Status of the LHCb upgrade

CERN-RRB-2014-092

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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. This capability will allow the experiment to collect data with high efficiency at a luminosity of $2 \times 10^{33}\,\mathrm{cm}^{-2}\mathrm{s}^{-1}$. Flavour-physics measurements will be performed with much higher precision than is possible with the current detector, and across a wider range of observables. The flexibility inherent in the new trigger scheme will also allow the experiment to diversify its physics programme into important areas beyond flavour.

The Upgrade was proposed in the Letter of Intent [1] in 2011, and its main components and cost-envelope were defined in the Framework TDR [2] one year later. Technical Design Reports (TDRs) have been written for all sub-systems and reviewed favourably by the LHCC, and the project costs scrutinised by the UCG. The Research Board approved the VELO [3] and Particle Identification (PID) [4] TDRs in March this year, the Tracker TDR [5] in June, and the Trigger and Online TDR [6] in September.

Following the completion of the TDRs clear technological solutions exist for each sub-system with well-defined costs. Furthermore the roles of each institute within the Upgrade projects is now understood. Therefore we are submitting to this meeting a second Addendum to the Memorandum of Understanding (MoU) which presents the sharing of responsibilities and core resources sought from each funding agency for construction of the detector components [7]. This second, detector, Addendum complements a previously submitted Addendum which specified the Common Project items [8]. The RRB is requested to endorse this detector Addendum so that procurement and construction may begin, allowing the Upgrade to be installed during the 18 month Long Shutdown 2 of the LHC (LS2).

In this report we give a brief update on the status for the Upgrade systems, reiterating the detector choices made in the TDRs and summarising recent progress. Information is also given concerning overall project organisation, infrastructure and funding.

2 Tracking system upgrade

After the approval of the tracking detector TDRs [3, 5], the VELO, Upstream Tracker (UT) and Scintillating–Fibre Tracker projects are now finalising their R&D activities and entering the construction phase. Project organization and schedules with milestones have been devised in order to plan in detail the construction activities. The first engineering design reviews are already planned for early 2015.

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 software optimisation and discussion with the groups responsible for VELO assembly and insertion, the decision was taken to rotate the VELO modules by 45° relative to the VELO movement axis, as shown in Fig. 1. This results in a design that has improved mechanical tolerances when inserting and retracting the detector, and one which has equivalent coverage but slightly better performance in terms of material. The design change has been adopted throughout the project. The z layout of the modules has also been adapted to optimise the project from the point of view of construction.

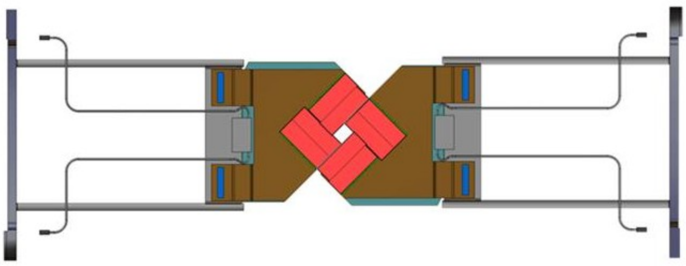

Figure 1: Schematic of two closed VELO modules, with the rotated sensors indicated in red.

A new microchannel layout corresponding to the design changes has been devised, and will be finalised following prototyping with vendors and progress on the electronic layout of the hybrid. The vacuum soldering of the microchannel connector has shown very good results, and work is in progress to establish the long term production and reliability of the complete substrate.

The project has very recently taken delivery of the first prototype radiation hard pixel sensors from two independent vendors. In addition to the baseline design of a 200 μm n-in-p substrate with 450 μm thick guard rings, alternative thicknesses and designs have been produced, as well as the n-in-n alternatives. An intensive testing phase is now planned with both lab and testbeam measurements of irradiated and non-irradiated samples. With the results of these tests we shall have sufficient information to be able to decide upon the most performant sensors in time for the sensor EDR in Q1 2015.

