ baryons often decay outside the VELO, thus their daughter particles are only reconstructible in the Fibre Tracker and the Upstream Tracker. The search for these displaced tracks starts in the Fibre Tracker. In the so-called Seeding algorithm Fibre Tracker standalone tracks are reconstructed, which are then extrapolated to the Upstream Tracker. Both algorithms are extremely challenging due to the dense environment in the upgrade running conditions. The studies for the TDR revealed a significantly worse (up to 20%) performance compared to the same algorithms in the current running conditions, especially for low momentum particles. Dedicated studies of the Seeding algorithm and the tuning of its internal track model have recovered half of this difference. Further studies have started to test how much the performance could be improved by a potential y segmentation of the Fibre Tracker module in the central region.

- **Track reconstruction for the trigger**
  The VELO pattern recognition is the first step in the LHCb software trigger. As the upgrade experiment aims for a 40 MHz read-out, this means the VELO pattern recognition is planed to be run for every event. The algorithm itself is well within the time budget, however the clustering was considered a critical issue (about 2 × slower than the pattern recognition). The option of clustering in hardware was discussed. A new software implementation of the clustering algorithm however resulted in a significantly improved timing performance (about 20% of the pattern recognition algorithm). Thus the clustering and the reconstruction of the tracks in the VELO are now fast enough for the trigger application. The VELO tracks are then passed to the UT detector. Adding UT hits allows for a rough momentum estimate. In the trigger only high momentum tracks are of interest. Thus the momentum information is valuable to reduce the number of interesting tracks, which are then passed to the forward algorithm to search for additional measurements in the Fibre Tracker. The momentum information can as well be used to adapt the size of the search windows in the Fibre Tracker. These windows have been re-tuned recently, which resulted in a significant increase in speed (an additional factor two) of the forward tracking algorithm running in trigger mode.

- **Documentation**
  Public notes with a detailed description of each of the studied algorithms and its performance have been written as supporting documents for the TDRs.

4 Particle Identification

The Upgrade Particle Identification (PID) TDR [4], summarizing the plans for the RICH, Calorimeter and Muon systems, was submitted in November 2013. The Research Board approved the document in March this year.

4.1 RICH system

The upgraded RICH system, as defined in the TDR [4], will consist of a re-designed RICH 1 detector, an essentially unchanged RICH 2, and new photodetectors that can be read out at 40 MHz. The key feature of the new RICH 1 is a modification of the optics (and hence also the mechanics of the gas vessel) in order to spread the image compared to the current detector, and thereby reduce occupancy. This re-design can however be performed within the "footprint" of the current RICH 1, and therefore is compatible with the existing magnetic shielding box, and the evolving plans of the VELO and the UT. Simulation indicates that the physics performance of the new RICH system at high luminosity will be very similar to that achieved with the existing detector in LHC Run 1.

The MaPMT is established as the baseline technology for the RICH photodetector. It will be read out by a customized ASIC named the CLARO.

Ongoing studies are focused on finalizing the mechanical design of RICH 1, and characterizing the magnetic field robustness of the MaPMTs and radiation tolerance of the CLARO. All results to date are satisfactory. A test-beam scheduled for November will evaluate the response of an ensemble of CLARO-equipped MaPMTs to Cherenkov light. The photodetector order will be placed early in 2015.

4.2 Calorimeter system

The existing electromagnetic and hadronic calorimeters will remain in the upgrade, but the Scintillating Pad Detector and Preshower will be removed, as they are considered inessential for the most important calorimeter-based physics topics of the upgrade, such as radiative penguin studies, and are no longer required for the trigger.

The principal challenge in the calorimeter upgrade lies in the front-end electronics, which must read out at 40 MHz, and cope with the five-fold reduction in gain that will be applied to the PMTs. Maintaining the noise level of the analogue components under these requirements is a demanding task, and two solutions are being considered and prototyped, one ASIC-based and the other making use of discrete components. The decision will be taken in the middle of this year, when a significant sample of boards based on both implementations has been assembled and evaluated. This timescale is compatible with that required for the final electronics design.

