Status of LHCb Upgrade I

CERN-RRB-2021-041

LHCb collaboration

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Contents

1 Introduction

The LHCb experiment completed its data taking at the end of 2018 and the installation phase of the Upgrade is in full swing. The upgraded 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 previous detector, and across a wider range of observables. The flexibility inherent in the new trigger scheme will also allow the experiment to further 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-detector systems as well as for the Software and Computing and the Computing Model [3–10] and approved by the Research Board. A draft of an additional document describing our luminometer system for Run 3 has also been recently supplied to the LHCC.

Addenda to the Memorandum of Understanding (MoU) were presented to the RRB in April and October 2014, covering the division of resources and responsibilities for Common Project items [11] and sub-system items [12], respectively. A Real-Time Analysis Project was created to organize the complex software developments for the upgrade trigger. The corresponding offline software developments to facilitate user analysis have now been organised in a Data Processing and Analysis Project.

The first part of this document (Sect. 2 and 3) gives a summary of major physics results and operational aspects concerning Run 1 and Run 2 data processing. A total of 10 fb^{-1} were delivered to LHCb in Run 1 + Run 2 data taking periods, with 9 fb^{-1} recorded. The LHCb Run 1 + Run 2 dataset comprises p-p, p-Pb, and Pb-Pb at various centre-of-mass energies, as well as p-A (A = He, Ne, Ar) collisions in fixed target mode, using the unique experiment's gas injection system.

Exploitation of Run 1 + Run 2 data is progressing very well with, at the time of writing, a total of 561 papers published or submitted, of which 49 were submitted in 2020, and 6 have already been submitted in 2021. Computing operations have proceeded well, with a notable increase in the use of fast simulation techniques allowing larger number of simulated events to be produced.

Physics highlights since the last report are discussed in Sect. 3. These include several notable results. LHCb is particularly designed to measure matter anti-matter asymmetries (CP Violation) and rare decay processes sensitive to new physics. The first observation of a new-type of CP Violation, time-dependent CP Violation in B_s mesons was reported, a significant milestone. We announced the discovery of several new particles, including an exotic hadron we have named the $Z_{cs}(4000)$, which is a tetraquark containing the strange quark. This brings the total number of hadrons discovered at LHCb to 52. In the week of writing, we have announced the measurement of a quantity known as R_K, testing lepton flavour universality, the results deviate from the Standard Model by 3.1 standard deviations. This is significantly below the threshold for a discovery but is a highly intriguing result which reinforces the previous results in the "flavour anomalies" that we have discussed here previously. The result has attracted significant media attention.

In the second part (Sect. 4, 5, 6, 7, 8, 9) an update on the status of the Upgrade is given, summarising progress since the previous RRB. All sub-detector and common projects have made significant progress in the past months and, despite the ongoing constraints of the covid-19 pandemic, the overall schedule from the previous RRB remains unchanged.

Finally, in Sect. 10 and Sect. 11 a brief update on the latest developments on the Upgrade II planning and on collaboration matters is given. The preparations for the Upgrade-II Framework TDR are now significantly advanced, with a dedicated collaboration meeting going to be held at the start of May.

2 Operations

2.1 Data processing and computing

In mid-2020 a full data re-processing campaign was completed and most of the effort was then devoted to the organisation of the legacy campaigns, in preparation for Run3. A new focussed partial re-processing campaign is about to start to profit of the available computing resource in 2021. The new campaign will allow to add selection lines to further extend our physics programme.

The exploitation of the full Run 1 and 2 data set for LHCb physics analyses requires large simulation samples to be able to validate measurements and evaluate systematic errors accurately. The computing operations are dominated by the production of large simulation samples. These requests are constantly growing and are using the largest fraction of the total computing power. The LHCb collaboration is devoting a lot of effort in developing fast simulation techniques which allow to greatly reduce the CPU usage while still generating large samples. Two approaches are followed by the LHCb collaboration to speed up the simulation: simulate only the elements of the detector essential in a particular measurement (*e.g.* simulating the tracker only, or simulating only part of the events under study) and re-using the underlying event (ReDecay [13]).

In order to further speed up the Monte Carlo simulation production and to profit from the resources available, during the Long Shutdown the online-farm is fully used for simulation and data processing jobs. As a results about 40% of the LHCb Monte Carlo events are being produced on the online-farm. The jobs running on the online-farm in the past months are shown in Figure 1 (left): at the moment more than 90% of the resources are devoted to MC production. The increased use of fast simulations is clearly visible. The number of simulated events per year, split in the simulated data taking year, is shown in Figure 1 (right). The requests for Monte Carlo samples is increasing over time and the employment of fast simulation techniques has allowed to increase the number of simulated events by a factor of four with an increase of the CPU usage of only ~30%.

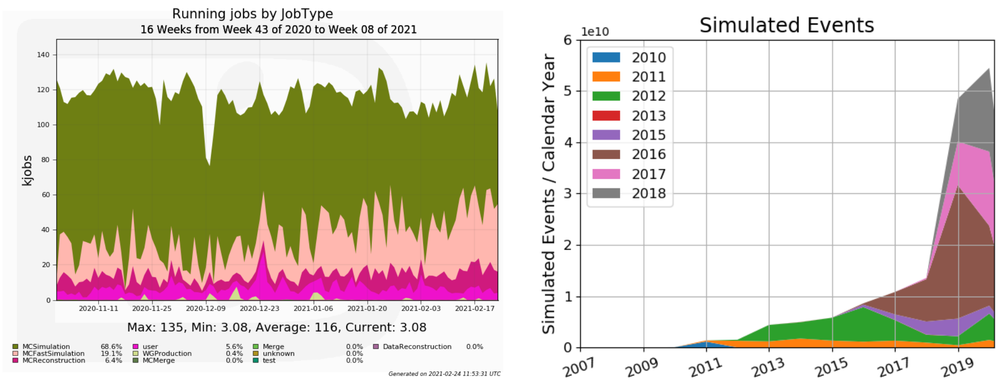

Figure 1: Left: The number of running jobs on the online-farm during the past months: the light-pink area indicates Monte Carlo jobs using a fast simulation technique, the green area Monte Carlo jobs using the full event simulation. Right: The evolution of the number of events simulated by LHCb over time. The growing usage of fast simulation techniques allows a larger number of events to be produced with similar computing resources.

The usage of computing resources for 2020 is discussed in a separate document [14]. A dedicated document [15] has also been prepared to present the estimates for the computing resources in 2022, the first full year of data taking for Run 3 and the first with the new LHCb Upgrade detector, including the evaluation of the CPU needs due to the increasing event complexity expected for the Run 3 data processing. The LHCb Computing Model for the Upgrade era and the associated computing requirements are presented in [8].

A register of risks and mitigation measures for Run3 has been prepared. This indicates that storage shortages are the most severe risk, followed by the potential for underestimation of the disk buffer size and the risk of insufficient write and read bandwidths from tape.

3 Physics

In 2020 the LHCb collaboration submitted 49 new publications, and a further six have been added this year. This gives a total of 561 LHCb physics papers at the time of writing, of which 547 have been published. A further 16 publications are being processed by the LHCb Editorial Board and are close to submission. In the following, some selected results from recent publications are highlighted.

3.1 CP violation and constraining the CKM triangle

Many measurements of CP violation and on CKM parameters have been submitted for publication.

The world's first measurement of time-dependent CP violation in B_s^0 mesons has been reported by LHCb [16]. In addition, the world best measurement on $A_{CP}(K^+\pi^0)$ [17] reinforces the intriguing $K\pi$-puzzle. A dedicated trigger selection made this achievement possible, despite the challenging experimental signature, with a single detached charged track.

In addition, impressive progress has been made on important variables that constrain the apex of the CKM unitarity triangle. The two most important ingredients to the determination of the phase of V_{ub}/V_{cb}, (known as the CKM angle γ) are the analyses of $B^\pm \to DK^\pm$ with $D \to K^0_S h^+h^-$ decays [18] and two-body D decays [19]. In addition, the time-dependent determination was done with $B_s^0 \to D_s^\mp K^\pm \pi^\pm \pi^\mp$ decays [20]. The magnitude of V_{ub}/V_{cb} was measured with the first observation of the decay $B_s^0 \to K^-\mu^+\nu_\mu$ [21].