The Timepix3 ASIC, precursor of the VeloPix, has been used to construct a dedicated high speed telescope benefitting from the dedicated SPIDR readout system. The telescope has been operated at the CERN PS and has demonstrated the excellent performance of the ASIC as well as the successful integration of the readout, together with the offline software. With the telescope is was possible to probe in detail the performance of a Timepix3 equipped hybrid pixel assembly operating under a range of conditions. Preparations have been successfully completed for irradiation tests of Timepix3 assemblies. Work is ongoing to produce a layout for the Timepix3 hybrid for the pixel Module-0, as well as a version which can be used for irradiation tests. The VeloPix design continues to progress well. The front-end has passed a design review and the design finalised. The dedicated GWT serialiser, which optimises bandwith and power consumption for the VeloPix, has completed bench testing and the design is fully approved, with small changes to improve the 'eye diagram'. Single event upset (SEU) tests are planned for October. In common with other aspects of the LHCb upgrade electronics the decision has been made to transfer the ASIC to TSMC technology. This will result in a delay, although the negotiations are well advanced and the new design kit is expected shortly. The impact of this delay can be minimised by streamlining the flip-chip assembly phase of the programme.

Work is progressing on the module design concepts. Two baseline developments are in progress, which differ in the way the microchannel substrates are supported and constrained in the z dimension. For both concepts, mockup construction is underway. Tests focussing on the mechanical performance of the module, and a full electrical hybrid based on Timepix3 are expected in Q1 2015.

Concerning the readout chain, a firmware integration workshop was held in June to launch the Minidaq test suite and make progress on the continuing integration of VELO firmware code into the LHCb framework. Further work on the elements of the readout chain and the detailed timing analysis are underway. The first test with the GWT prototype chip is planned for the end of the year. A prototype of the data line has been designed and simulated with a thinner profile (100 μm) kapton layer, and prototypes are expected to be shortly delivered and characterized.

2.2 Upstream Tracker

Following the approval of the LHCb Tracker TDR, the Upstream Tracker (UT) has been organized as a new independent Project within LHCb, with Prof. Marina Artuso of Syracuse University as Project Leader.

An intense R&D programme for the UT sensors is underway. Tests of sensor prototypes, 10×10 cm^2 with n-in-p and p-in-n technologies, produced by Micron and Hamamatsu, are being carried out. A sensor test stand has been commissioned and the first detectors show leakage currents well within the expectations. Smaller detectors from the same batch, exposed to radiation levels from 1.4 MRad to 20 MRad, will be studied in an upcoming test beam in October. In a second phase, sensor prototypes with a circular cut-out on a corner, foreseen for the UT region near the beam pipe, and sensors with embedded pitch adapters will be tested. Prototype delivery is expected in early 2015.

The front-end ASIC (SALT) design and characterisation are progressing well. The current prototype (8 channel SALT encompassing full functionality) is being developed in TSMC 130 nm CMOS technology. A submission readiness review is planned for October 2015. Prototypes of building blocks of the ASIC have been tested and validated successfully. The analogue section is found to meet the desired noise and spill-over requirements. A review of the ADC prototype irradiated at the MGH proton irradiation facility in Cambridge, MA, USA took place in July. Preliminary results show that the SEU probability is well within the specifications.

Low mass flex cables are being designed to transmit data from the SALT chip and to distribute high and low voltages to the modules. Flex cables servicing the innermost staves, which have the most challenging requirements due to the higher granularity of the inner detectors, have been studied first and are currently being fabricated. Tests will start early next month. Mechanical prototypes of these cables will be used to perfect the gluing technique to the stave carbon fibre facings.

The design of the near detector electronics is progressing well. Prototype studies of the detector power regulators, based on the radiation hard LHC4913 device, are near completion. They will be used to test the prototype cables and finalize the layout of the mechanical infrastructure surrounding the staves. The data readout architecture is also being finalized.

Similarly, significant progress has been achieved in the mechanical design. Thermal and mechanical simulation studies of increasing complexity have been implemented, and mechanical tests of several components have been pursued. The design of the instrumented staves has been refined and critical issues have been studied in detail, such as the insulation of surfaces or edges with exposed high voltage, and the impact of the multilayer structure on the data integrity and analogue noise immunity of the front-end electronics. A design allowing for repairs and replacement of defective sensor-hybrid modules is also under active consideration. Adhesive materials allowing detachment of modules have been identified and shear tests and study of behaviour upon irradiation are under way. Full size stave mock-ups with realistic materials for all the relevant components are being fabricated and will shortly be tested. The design of the strong-back fixtures needed for the integration and safe shipment of the staves to CERN is almost complete.

Progress towards the design of a CO_2 cooling plant supporting the VELO and UT subsystems in a coherent fashion has been achieved. A detailed description of the UT detector requirements is currently being prepared. A prototype recirculating cooling system (TRACI) is currently being assembled in Milano and will be used in studies supporting the ongoing simulation.