4.3 Muon system

The upgrade plan for the muon system consists of:

- the removal of station M1, which is no longer needed with the new trigger strategy of the experiment;
- the design of new off-detector readout electronics compliant with full 40 MHz readout and the new GBT-based communications protocol;
- installation of additional shielding around the beam pipe in front of station M2.

Hence, the critical tasks at present involve the prototyping and testing of the new components of the readout electronics. This work remains on schedule.

Although not essential for the first period of upgrade operation, it is considered that longer term (post-LS3) it will be beneficial to deploy new detectors in the hottest regions of the first two upgrade stations. Work is already underway in defining the technology for these new detectors, with triple GEM and cathode-readout MWPCs being the chosen solutions for innermost and next-to-innermost regions, respectively.

5 Data processing

The task of the data processing concerns the transport of the data from the output of the FE electronics up to their reconstruction. It encompasses data acquisition, trigger and computing.

5.1 Data acquisition

The reviews of the sub-detector readout electronics have been completed with the Upstream Tracker in November and with the Scintillating Fibre Tracker in December.

The readout electronics can be located either underground close to the detector or on the surface close to the network switches. The latter option is the preferred one. The performance of the long distance optical link between the underground area and the surface, as well as the details of the installation procedure, show that this is feasible at an affordable cost. In November, the Technical Board endorsed the location of the readout electronics on the surface. A couple of optical fibre ribbons will be installed in the second part of 2014 in order to test the deployment procedure and to run long-term tests in-situ with a significant number of links.

The studies to determine the optimum readout system continue. On one hand, a methodology has been developed to design a very dense and compact readout board. This has been used to determine the feasibility of a readout board with a large buffering capability. The study shows that such an AMC40 board will be feasible with the Arria10 family of FPGAs, which will be available in 2015. On other hand, the new building at the surface opens the road to a cost effective approach for the event building, the *bi-directional event builder,* which hosts the readout board as well as the CPU running the event builder task in the same entity, a PC server. The data transfer between the PC servers are handled by a large bi-directional router with input and output ports at 100 Gbps each. The detailed review of the readout system including time and fast command distributions, slow control and low-level trigger took place in March 2014. The Technical Board endorsed the implementation with the bi-directional event builder, which implies that the form factor of the readout board moves from AMC to PCI Express. The prototype of the PCIe40 will be developed in 2014.

5.2 Trigger

In the past year, three alternatives have been studies for the LHCb trigger running in the upgrade conditions. The first one is based on very flexible software running in the Event Filter Farm. It performs the full track reconstruction and particle identification as well as inclusive and exclusive selections. The second one is similar to the first, but the track finding is helped by a co-processor named TPU. It finds upstream tracks between the VELO and UT by running the retina algorithm in FPGAs. The last one is the low-level trigger (LLT), a “safety belt” to regulate the rate at the input of the event filter farm. The LLT could be implemented in hardware using the common readout board, or in a software running in the event builder PC servers. These studies show that the LHCb trigger can be implemented in several ways with a good efficiency when the instantaneous luminosity is $2 \times 10^{33}\ \mathrm{cm}^{-2}\mathrm{s}^{-1}$. The Technical board endorsed the first approach, the full software implementation, which has been reviewed at the end of March.

5.3 Computing

Although it is rather difficult to define the Computing model for 2020 at this time, it will rely on the new developments which will be available after LS1 and on an intelligent data management and replication system.

6 Preparation for the LHCb upgrade

6.1 Interactions with LHC machine groups

In the RRB report of April 2013 it was pointed out that the installation of a Target Absorber for Neutrals (TAN) is recommended in the vicinity of the LHCb interaction region IR8 in order to reduce the heat load on the dipole magnet D2 and to operate the LHC safely under LHCb upgrade conditions with an instantaneous luminosity of $2 \times 10^{33}\mathrm{cm}^{-2}\mathrm{s}^{-1}$.