3.2 Surpassing 50 hadrons discovered at the LHC

Similar to the existence of radial and angular excitations of the bound states of electrons and nuclei within atoms, also the bound states of quarks within hadrons can be radially or orbitally excited. These energy levels manifest themselves as different mass values of the observed resonances. Many new excited hadron states have been reported in 2020, culminating in a collection of 59 newly discovered

Table 1: Full list of LHCb publications submitted for journal publication since October 2020.

Title	arXiv
Observation of new excited B_s^0 states	2010.15931
Observation of a new Ξ_b^0	2010.14485
Measurement of the relative branching fractions of $B^+ \to h^+h'^+h'^-$ decays	2010.11802
Measurement of the branching fraction of the $B^0 \to D_s^+\pi^-$ decay	2010.11986
Measurement of differential $b\bar{b}$ and $c\bar{c}$-dijet cross-sections in the forward region of pp collisions at $\sqrt{s}$= 13 TeV	2010.09437
Measurement of the CKM angle γ in $B^\pm \to DK^\pm$ and $B^\pm \to D\pi^\pm$ decays with $D \to K^0_S h^+h^-$	2010.08483
Strong constraints on the $b \to s\gamma$ photon polarisation from $B^0 \to K^{*0}e^+e^-$ decays	2010.06011
Observation of the $\Lambda_b^0 \to \Lambda_c^+ K^+K^-\pi^-$ decay	2011.13738
Measurement of the CKM angle γ and $B_s^0 - \bar{B}_s^0$ mixing frequency with $B_s^0 \to D_s^\mp h^\pm \pi^\pm \pi^\mp$ decays	2011.12041
Observation of a new excited D_s meson in $B^0 \to D^+D^-K^+\pi^-$ decays	2011.09112
Search for the rare decay $B^0 \to J/\psi\phi$	2011.06847
Search for heavy neutral leptons in $W^+ \to \mu^+\mu^\pm$jet decays	2011.05263
Study of $B_s^0 \to J\psi\pi^+\pi^-K^+K^-$ decays	2011.01867
Searches for 25 rare and forbidden decays of D^+ and D_s^+ mesons	2011.00217
Angular analysis of the $B^+ \to K^{*+}\mu^+\mu^-$ decay	2012.13241
Measurement of CP Violation in the Decay $B^+ \to K^+\pi^0$	2012.12789
Observation of the $B_s^0 \to D^{*\pm}D^\mp$ decay	2012.11341
Evidence of a $J/\psi\Lambda$ structure and observation of excited Ξ^- states in the $\Xi_b^- \to J/\psi\Lambda K^-$ decay	2012.10380
Measurement of CP observables in $B^\pm \to D^{(*)}K^\pm$ and $B^\pm \to D^{(*)}\pi^\pm$ decays using two-body D final states	2012.09903
Observation of CP violation in two-body $B^0_{(s)}$-meson decays to charged pions and kaons	2012.05319
First observation of the decay $B_s^0 \to K^-\mu^+\nu_\mu$ and Measurement of $\lvert V_{ub}\rvert/\lvert V_{cb}\rvert$	2012.05143
Search for long-lived particles decaying to $e^\pm\mu^\mp\nu$	2012.02696
Test of lepton universality in beauty-quark decays	2103.11769
Search for CP violation in $D^+_{(s)} \to h^+\pi^0$ and $D^+_{(s)} \to h^+\eta$ decays	2103.11058
Measurement of prompt-production cross-section ratio $\sigma(\chi_{c2})/\sigma(\chi_{c1})$ in pPb collisions at $\sqrt{s_{NN}}$=8.16 TeV	2103.07349
Precise measurement of the f_s/f_d ratio of fragmentation fractions and of B_s^0 decay branching fractions	2103.06810
Observation of the decay $\Lambda_b^0 \to \chi_{c1}p\pi^-$	2103.04949
Observation of new resonances decaying to $J/\psi K^+$ and $J/\psi\phi$	2103.01803

hadrons at the LHC since its beginning, of which 52 of the discoveries were made by LHCb.

In particular, we reported new excited B_s^0 states [22], new Ξ_b^0 state [23] and a new excited D_s^+ meson [24].

Conventional spectroscopy described above, aims to understand the pattern of (excited) hadrons from the quark model of mesons (quark content $\bar{q}q$) and baryons (quark content qqq). However, many exotic structures have been observed since the report by the Belle collaboration in 2001 of the $\chi_{c1}(3872)$ state. These exotic structures can be composed of four or five quarks, or be a (molecular-like) bound state of mesons and/or baryons.

LHCb studied in detail the structures in the final states of the decays $\Lambda_b^0 \to \Lambda_c^+ K^+ K^- \pi^-$ [25], $\Lambda_b^0 \to \chi_{c1} p \pi^-$ [26], $B_s^0 \to J\psi \pi^+\pi^- K^+ K^-$ [27], $\Xi_b^- \to J/\psi \Lambda K^-$ [28] and $B^+ \to J/\psi K^+ \phi$ [29]. In particular the observation of the tetraquark with strangeness, $Z_{cs}(4000) \to J/\psi K^+$ is remarkable [29].

3.3 Rare Decays

The area of rare decays has shown a number of intriguing surprises, commonly referred to as flavour-anomalies. In the last few months spectacular progress has been made.

A search for 25 rare and forbidden charm decays has been performed [30]. With the B decays $B^0 \to K^{*0} e^+ e^-$ [31] and $B^+ \to K^{*+} \mu^+ \mu^-$ [32] the knowledge on the Wilson coefficients C_7, C_9 and C_{10} have been further increased. These Wilson coefficients describe the effective couplings in B decays, and are the first step towards the understanding of potentially underlying new physics models.

In anticipation of the publication of the analysis of $B^0_{(s)} \to \mu^+\mu^-$ decays with the full data set, the ratio of fragmentation fractions f_s/f_d has been determined [33] with an improved precision of a factor two, by combining five existing LHCb publications spanning different p_T ranges and different values of centre-of-mass energy. This is essential for the upcoming publication of $BR(B^0_{(s)} \to \mu^+\mu^-)$.

Clearly, the observable with the highest sensitivity, both experimentally and theoretically, to potential new physics effects is the ratio of decay rates [34],

$$R_K = \frac{N(B^+ \to K^+ \mu^+ \mu^-)}{N(B^+ \to K^+ e^+ e^-)} = 0.846^{+0.042+0.013}_{-0.039-0.012},$$

where the Standard Model predicts $R_K = 1.00 \pm 0.01$.

On the 23rd March the new results on R_K and $BR(B^0_{(s)} \to \mu^+\mu^-)$ were presented at a CERN seminar and the renowned Moriond Electroweak Interactions conference. The CERN seminar had an unprecedented online attendance of 850 colleagues on zoom, and 350 connected by webcast. The new result on R_K surpasses the threshold of three standard deviations for evidence of lepton non-universality, with a p-value of 0.001. This result received significant international media coverage.

4 Status of upgrade: tracking system

The tracking system is composed of three detectors, the Vertex Locator (VELO), the Upstream Tracker (UT) and a large Scintillating-Fibre (SciFi) tracker. Significant progress is reported for all systems.

The UT is nearing completion of the primary A-type modules. The 8-chip hybrid, required for the innermost modules, has been demonstrated to meet the specification. Indeed, this is the final key detector component for the full upgrade to enter production. More than a third of the required instrumented staves have been produced. The near detector electronics production is complete. Preparations for the detector assembly and integration at CERN are advancing.

The preparation for detector installation of the SCiFi has proceeded well, notably including a full test installation of the cable chains. The assembly of C-frames had been suspended since the last meeting, due to covid-19 travel restrictions for staff from institutes travelling to CERN, but has recently restarted. The ongoing development of the covid-19 pandemic naturally remains a major concern for this project.

A more detailed summary of recent progress and plans for the next half year is given below for each of the three sub-detectors of the tracking system.