2.3 Scintillating-Fibre Tracker

Following a Technology Review the collaboration decided in November 2013 to replace the Outer and Inner Tracker by a high granularity tracking system built from scintillating fibres. The technology and the full detector design is described in the LHCb Tracker Upgrade TDR [5]. The location of the scintillating–fibre tracker is shown in Fig. 2.

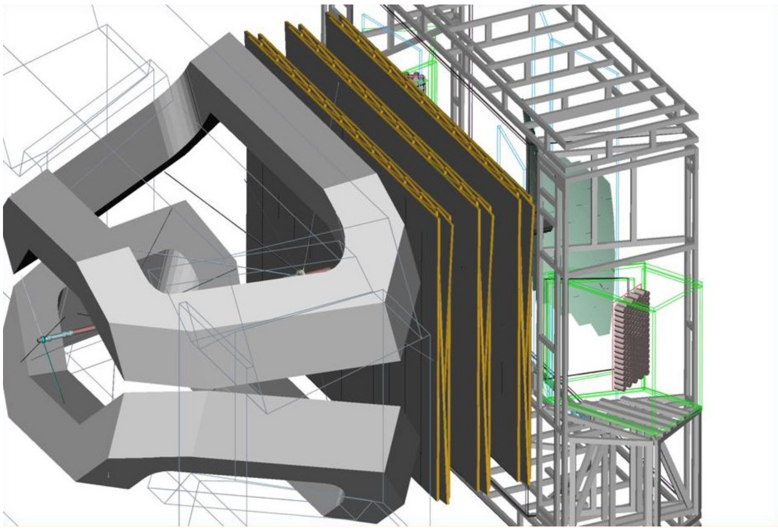

Figure 2: The three stations of the scintillating-fibre tracker shown between the dipole magnet on the left and RICH 2 on the right.

The detector will consist of 250 μm thick and 2.5 m long scintillating fibres placed next to each other and forming 135 mm wide mats of 5 or 6 fibre layers. Eight of these mats will be joined together to form 5 m long and 50 cm wide modules. The fibres will be read out with multi-channel Silicon Photo-multipliers (SiPM).

In the last six months the Scintillating–Fibre Tracker (SciFi) group has worked on the technical details of the various detector components and on the production tooling, and significant progress has been made in both areas.

In cooperation with two different industrial suppliers the candidate SiPMs have been optimised to achieve a higher photo-detection efficiency and to reduce the cross talk. Further, the geometry of the single SiPM channels has been adapted to meet the SciFi requirements.

Test benches to determine the properties of the scintillating fibres, such as attenuation length, light yield and diameter have been built and commissioned. The fibre attenuation length and the light yield have been studied for different samples, and are found to have some variation between production samples. Furthermore, the fibre diameter sometimes deviates from the nominal value of 250 μm by more than 50 μm. The SciFi group is in contact with the industrial producer to understand and eliminate the cause of these undesirable features.

Prototype winding machines to produce fibre mats have been built and are operated routinely in two institutes. Both groups are able to produce 2.5 m long fibre mats of high quality. Several fibre mats will be tested using high-energy pions in October. The SciFi group is currently in contact with companies to optimize and produce winding machines for the mass-production of the fibre mats. Currently we foresee four production centres.

For the readout of the 600k SiPM channels the SciFi group is developing a fast 64-channel ASIC which provides 2-bit pulse-height information for every hit by using three adjustable thresholds. A first prototype of this chip, comprising the full readout for eight channels, was submitted in May.

A SciFi Project has been established to help organise the activities of the group members, drawn from 17 institutes in seven different counties. Prof. Ulrich Uwer of Heidelberg has been appointed Project Leader. The project is organized into seven different work-packages, each with a work-package coordinator. A management team of three people chaired by the Project Leader coordinates the overall project and monitors progress. The institutes have agreed on a detailed list of task and finance sharing.

3 Track reconstruction

The proof-of-concept of the pattern recognition algorithms for the LHCb Upgrade was demonstrated in the VELO and Tracker TDRs [3, 5]. In the post-TDR phase the main focus of the tracking software efforts is to implement in detail the geometry, the digitisation and the pattern recognition according to the design choice of the hardware, which is about to be finalised for most of the components.