The requirements of the TAN have been further addressed in the past months by colleagues in the LHC machine groups. The emphasis has been on the angular coverage needed to catch neutral particles coming from the interaction region before they would reach the D2 magnet. This has been determined for any optics configuration under consideration. The studies showed that a length of three to five interaction lengths of copper (46 to 77 cm) would be sufficient. The block would have lateral dimensions of about 12 cm × 10 cm in the horizontal and vertical planes. It would be located at a position of ±114 m from IP8, and can be prepared without a major effort.

6.2 LHCb upgrade infrastructure

The preparation for the upgrade has started and the routing of optical fibres that will send the data from the detector to the readout boards at the surface has been defined. In close collaboration with the engineering department the support structure for the fibres will be mounted in the machine shaft of Point 8. Some civil engineering work to shorten the distance will be required. Optical fibres of different type will be installed for testing the installation procedure and its quality. A new technical gallery at the surface, connecting the main surface hall and the location of the upgrade PC farm, is in preparation. Replacing the present LHCb assembly areas is under discussion. The construction of two new halls for the upgrade is planned at Point 8.

6.3 Schedule

The TDRs for the Vertex Locator [3] as well as for the Particle Identification detectors [4], i.e. RICH, Muon and Calorimeter systems, were presented to the LHCC in November 2013 according to schedule. In addition, the tables of cost and personnel for these sub-detectors were presented to the LHCC Upgrade Cost Group and discussed in a dedicated meeting. As a result, the LHCC recommended the TDRs for approval, and the Research Board approved the VELO, RICH, Calorimeter and Muon systems for the upgrade in March 2014. The LHCb Tracker TDR, containing the Upstream Tracker, SciFi Tracker and the tracking performance, has been delivered to the LHCC in February 2014, as scheduled. The tables for the cost and personnel will be submitted to the LHCC Upgrade Cost Group before the RRB in April and shall be discussed with the LHCC well before their next meeting in June 2014. The LHC schedule beyond LS1 has been discussed and approved by the CERN Management and by the LHC experiments. Long Shutdown 2 will start mid-2018, with the consequence that the installation of the LHCb upgrade is moved by six months, allowing for some margin that will be reserved for the production of the new detector systems. The end-of-year extended technical stop in 2016 will be used for some preparatory work in view of the LHCb upgrade installation in 2018/19.

6.4 Funding

Following approval of the Framework TDR for the LHCb Upgrade [2] a Memorandum of Understanding (MoU) for Common Projects [6] was submitted to the RRB in April 2012. In both these documents the overall cost of the LHCb upgrade was estimated to 57 MCHF, including a 30% Common Fund contribution.

An updated breakdown of the cost for the different detector sub-systems and the sharing of responsibilities among institutes has been described in detail in the sub-detector TDRs [3–5]. We now are confident that the upgraded detector with 40 MHz readout and with a fully efficient and flexible software trigger can indeed be constructed and installed within the cost envelope of 57 MCHF, provided that the requested funds will be available according to the expected spending profile.

Whilst negotiations with the funding agencies are still to be finalized for covering the expected CORE contributions to the various sub-detector components to which the participating institutes have committed, we now encourage the funding agencies to proceed with signing the above quoted Addendum, revised with the M&O Cat.A author sharing updated to April 2014 [7].

References

[1] LHCb collaboration, *Letter of Intent for the LHCb Upgrade*, CERN-LHCC-2011-001, LHCC-I-018.

[2] LHCb collaboration, *Framework Technical Design Report for the LHCb Upgrade*, CERN-LHCC-2012-007.

[3] LHCb collaboration, *LHCb VELO Upgrade Technical Design Report*, CERN-LHCC-2013-021.

[4] LHCb collaboration, *LHCb Particle Identification Upgrade Technical Design Report*, CERN-LHCC-2013-022.

[5] LHCb collaboration, *LHCb Tracker Upgrade Technical Design Report*, CERN-LHCC-2014-001.

[6] LHCb collaboration, *Addendum No. 01 to the Memorandum of Understanding for Collaboration in the Construction of the LHCb Detector. The Upgrade of the LHCb Detector: Common Project items*, CERN-RRB-2012-119 Annex A.

[7] LHCb collaboration, CERN-RRB-2012-119 Annex A, rev. 10 April 2014.