4.1 Vertex Locator (VELO)

The VELO Upgrade is a new pixel detector consisting of 52 modules, each equipped with four hybrid planar pixel tiles, arranged in thin walled RF boxes which form secondary vacuum enclosures within the LHC primary vacuum. It is cooled with evaporative CO_2 and provides a data push triggerless readout, with the total rate reaching 1.2 Tb/s. The project is dispersed over multiple production sites and relies on close collaboration from international experts. For this reason the Covid-19 crisis has had a significant impact on progress since March 2020. In the following sections the status of production of the different VELO Upgrade elements are summarised.

4.1.1 Module Components

The module production relies on a number of components which are assembled, tested, and delivered from the VELO institutes. Due to the gluing problem of 2019 which affected nine modules a greater fraction of components than expected have been consumed in the pre-production process. While the number of components is still adequate for production, they are being complemented with additional production steps as a precaution. The microchannel plates can be considered the most complex component. Each VELO Upgrade module has a backbone of one microchannel cooling plate within which tiny microchannels circulate evaporative CO_2 which directly cool the hybrid pixel tiles and power consuming electronics on the module. The silicon plates are manufactured in industry following quality assurance steps defined together with LHCb, and this production is complete. The CO_2 is delivered to the microchannel plate via a manifold brazed to inlet and outlet pipes, a procedure which is achieved in partnership between industry and Oxford University. This is then attached to the manifold and pipes with a fluxless soldering procedure and the cooling plate undergoes thermal cycling and quality checks for leaks and pressure resistance. The microchannel production was re-qualified after lockdown and streamlined in order to allow the team to function respecting covid-19 regulations. A total of 69 fully qualified microchannel plates have been produced from the available production batches, completing the production. As a complement, an additional processing run of microchannel plates with imperfect dicing is now being used to recuperate any possible additional cooling plates. Each cooling plate from this run undergoes additional treatment and qualification steps for the edges and surfaces to ensure suitability for production. So far four additional microchannel plates have been produced from this lot. Due to the covid-19 restrictions the delivery method of the microchannel plates to the production sites also had to be modified, and the shipping is now being successfully completed with specially constructed boxes by air. A fresh sensor run was launched in 2020 and the tile production is now at the bump bonding stage, to produce an additional 50 pieces. New runs have also been launched for the module front end hybrids. In total the number of pieces are now more than adequate for production.

4.1.2 Module Production

When the module production was resumed after lockdown the strategy was followed to have a thorough re-evaluation of all the quality control steps on the first produced modules, in order to give full confidence, consistency across the production sites and stability for production. The electrical procedure was qualified in parallel at the slice test at CERN in order to iron out remaining issues. At the University of Manchester assembly site the first module to be constructed after lockdown met or exceeded all targets with respect to assembly and the production was greenlighted to continue. Since then the assembly has proceeded reliably and consistently at the rate of approximately one per week, adding a further 17 fully qualified modules and three which are currently in process. Various production parameters have been consolidated, in particular the wire bonding since the start of production has shown excellent pull strengths. The tile placement has been carefully tracked across production in order to detect any possible slippage of the jigs, and the temperature change on module powering before and after thermal cycling, which is crucial to track any problems in the glue joints, has been shown to be extremely stable, as illustrated in figure 2. The module production at Manchester is well on track to fully complete 50% of the total VELO module production by mid-May. The second module production site at Nikhef has experienced a number of setbacks which has led to a pause in production, driven by the decision to conserve module components until the module production process is completely secure. At the production restart there were problems experienced with the cooling system and with the cleanliness of the vacuum tank. In the context of covid-19 solving these problems posed additional challenges. At the start of 2021 the team was partially changed due to planned departures and the time was taken to requalify the procedures, in particular to address issues on the fragile signal chain infrastructure and feedthroughs which led to glitches in the electrical testing. During the requalification process three assembly issues have been identified. A slippage on a jig led to too-close tile placement on one module, which can cause sparking, a gluing step on the GBTX hybrid can lead to a too-warm operation, and the gluing step on the bare module construction led to detachment of one microchannel plate. At Nikhef there are currently 12 modules in process, and it is expected that taking into account the assembly issues described, 10 will be shortly fully qualified for installation. The module production is now being resumed and is shortly expected to reach a rhythm of 1-2 modules per week. Even taking these delays into account the module assembly project is well on track to supply modules at the required rate to the assembly site.

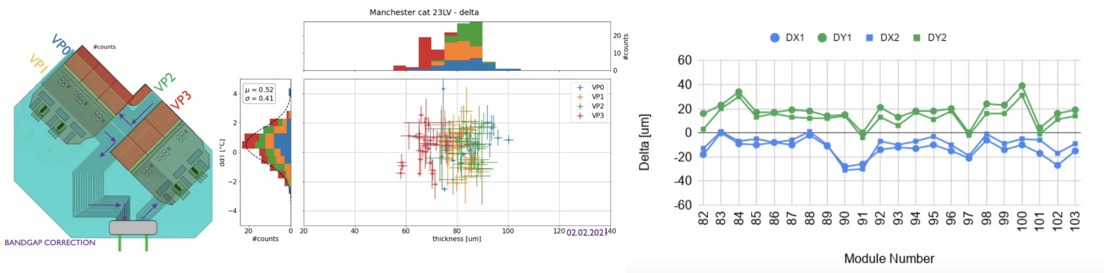

Figure 2: Quality control steps on fully assembled modules. On the left, thermal stability pre and post thermal cycling. On the right, consistency of tile positioning.

4.1.3 Assembly

The mechanical assembly has been heavily impacted by the string of lockdowns, the occasional Covid-19 related complete closure of the laboratory of Liverpool and the restrictive quarantine regulations which have brought travel to a standstill. In addition the assembly has been impacted by unexpected failures in the LUCASZ cooling plant, including the silicon oil contamination which necessitated a complete cleaning procedure, the failure of relief valves, and the breakdown of an internal chiller fan, which while not serious in itself required a major intervention on the system to gain access for replacement. Due to covid-19 the support and travel of experts from CERN which normally could be expected, was not possible, and supply chain delays of replacement parts have led to long accumulated delays. Concerning the assembly, the C side is fully equipped with all mechanics and cooling circuits, and the vacuum tests with blind flanges are successfully completed. The next pre-assembly steps consist of assembling the data, temperature, HV and LV cables to the feedthrough flanges and inserting them into the hood, then the verification of the module insertion, cooling and testing steps with pilot pre-production modules. Following the issues discovered at one of the assembly sites with the possible contamination of cold surfaces in vacuum, an additional pre-assembly step to check for contaminants in the complete signal chain has been added. After these steps are complete the first two production modules will be installed, and following a review, the installation will proceed to completion. The feedthrough flange assembly is a complex process which includes the TDR testing of all signal paths, and has so far been completed for two out of the five flanges of the C side. The schedule has been adjusted taking into account the covid-19 working conditions and the laboratory and the need to work in small 'bubbles' of personnel. The services on the C side are expected to be completed within the next two weeks, followed by assembly of the C side and delivery to CERN in September 2021, and delivery of the A side for the end of the year. The planning for the transport is in the procurement stage, the transport company has been selected and the special terms relating to the VELO transport have been negotiated. The monitoring system will use the Monilog Sensor network, which is currently being evaluated and tested with dummy loads.