3.1 Update of the SciFi geometry and response

The design of the SciFi module has a simple rectangular shape. This geometry and the $\pm$ 5° rotation of the stereo layers lead to the consequence that a triangle shaped corner of the module of the upper half overlaps with the lower half of the detector, and vice versa. The original pattern recognition software, however, had assumed a clear separation between the upper and lower halves of the tracker; this feature was beneficial as it limited the number of hit combinations to be tested. The overlap was not correctly simulated in the TDR studies. It is found that introducing the correct description of the rectangular module in the simulation results in a significant loss of efficiency. This loss can be recovered by appropriate treatment in the pattern recognition software, without a noticeable degradation in timing performance. Thus it is concluded that there is no need to redesign the shape of the module edges.

Additionally the correct shape for the beam-pipe hole has been properly implemented in the geometry.

Work is ongoing to implement a more realistic fibre response in the simulation. In parallel the algorithms are being adapted to these changes. No significant change in the detector performance has yet been observed.

One remaining open issue is to study the impact on performance of a potential y segmentation of the innermost modules. A preliminary study indicates a significant reduction in the ghost rate due to fewer possible hit combinations. To verify the impact on the efficiency the pattern recognition algorithms need to be adapted to exploit this additional information. Results are expected soon.

3.2 Changes in the orientation of the VELO modules

As discussed in Sect. 2.1, it has been decided to rotate the L-shaped VELO modules by 45°. The new orientation and design of the RF foil have been implemented in the simulation. It has been verified that the performance is not affected. Marginal improvements have been observed in resolution related quantities.

3.3 Track reconstruction of daughters of long-lived particles

Long-lived particles, such as K^0_S mesons or Λ^0 baryons, often decay outside the VELO acceptance. To reconstruct their daughter particles the 'downstream algorithm' is used. This algorithm extrapolates SciFi standalone tracks to the UT and picks up additional hits in this detector. At the time of the TDR the downstream algorithm used in the current experiment had been ported to the Upgrade software, but had not yet been optimised for the new environment. The corresponding performance was rather low, with an efficiency of $\sim$ 80%. Significant work has been invested into rewriting this algorithm, with efficiencies now obtained of around 90% for the same ghost rate and timing performance. Potential further improvements are being investigated.

4 Particle Identification

The Particle Identification (PID) system of the upgraded LHCb consists of the RICH, Calorimeter and Muon systems. Following the approval of the PID TDR [4] all the sub-systems are progressing rapidly towards the construction phase.

4.1 RICH system

The upgraded RICH system 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 kaon identification and pion misidentification efficiencies are shown as as a function of momentum in Fig. 3. Further studies have focused on finalising the optical and mechanical concept of RICH 1, which is now entering the phase of detailed engineering designs.

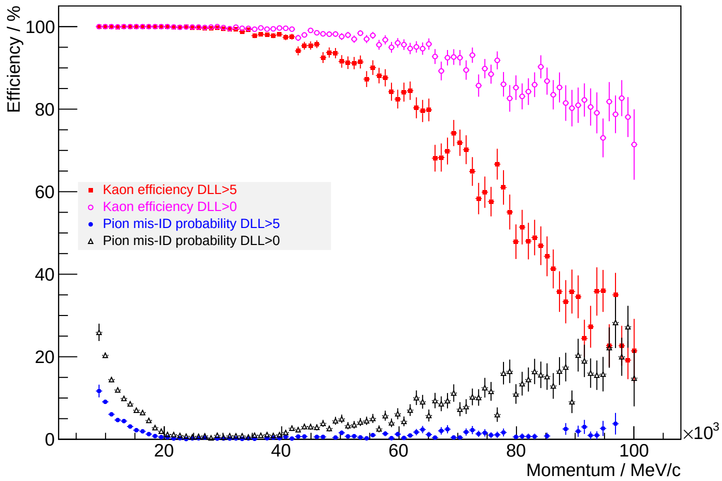

Figure 3: Performance from simulation of the upgraded RICH system, showing kaon efficiency and pion misidentification probability against momentum. Two working points are shown, corresponding to different cuts on the 'Delta log likelihood' returned by the RICH pattern recognition and reconstruction.

The MaPMT is established as the baseline technology for the RICH photodetector. It will be read out by a customized ASIC named the CLARO, which has been produced in its version-0 and tested. The magnetic field robustness of the MaPMTs and radiation tolerance of the CLARO have been fully characterised. All results to date are satisfactory. The modularity and mechanical design of the opto-electronic chain, arranged in photo-detector planes, its supporting mechanics and cooling system have been mostly defined and are undergoing tests. A prototype of the system, made of several MaPMTs together with the accompanying front-end, digital and acquisition electronics and mechanics, is being readied for test beam studies to be carried out at the end of October.