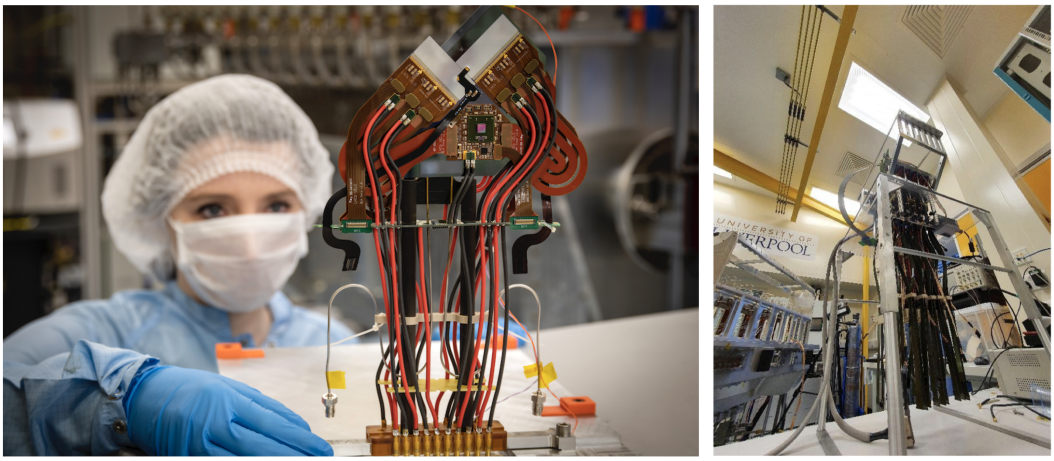

Figure 3: Photographs from the assembly process. Left: Pilot (mechanical) module being prepared for test installation on the base Right: Photograph of fully dressed vacuum feedthrough flange prior to installation

4.1.4 Electronics, Installation, Commissioning

Following the successful installation of the VELO foils, the remaining elements of the vacuum system have been completed. An additional pressure switch has been installed as part of the upgraded safety system, and to address in particular the safety during the venting procedures and when the VELO is under neon. A manual procedure has been developed and tested for the opening of the VELO, such that in the unexpected event of catastrophic failure of the movement system it will be possible to retract the VELO by hand to allow the LHC to continue operation while repairs are carried out. The downstream wakefield (WF) suppressors of the old VELO have been removed and the new WF suppressors compatible with the new "L" shaped pixel VELO have been successfully installed into the VELO exit window, and in a final step have been connected in situ to the installed RF foils. The vacuum tests are complete and the final movement tests are expected to be completed in the coming weeks.

Figure 4: Photographs from the wakefield installation process. Left: Installation of the WF suppressor into the exit window Right: Final connection of the WF suppressor to the VELO RF foil

The remaining infrastructure is making good progress. The installation of the LV system is well underway, the long cabling is complete, the power modules have been assembled and are ready for installation, the final temperature and HV patch panels are being completed. Major design effort is being deployed for the OPB cooling system, a candidate for the cooling cassette and fan have been identified and will be fully qualified in the slice test before installation. The VSS rack is in the final stage of development and installation to provide the full temperature readout and interlock to the power supplies. The additional pressure sensors and associated cabling are being ordered, tested and finalised. All elements are currently on schedule for installation.

4.2 Upstream Tracker (UT)

In the course of the last few months the Upstream Tracker project (UT) has made significant progress, despite significant challenges and restriction related to the global Covid-19 pandemic.

4.2.1 Instrumented staves

The components that are needed to construct the majority of the detector planes are in advanced production status, with some items already available in quantities sufficient to construct the whole detector. For example, the production and test of the type A modules, encompassing 4-chip hybrids and n-type Si microstrip detectors hosted by a stiffener, is nearly completed: 840 detector-grade modules have been assembled and tested; 888 are needed to complete the project. This allows to instrument the largest area of the four UT detector layers.

The last component to be validated, namely the eight-chip hybrid, has been thoroughly studied and found to meet electrical specifications. The first production panel, comprising 6 hybrids, is currently being prepared for shipment. Thus we are now ready to construct all the different flavours of staves needed to complete this subsystem.

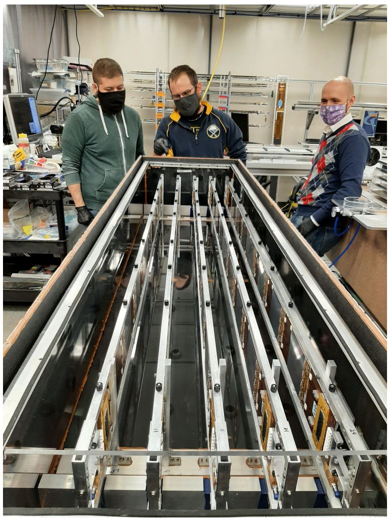

Figure 5: First completed stave with final construction procedure ready to be shipped to CERN

The production of type A staves, comprising 14 modules hosting type A sensors (full-size p-in-n strip detectors) and 4 chip hybrids is well underway. Currently 27 fully instrumented staves have been completed. Another significant milestone has been the shipment of the first group of 5 fully instrumented staves to be mounted on the UT frame in the UT assembly laboratory. Fig. 5 shows the staves in the innermost box ready to be shipped. The transport box shown is the inner layer designed for this purpose is carefully planned to maintain the sensor in a controlled humidity environment, it is enclosed within two additional boxes with provisions to protect the staves from mechanical shock and vibration. Fig. 6 shows these staves safely stored after being received at CERN and undergoing a thorough visual inspection.

4.2.2 Near-detector electronics

The near detector electronics production is completed and currently the task being undertaken is the integration of the boards in their mechanical infrastructure and

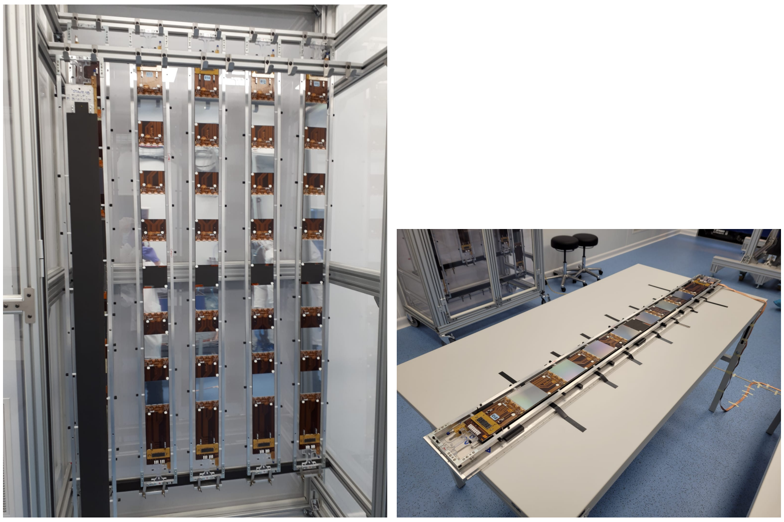

Figure 6: Instrumented staves received at CERN (left) seen in their storage cabinet in UT clean room, (right) stave 13 on the inspection station in the UT clean room, after being checked with a microscope

their burn-in prior to shipment to CERN from Maryland. A last shipment is imminent with all the components needed to complete this subsystem.

4.2.3 Mechanical infrastructure and cooling

The UT detector is being assembled in a laboratory close to the experiment at P8. The detector box is comprised of two parts. Each half is mounted on a movable transport element (chariot) which will be used to transfer the detector half to the experimental area. The C-side mounting infrastructure is currently being integrated with the electronics infrastructure that needs to be in place to be able to connect the staves to the near detector electronics.

4.2.4 Integration in the experiment

The stave integration in the UT box requires a controlled humidity (35% R.H) clean room, which was scheduled to have been assembled in June 2020. Due to Covid-19 restrictions, the company responsible for this installment was not able to complete this task. Nonetheless this task was recently completed, by the LHCb team under remote supervision, and the clean room is in operation, ready for the mechanical assembly tasks and electrical tests envisioned in our assembly and commissioning plans. The first activity was the visual inspection and preparation of the five staves received for mounting in the UT box. Now the staves are stored in a dedicated cabinet. We expect to mount and test the first stave in the UT box with the near detector electronics, final powering scheme and CO_2 cooling in late April.

4.3 Scintillating-Fibre Tracker (SciFi)

The technology and the full detector design of the SciFi system is described in the LHCb Tracker Upgrade TDR [5]. The SciFi will consist of 250 μm thick and 2.5 m long scintillating fibres arranged as hexagonally close-packed six-layer mats of 135 mm width. Eight of these mats are joined together to form 5 m long and 52 cm wide modules. The fibres will be read out by 128-channel arrays of Silicon Photo-multipliers (SiPMs), which have to be operated at -40°C to limit the dark count rate after irradiation. The readout electronics is based on a custom-designed ASIC followed by digital boards for further data-processing and the optical data-transmission. The modules including the readout electronics are mounted on support frames and will be arranged in 12 stereo layers. The detector layers will be installed onto the support bridge of the former Outer Tracker.

The CERN Covid-19 lock-down as well as the Covid-19 travel restrictions of several European countries have been impacting the progress of the SciFi project significantly. The assembly of the C-frame had been suspended for several months, though in March 2021 the SciFi groups have resumed regular travels to CERN and have restarted the assembly work at CERN.

4.3.1 Mat, module and SiPM production

The serial production of the fibre mats, the module production and the production of the SiPM and flex-cables were finished in 2019.

4.3.2 Electronics and read-out box production

The readout ASIC (PACIFIC) has been produced, packaged and tested. The production of all PACIFC carrier boards and cluster boards was concluded in 2019. The last master boards arrived from the industrial producer in January 2020. The front-end boards are mounted on cooling frames and form the so called readout-box (ROB). After an in house (Clermont-Ferrand) pre-production, the remaining ROBs were assembled by an industrial producer and the last ROBs arrived at CERN in spring 2020. Detailed tests of the assembled front-end electronics have been performed at CERN. The tests had been interrupted by the Covid-19 lock-down but were resumed in summer 2020 and have been concluded. The quality of the assemblies is high and no major problems have been found. For a small fraction of ROBs an exchange of bad components is necessary.

On the detector, the ROBs are mounted on water-cooled aluminium blocks to ensure the cooling of the electronics. The aluminium-blocks and also the water-pipes are integrated into the C-frame structure. All water-cooling components, blocks and pipes, for the full detector have been produced.

4.3.3 Cold-box

The SiPMs are not part of the readout boxes but are mounted in a separate mechanical unit, the so-called cold-box. The SiPMs are carried by a cold-bar which will be cooled down to -40°C using Novec, a modern cooling liquid with minimal environmental impact. The cold-bar further allows the precise mechanical positioning of the SiPMs on the ends of the fibre modules. Sufficient thermal insulation and gas-tightness to avoid ice building is provided by the cold-box enclosure. The mass production of the cold-boxes at Nikhef was completed during the first Covid-19 lock-down in 2020.

The cold-boxes are mounted on both ends of the fibre modules before installation. The flex-cables of the SiPMs will later be connected to the front-end electronics. The module finishing, i.e. the mounting of the cold-boxes onto the modules, was stopped during the 2020 lock-down and a second time in September 2020 as a consequence of the Covid-19 related travel restrictions. At that time more than 90% of the detector modules had already been equipped with cold-boxes and had been tested. The module finishing was resumed at the end of March 2021. We expect to finish the remaining 10% by the beginning of May 2021.

4.3.4 Mechanical structure, services, detector assembly and commissioning

Groups of five or six detector modules and their corresponding cold-boxes and read-out boxes will be mounted on C-shaped support frames. Each C-frame will carry a vertical and stereo half-layer. The modules of two C-frames closing around the beam-pipe form the detection layers. In total 6×2 C-frames will be arranged along the beam-pipe. In addition to the mechanical support the 12 C-frames will also provide the necessary services to power, read-out and cooling of the detector elements.

The production of the mechanical components of all 12 C-frames has been concluded in early 2020 and all parts have been delivered to CERN. The assembly of the first C-frames started in early 2019 and by February 2020 the mechanical structures of seven C-frames (C1 to C7) was completed. The construction of the next two C-frames (C8 and C9) was postponed due to the Covid-19 restrictions. The restart of the mechanical assembly of C8 and C9 is foreseen for April 2021.

After assembly of the mechanical C-frame structure, cables, services, modules and the readout boxes are being installed. The different assembly steps require the presence of trained experts from the different contributing institutes. In July and August 2020, when travelling to CERN was possible, we progressed very well. The assembly procedure however was suspended a second time in September 2020 and was only relaunched at the end of March 2021, when the groups resumed traveling to CERN. Table 2 summarizes the status for the first seven C-frames (C1 to C7) at the end of March 2021.

After assembly, the C-frames are cooled down to a temperature of -40°C on the cold-bars. This requires the operation of a cooling plant for the Novec, a stable

Workpackage	C1	C2	C3	C4	C5	C6	C7
Mechanics	ok	ok	ok	ok	ok	ok	ok
Services:							
Water	ok	ok	ok	ok	ok		ok
Novec	ok	ok	ok	ok			
Dry-Gas	ok	ok	ok	ok			
Modules	ok	ok	ok	ok	ok	i.p.	
Heating	ok	ok	ok	ok			
Cabling	ok	ok	ok	ok	ok	ok	ok
Electronics	ok	ok	ok	ok			
Optical Fibres	ok	ok	ok	ok			
Commissioning	ok	ok	ok	ok			

Table 2: Status of the assembly and commissioning of the C-frames as of calendar week 13 (2021). *ok* means concluded, *i.p.* means in progress.

vacuum insulation of all Novec lines, and, to prevent icing of the SiPMs, dry air flushing of the inner cold-box volume.

For the four C-frames (C1-C4) which have been tested so far, the vacuum reached the required level (better than 10^{-4} mbar) to guarantee a good insulation of the Novec pipes. By flushing the cold-boxes with dry-gas a dew-point of -50°C in the cold-boxes was reached. To prevent condensation at the outside of the cold-boxes a heating system is installed. It has proven to efficiently avoid any condensation and cold spots when the Novec cooling was operated at -40°C even during the very humid summer days.

All other service systems (high-voltage and low-voltage supplies, data-acquisition system) have also been commissioned for C-frame C1 - C4. Readout tests at 40 MHz readout frequency have been performed for the installed readout boxes for these C-frames and a bit error rate smaller than 10^{-15} has been achieved. The four C-frames (C1 - C4) are ready for the installation in the experimental cavern which is foreseen for the second half of April 2021.

The remaining C-frames, C5 and C6, necessary to finish the C-side of the detector (detector side behind the beam-pipe) are expected to be assembled and tested until the end of June to be installed in July. According to the very tight assembly schedule the remaining six C-frames (C7 to C12) can be finished by the end of 2021. This schedule however assumes that there are no new Covid-19 related restrictions.

4.3.5 Preparation of detector installation

For the installation of the SciFi C-frames into the LHCb detector, the support mechanics of the former Outer Tracker had to be modified. The modification of the top and bottom rail system on the support bridge has been concluded. Cable trays and the distribution panels for Novec, water and dry gas have been installed. The cooling plant and the dry-gas system are ready.

To test the installation procedure, two C-frames (C-frame C7 and a prototype frame) have already been transported to the cavern and have been successfully inserted onto the rails. Flexible cable chains to guide the cables and services to the detector frames are being installed and filled. Fig. 7 shows a full set of cable chains installed and connected to a C-frame.

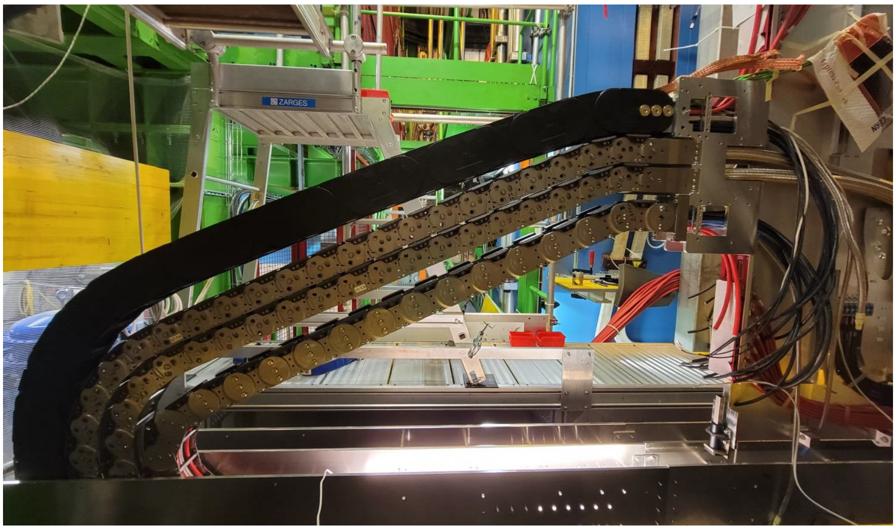

Figure 7: Test installation of the four cable chains of a single C-frame. The cable chains have been filled with cables.

4.3.6 C-frame installation, integration and commissioning

The cable chain installation for the first detector half (C-side) will finish at the beginning of April. It will be followed by the installation of the first four C-frames (C1 to C4). According to the current planning, the last C-frames of the C-side (C5 and C6) will be installed in July. Assuming no further delays related to new Covid-19 restrictions, the second half of the detector frames (C7 to C12) can be installed by February 2022.