Engineering design reviews for the CLARO, the Front-End Board and the Elementary Cell (the basic module hosting four MaPMTs with their base–boards, and the CLARO boards) are being held on the second week of October. 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 gain of the calorimeter PMTs will be reduced by a factor five. The electronics must compensate for this gain reduction and send the data at 40 MHz to the Event Filter Farm. Two solutions are under consideration for the analogue electronics: an ASIC, or a circuit based on discrete components. Prototypes of both solutions are available and are currently being tested. In particular a full four-channel prototype of the ASIC has been received last summer and it is now under evaluation. The choice between the two designs will be made in October 2014, taking account their relative complexity and costs, and the test results. A new prototype of the front-end board has been designed and will be produced soon. The design is very close to the final version in terms of number of channels, and it integrates almost all the target components for the upgrade.

The control board design is well advanced and a first prototype will be produced early next year.

It is the inner modules of the ECAL that are most at risk from radiation damage, but even these are expected to remain operational up to LS3. During this shutdown they will be replaced by spare modules that are already available.

4.3 Muon system

The work towards the upgrade of the Muon system has progressed steadily during 2014. The preparatory work for the spare MWPCs construction is ongoing on the two construction sites, Frascati and PNPI. In Frascati the infrastructural work has been completed and the site is ready for the production of honeycomb panels, foreseen to start by the end of September. The wiring machine, already used for the production of MWPCs in the past, has been refurbished and tuned for M5R4 chamber production. The chamber wiring is expected to start in early 2015. The situation is similar at PNPI: the assembly site is being prepared and the shipment of material for chamber construction is being organized. Most of the material needed to build the 51 spare chambers was ordered by Frascati during 2014 and is now being delivered.

The new Muon readout and control electronics architecture has been defined. The design of the nSYNC ASIC has started in Cagliari, although with some small delays due to the switching of technology from IBM to TSMC. An important block of the new ASIC (the digitally controlled oscillator, a key element of the fully digital PLL, used for the TDC) was already implemented in UMC 130 nm and was found to operate according to expectations.

Studies are ongoing to optimise the shielding in front of the Muon system, aiming at a background reduction in the regions of highest occupancy behind the calorimeters.

5 Data processing

'Data processing' is here defined to encompass the transport of the data from the output of the front-end (FE) electronics through to the offline reconstruction. It includes data acquisition, trigger and computing.

5.1 Data acquisition

Activities on the readout electronics are being driven by the design reviews of the FE systems. These reviews are scheduled for each detector over the coming months. The design of the readout board, PCIe40, is progressing. The number of optical links has been extended from 36 to 48 both in input and output. The first prototype is based on the engineering sample version of the Arria10 FPGA and is expected by the end of 2014.

In the current architecture the front-end electronics and the readout electronics are connected via long distance optical links between the underground area and the surface. The support for the optical cabling has already been deployed in the PM 85 shaft. Tests of the fibre installation, using blowing technique, are ongoing. More information is given in Sect. 6.2. A small set of OM3 fibres will be installed at the end of LS1 in order to measure the performance of the link and to run long-term tests.

5.2 Trigger and online

The core of the online system is the event-builder assembling the event at 40 MHz. It is based on large bandwidth bi-directional network interconnecting event-builder PC-servers. The trigger will analyse all collisions and select those to be written for offline storage. It consists of a collection of identical software task running on the event filter farm.

The Trigger and Online TDR [6] was submitted to the LHCC end of May and approved in September. The architecture of the upgraded LHCb readout-system is shown schematics in Fig. 4.

In order to monitor progress, a set of milestones has been prepared for the Trigger and Online projects.

5.3 Computing

Twice a year a workshop is organised to discuss all aspects of the computing, including the Upgrade requirements. Recently, a small group of computing experts has started to discuss and evaluate the different techniques for vectorization.