The software integration of the new detector into the LHCb data acquisition system and into the detector control system has already started. Once the six C-frames of the C-side are installed, the hardware integration will start and the new detector will be commissioned.

5 Status of upgrade: particle identification system

The Particle Identification (PID) system of the upgraded LHCb detector consists of the Ring-Imaging Cherenkov (RICH), Calorimeter and Muon systems.

The RICH1 gas enclosure, the seal to the VELO, and embedded beam-pipe section have been successfully installed and leak-tested. The A-side RICH2 photodetectors have been installed, the first new active detector system of the Upgrade.

The Calorimeter has now received the first batches of the front-end boards. An oxidation issue occurred on the control boards, but the delivery of the full batch is expected soon. The new tungsten muon filter has been installed in place.

The muon system completed the installation of all electronic boards and was the first system to move into commissioning stage. Some boards have been sent back to an institute for additional tests, but all commissioning activities are proceeding well.

A more detailed summary of recent progress and plans for the next half year are given for each of the three sub-detectors of the PID system.

5.1 RICH system

The upgraded RICH system consists of new photo-sensors with new front-end electronics that can be readout at 40 MHz, a re-designed RICH1 detector and RICH2. Simulations indicate that the physics performance of the new RICH system will achieve a similar performance to the previous detector but at a ten-fold higher luminosity.

While the RICH2 Optics remain in place, and are the same as from 2005, the RICH1 mirrors and transmission windows had to be modified due to the new running conditions. Consequently, also the RICH1 gas enclosure had to be changed and adapted to the improved optical scheme. The carbon-fibre spherical mirrors and the glass flat mirrors for RICH1 have been both ordered and received. Both types of mirrors have undergone QA and characterization before being accepted. The quality is excellent. They have now undergone a special coating process at CERN, which is expected to provide them with a reflectivity in excess of 90% over the relevant wavelength range.

After being produced and tested, the new RICH1 gas enclosure was installed on the beam line of LHCb in August 2019. However, shortly following its installation, one of its quartz window cracked, which led to an extensive and critical study of the incident and its consequences. Solutions were found and have been applied that do not disrupt the overall LHC schedule. The gas enclosure is now in position on the beam line and its upper quartz window safely installed. The leak rates are excellent and the embedded section of the beam pipe has been installed together with the RICH to VELO seal.

Multi-anode photomultipliers (MaPMTs) are the technology for the RICH photon detectors and are read out by a custom ASIC named the CLARO. The order for the MaPMTs was placed in 2015, the pre-series was delivered and accepted in April 2016 after Quality Assurance (QA) tests. The full production was carried out and has been qualified. The MaPMT, CLARO, front-end electronics and system integration have been tested in test-beams and radiation areas. All results meet the requirements.

The photodetector arrays, including the MAPMTs, all on-detector electronics and ancillary systems, is common to RICH1 and RICH2. All components have gone through the production and QA phases for the RICH1 and RICH2 42+4 Columns. The commissioning and installation of the whole photon detector is being carried out at CERN. A Quality Assurance process has been set-up and strictly followed in the last two years, following from single components to the assembly and commissioned functional elements. Two laboratories at CERN have been set-up to test, characterize and study, and to commission in parallel single or multiple components (SysLab and ComLab). Both of the RICH2 Photodetector Arrays have now been fully commissioned, readied and the A-side is now installed at the pit (see Figure 8).

Important studies have been carried out to assess the compliance of all the electronic and mechanical components to the future hostile radiation environment. One important decision was the choice of the FPGA to adopt for the Digital Boards. Following these tests, we arrived to the conclusion that the Xilink Kintex7 is suitable for the RICH specifications and therefore we gave the green light for production and the following QA to start. The full production and the specific QA for the Digital Boards is now finished, they are installed in the RICH2 and are being installed in the RICH1 Columns, which are in the process of being commissioned in the ComLab.

Further studies are being carried out in order to assess the feasibility of our RICH system being equipped with a time-resolution ability. We have confirmed a gating capability of 3.125 to 6.25 ns at present. This would improve PID performance and strongly decrease background from both beam interactions and photoelectronic noise sources.

Finally, we are very sensitive to the environmental issues and are endeavoring to recuperate as much as possible of our radiator gases, both during beam operation as well as during maintenance, gas purification and filling operation. We are constantly improving our gas system, with the help of the support group EP-DT at CERN, and the leak tightness of our two gas vessels.

5.2 Calorimeter system

The upgrade of the calorimeter system consists in the replacement of the electromagnetic (ECAL) and hadronic (HCAL) calorimeter readout electronics and the removal of the Scintillating Pad Detector (SPD) and of the Preshower (PS). The gain of the photomultipliers has been reduced by a factor up to five in order to keep them operational throughout the higher luminosity runs of the upgrade. The

Figure 8: Complete photodetector array ready to be installed in RICH2. The two RICHes features four arrays. One of those for RICH2 has been installed after having been assembled and commissioned at CERN. The use of both 1" and 2" MaPMTs in the RICH2 design is visible.

new analogue electronics partially compensates for the gain reduction by boosting signals by a factor of 2.5. The remaining factor of two is used to extend the dynamic range of the calorimeter system and thus to extend the physics case to some new topics. The upgraded detector will send the full data flow to the counting room at 40 MHz by means of four optical links per Front-End Board (FEB). The earliest-level trigger calculations are performed on the FEBs and the results are sent to the trigger farm in order to optimize the software trigger. The front-end electronics should be fully replaced. The high-voltage, monitoring and calibration systems have been adapted to the new slow control based on the GBT driven optical links. The data-acquisition system relying on the PCIe40 boards is used, which requires a dedicated firmware adapted to the calorimeter data format.

5.2.1 Status of the production and validation of the systems

The main ingredients of the upgrade are the new FEBs, the control units and the adaptation of the high-voltage, calibration and monitoring systems. The design of those systems is at level of the production or of the post-production tests.

The Front-End boards The production of the front-end boards was delayed by a couple of months. Nevertheless, the PCB production started in Autumn 2020 and is now completed. The quality of the PCB appears to meet the requirements. They have all been shipped to the company taking care of the cabling of the boards. At present 80 boards have been produced. Of these, 20 of them have been delivered to our laboratory, IJCLab (Orsay), for detailed functional testing. A problem has been identified on one of these boards which is most probably related to a faulty GBT-SCA component. This is not related to the work of the company and if the diagnostic is comfirmed, we will just request a replacement of the component. The boards which have been produced but not yet delivered to IJCLab are still the responsibility of the company based in Toulouse. They have to pass an ageing test where they will be baked out in an oven for a couple of days and will then undergo basic tests before being delivered to Orsay. We expect to receive them in the next two weeks, in two batches.

The planning is at present to sustain a production of 30 boards per week, the different steps (cabling, control, ageing, mounting of components and of the front-faces, X-rays, measurements, etc) being synchronized so that the delivery schedule should follow the same planning. The production is planned to be completed by the end of April or start of May. The bottleneck in the production of the boards is the cabling, neither the ageing nor the tests done in Toulouse should cause delays. Two ageing/test setups have been mounted at Orsay and provided in order to bake out and test 32 FEBs in parallel. Utilising slightly more human resources for the cabling, 40 boards could be fabricated in a week on average. This is the aim. Such a production rate would permit to complete the production by the end of April 2021.

The functional tests are done at IJCLab. Two test benches have been mounted and are ready. A first setup permits to load the firmware in 16 boards in parallel (9 FPGAs per boards). The processing takes a couple of hours. The boards are then moved in a second test bench where detailed measurements of the boards are performed (see screen captures of some test panels of the corresponding programs in fig 9). A couple of hours are sufficient to fully test 40 boards, they are tested in batches of 5 FEB. The results of the tests are archived for future tracing.

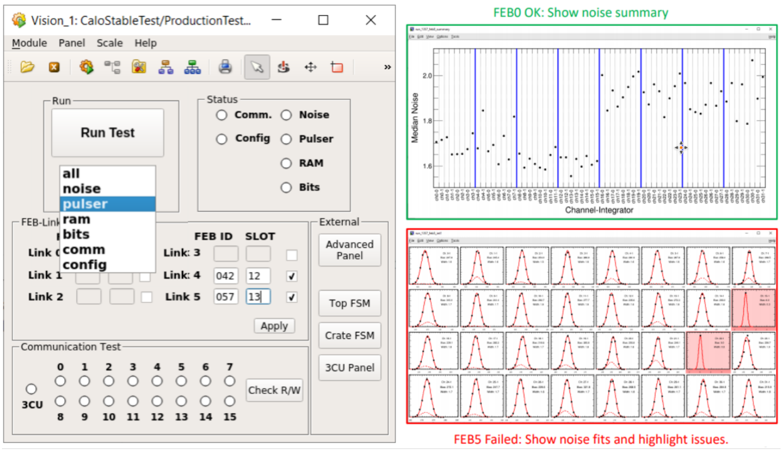

Figure 9: Screen captures of the test programs of the FEB production.

The first setup is used to load the firmware on the boards. This serves also to provide the experts to diagnose the issues with the faulty boards which do not pass the functional test or the firmware loading.

A problem has been identified in the last months on the optical emitters VTTX that equip our FEBs (4 per board). A fraction (approximately 15%) of our emitters may not light on at power up. Observing such an issue requires having a sufficient number of FEBs and we discovered it only after the delivery of the 16 pre-production boards. After discussions with the CERN electronics group and performing tests on some samples, the cause has been tracked and is due to the rising time of the power supplies (40 μs). The CERN electronics group confirmed that some emitters could not respond to a slow rising time and proposed to replace them. We designed at Orsay a test bench to sort the affected components from the thousand pieces which had been returned from the company in charge of mounting them. A fraction has been replaced by CERN and have been sent back to Toulouse. Fortunately, the procedure did not affect the schedule of the production.

It is foreseen to install and connect the front-end electronics to the signal (PMT) cables and to the optical fibres in two stages, corresponding to the fabrication and test of the first and second half of boards. The computers of the farm will be used to start the commissioning.

Control units The production of the control units started in November 2020 with the fabrication of all the PCBs. An oxidation problem appeared on some of them and a second PCB production was launched at the start of 2021. An analysis has been performed and a bad nickel-gold layer deposition was identified as the cause of the issue. The cabling of the first batch of PCBs has been completed while the cabling of the second batch is almost completed. The ageing tests of the control units will be done for the full production by the end of March. The delivery of the full production is foreseen for the beginning of April, including two extra boards for the use of the Plume luminometer.

The control unit will be installed in parallel with the installation of the first half of the FEBs as they are needed for their commissioning.

High-Voltage, calibration and monitoring The high-voltage, calibration and monitoring systems have been in standby situation mostly because of the difficulty for the experts to come to CERN due to the Covid-19 travel restrictions. Fortunately, this part of the project was well advanced. All the boards (a total of 144 boards of five types, including mezzanines and GBT fanouts or ELDM boards) had been designed and fabricated. Most of those boards have been also validated in functional tests and the firmware of the FPGA is close to the final version.

At the beginning of March 2021, the experts have been able to come back to CERN and resumed the work on the firmware and the tests. A total of a month of work is still needed and we hope to start the installation of the mezzanines around April-May. The motherboards that will host the mezzanines have already been dismounted and removed from the pit for modification.

5.2.2 Status of the installation and infrastructure at the LHCb pit

Before the installation of the hardware, which is produced in external institutes, the installation of the infrastructure has already started in the LHCb cavern. Recently, the optical fibres for data (connecting the FEBs to the farm) have been connected on one end to the computer farm. The connection of the slow control bi-directional fibres (connecting the control unit to the control servers) should be done soon.

The GBT fanout boards (ELDM) produced to equip the high-voltage, calibration and monitoring systems have been already installed on the calorimeter platform and on the chariots.

The electromagnetic and hadronic calorimeter motors for the movement of the A and C sides have been replaced (see figure 10, left). The hardware and software of the control system of the motors must also be upgraded. The hardware upgrade is almost completed and leads to a much more reliable operation. The new software implementing a better interface should be ready by the summer. The new tungsten muon filter is now installed in place of the hadronic calorimeter innermost cells (see figure 10, right).

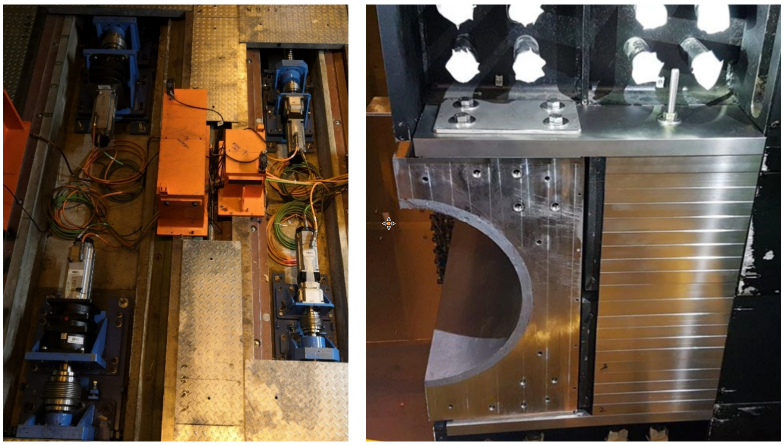

Figure 10: Left : picture of the motors to move the A and C sides of the calorimeters of LHCb. Right : the new tungsten muon filter installed in place of the hadronic calorimeter innermost cells.

Finally, after the modifications of the backplanes and power supplies of the front-end crates in 2019-2020, it was decided to replace the turbines of the racks. This is now completed and the crates are waiting for the boards to be plugged in place.

5.3 Muon system

The Muon detector has performed exceptionally well in Run 1 and Run 2 of the LHC. The main changes for the Run 3 are the removal of M1 (done at the beginning of LS2), the redesign of the off-detector electronics, and the installation of a new shielding in front of the inner region of M2.

5.3.1 Electronics

The electronics of the Muon Detector Upgrade consists of a new readout board (nODE), equipped with four custom ASICs (nSYNC) redesigned to be compliant with a 40 MHz readout of the detector, and of new control boards, the Service Board (nSB) and the Pulse Distribution Module (nPDM), redesigned to be compliant with the new ECS/TFC system. On the detector, a total of 144 nODE, 120 nSB and 8 nPDMS are needed. Taking into account the spares, we will produce 190 nODE, 150 nSB and 14 nPDMs boards in total.

The test and selection of all the needed nSYNCs (760) has been completed and the full set is at the company; 740 have already been installed on 185 completed nODE boards. Furthermore, about 100 additional spare nSYNCs have been selected for future usage.

The supply of nODE boards had undergone delays, due to the Covid-19 pandemic. The producing company experienced some difficulties with component procurement and board assembly, causing a few months of delay in the production. However, at the end of 2020 the company sent the final batch of boards. At present a total of 185 nODE boards have been produced and tested at LNF (the last 5 out of 190 will be produced in the next months). In January 2021 we installed the last tested good boards and all the muon stations were fully equipped with the new electronics. Testing is ongoing with a number of boards sent back to LNF for further tests. The situation at CERN is now the following: 128 boards are installed (89% completion) of which five temporarily accepted with degraded BER (<1E-12); the missing ones are seven in side C and nine in side A. These "holes" do not block the connectivity test. For the boards now in LNF, we have seven good nODEs, 13 sent to the company for reworking, and finally 36 under investigation (18 found not good after the delivery by the company, and 18 just sent back from CERN).

All the nSB (150) and nPDM boards (14) needed were delivered and tested in Roma1, and sent to CERN in March 2020, just before the pandemic closure. This allowed us to complete their installation on the detector in June 2020. Their installation is 100% complete, and they are currently being used in the connectivity test.

5.3.2 Commissioning

All the activities needed for the commissioning of the muon system are progressing well, ideally to have the system ready for the test with beams foreseen at the end of September 2021. For the tests, in the last months we moved from the "commissioning rack" close to the detector to the data centre; all muon Tell40 and SOL40 boards are connected and the firmware is being updated to the latest version in these days. The connectivity test will start soon on side C, followed by side A. The ECS project is well advanced for all the sub-projects. For what can be said now, the pandemic should affect only marginally the plans for the commissioning.