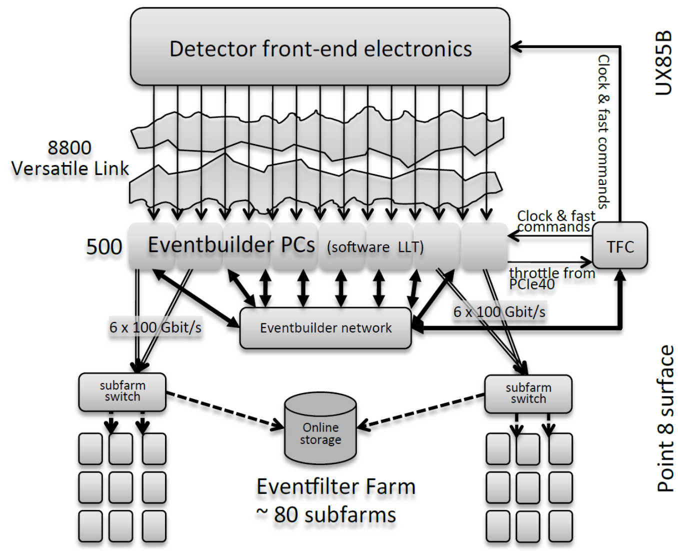

Figure 4: The architecture of the upgraded LHCb readout-sysem.

Although at present it is rather difficult to define the computing model for 2020, key dates have been established in this direction. These include a road map at the end 2014, the computing TDR at the beginning 2017 and the finalisation of computing model during Autumn 2018.

6 Preparation for the LHCb upgrade

6.1 Organisation

The Upgrade organisation has been adjusted to meet the requirements of the new, post-TDR phase of activities. The management has created an Upgrade Planning Group (UPG) which meets regularly to review progress. The UPG membership consists of an Upgrade Detector Coordinator, an Upgrade Resources Coordinator, an Upgrade Performance Coordinator and an Upgrade Data Processing Coordinator, as well as the management and a representative of the Physics Coordinator.

Detector upgrade activities are organised within the existing Projects, to ensure efficient sharing of resources between operational needs and Upgrade work. The two exceptions are the UT and SciFi systems, where new Projects have been created.

6.2 LHCb upgrade infrastructure

Infrastructure developments at point 8 for the Upgrade are already underway. Support structures for the optical fibres have been installed and first OM3 fibres that will send the data from the detector to the readout boards at the surface have been blown from the experimental cavern to the surface. The optical fibres are routed through the LHC machine shaft. The overall distance has been reduced after the completion of some civil engineering work. This work has been carried out in very close collaboration with the EN and GS departments.

Work on the new technical gallery between the surface building, the future upgraded PC farm and the new assembly area has started. The new building for the control room and office space is under construction.

Discussions with the sub-systems groups on the service for the upgraded detector have recently started. A first document will be prepared for early next year.

6.3 Schedule

A new schedule for the re-start of LHC Run 2 after LS1 has been issued, but the start of LS2 and the installation of the LHCb Upgrade are kept unchanged.

A list of milestones for the upgraded sub-systems has been prepared and will serve as a monitoring tool for the overall progress for the upgrade. The first sub-system engineering design reviews are scheduled for October 2014.

6.4 Funding

Funding of the LHCb Upgrade is considered in two categories: Common Projects and the upgrade of the Sub-Detector Systems.

Following approval of the "LHCb Upgrade Framework Technical Design Report" (FTDR) [2] in 2012, the Addendum No. 1 to the Memorandum of Understanding (MoU) for Common Projects [8] was endorsed by the RRB and submitted to the relevant Funding Agencies for signature.

In the past year all sub-system TDRs for the LHCb Upgrade [3–6] have been submitted to the LHCC and approved by the Research Board. Based on the cost estimate of all sub-systems as detailed in the TDRs, we are now submitting the Addendum No. 2 to the MoU for upgrade of the Sub-Detector Systems [7] that lays down the terms of participation of the Institutes and Funding Agencies in the construction, installation and commissioning of the LHCb upgraded sub-systems. The total cost of the LHCb upgrade of 57.2 MCHF which is divided into a Common Project component of 15.7 MCHF and a Sub-Detector System component of 40.6 MCHF. According to the Addendum No. 2 the sharing of responsibilities in the detector upgrade has been fully defined among all participating institutes, and the funding is secured up to a missing 1.6% of the total upgrade cost. This underfunding of 0.9 MCHF, if persisting, would affect the risk reserve and lead to a delay in the purchase of spare parts for the RICH detectors.

With the submission of both Addenda, the overall funding situation for the LHCb upgrade is now fully defined and we encourage the funding agencies to proceed with signing these Addenda to ensure a timely start of the construction of the upgraded LHCb detector.

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, *LHCb Trigger and Online Technical Design Report*, CERN-LHCC-2014-016.

[7] LHCb collaboration, *Addendum No. 02 to the Memorandum of Understanding for Collaboration in the Construction of the LHCb Detector. The Upgrade of the LHCb Detector: Sub-Detector Systems*, CERN-RRB-2014-105.

[8] 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.