5.3.3 Additional Shielding in front of M2

In parallel the activities related to the addition of material in front of M2 are well advanced. This is foreseen to reduce by about a factor two the low energy background rate in this region. The material consists of three parts: a new HCAL beam plug, which goes closer (up to 1 cm) to the beam pipe, tungsten slabs in place of the innermost HCAL cells, and a new M2 beam plug, partially made of lead.

The new HCAL beam plug and the tungsten shielding in the innermost cells of HCAL have been both successfully installed. The M2 beam plugs are ready to be installed in the next weeks.

6 Status of upgrade: fixed target (SMOG2)

LHCb is the only experiment at the Large Hadron Collider (LHC) that can take data both in collider and fixed-target mode. The LHCb fixed-target system, called SMOG (System for Measuring the Overlap with Gas) [35] allows to inject a low rate of noble gases into the vacuum vessel of VELO. This gives the unique opportunity to operate an LHC experiment in fixed-target mode, and to study proton-nucleus and nucleus-nucleus collisions on various target types and at different centre-of-mass energies.

An upgrade of the SMOG system, SMOG2 [9], has been installed during LS2. The main element of SMOG2 is a storage cell for the injected gas, which is positioned at the upstream edge of the VELO, coaxial with the LHC beam line and displaced by 30 cm from IP8. One of the main advantages of SMOG2 is the possibility to reach much higher effective areal densities (and thus luminosities) with respect to SMOG at the same injected gas flux.

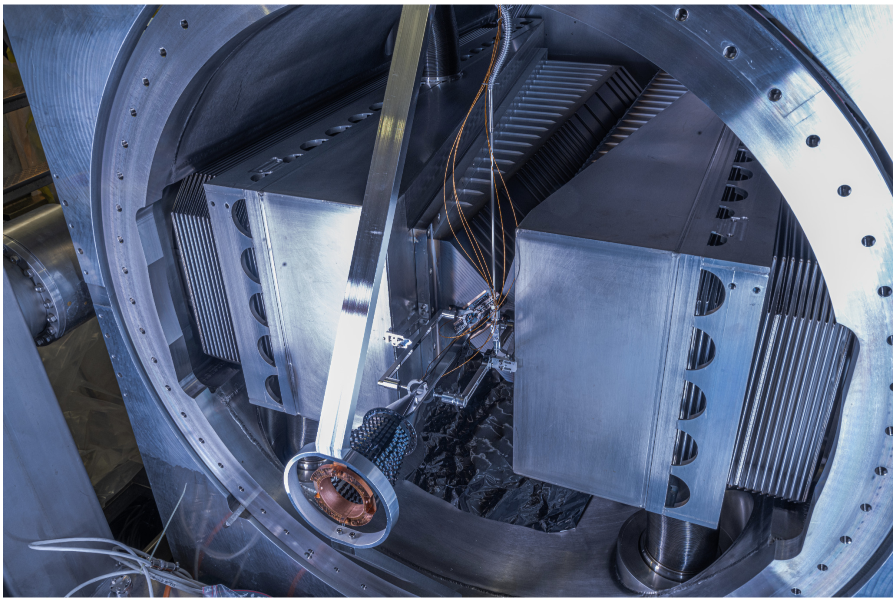

Figure 11: The installed SMOG2 storage cell with wake field suppressor, attached to the VELO RF box in the VELO vacuum vessel at IP8.

A detailed physics programme with a fixed target at LHCb has been presented in a dedicated report of the Physics Beyond Colliders study group in Ref. [36].

In August 2020 the storage cell was successfully installed inside the VELO vacuum vessel, see Fig. 11.

After the installation of the storage cell, the other key component of SMOG2 is the Gas Feed System, now in its assembling and calibration phase. Using this system it will be possible to inject precise fluxes of gas, from hydrogen to heavy noble gases. Software and trigger implementations are already well advanced in the Real Time Analysis framework.

7 Status of upgrade: online, trigger and real-time analysis, computing

7.1 Online

The heart of the online system is the event-builder, which assembles the events at a rate of 40 MHz. The design relies on a large bandwidth bi-directional network interconnecting the event-builder PC-servers and on a generic (PCI Express) readout module, the PCIe40 board, embedded in each PC-Server.

The event-builder has to aggregate 40 Tbits/s. The architecture relies on 200 PC-servers interconnected through a 200 Gbits/s bi-directional network. The installation of the PC-servers equipped with their PCIe40 boards and network interface is finished. The 200 Gbits/s bi-directional network is ready. Validation procedures as well as connection to the optical fibers from detector is going on. The event builder hardware will be operational by mid-April.

The ECS and TFC distribution relies on nine PC-Servers equipped with eight PCIe40 each and connected to the Front-end electronics. Those for CAL0, MUON, RICH1 and RICH2 are ready.

The commissioning with the MUON and RICH systems has started.

To house the event-builder and the event-filter farm, a new data centre has been built on the surface at the LHCb experimental site. It is composed of six containers located at LHC Point 8. Five out of six containers are now fully operational. The last one will be added by the Summer of 2021.

7.2 Trigger and real-time analysis

The Upgrade trigger [6] consists of a collection of identical software tasks running on the event-filter farm. All collisions are reconstructed in real time with the best possible quality and then selected to be written for offline storage. This process is done in two steps. In the first one, HLT1, the fast reconstruction sequence is run in order to reduce the rate to about 1 MHz. Data are then stored locally waiting for the calibration and alignment constants. Once ready, the second step, HLT2, performs the full reconstruction and selects collisions interesting for the physics. In this scheme, the full reconstruction is done once and never redone at later stages.

The fast reconstruction has been ported to an heterogeneous architecture in which the CPU uses a GPU co-processor. The new generation of GPU cards, available since the end of 2020, increase the processing rate per GPU by a factor up to 1.4. Therefore, the fast reconstruction can run with one GPU card per event-builder node without global event cuts, leaving about 10% headroom. Work is on-going to run the software on GPUs from different vendors.

The full reconstruction is working in the new framework. In past months, many improvements were deployed on seeding, downstream tracking and calorimeter reconstruction algorithms. The throughput reached 300 Hz per reference server allowing to process an HLT1 output rate of about 1 MHz.

A first implementation of the HLT2 selections has been put in place during summer 2020. Work is ongoing to fully move selections over to the new vectorized framework.

The next milestone is the *Freeze partial (HLT1) and full (HLT2) reconstruction sequence* which has been pushed back to June 2021, taking advantage of the additional time in the new schedule. In parallel, we are preparing the tender to buy GPU cards by the end of 2021.

A collaboration agreement has been elaborated on the sharing of the maintenance and Operation Resources of the RTA project. It will ensure long-term support for the development, maintenance, and operation of the RTA software, covering both personnel and financial contributions, in full analogy to any other sub-detector project. The document is currently under signature by the contributing institutes.

7.3 Computing and offline processing

Work has been continuing on the framework upgrade for Run 3: a conditions database has been setup for Run 3, whose values can be loaded using the new framework element (DD4hep). Improvements have been made on the design of the conditions system for the various LHCb sub-detectors, implementing the functionalities required by alignment and calibration, which have the most stringent requirements. The prototype of the alignment code is now undergoing final tests. The implementation of the LHCb sub-detectors material description (in DD4hep) is also ongoing, with visible progress.

The configuration tools (CMake-based) for core applications are being improved for speed and ease of use, and therefore increased developer productivity.

Significant efforts are also ongoing to improve the LHCb software infrastructure, with the goals of improving quality assurance and getting faster releases, streamlining the processes and reducing manual operations. The LHCb continuous integration system is being redesigned, to allow for more tests and improved speed. The LHCb performance and regression testing system (LHCbPR) is also being upgraded accordingly.

Work has started towards a future Event Display application that will be integrated with the new detector geometry package (DD4hep) and based on the latest web technologies supported by the HEP Software Foundation (HSF).

Investigations on the use of computing architectures other than the usual standard (x86_64) continue along two major axes. The first one is the port and optimization of LHCb software stack, (e.g. using the SVE instruction set on ARM). The second one is aimed at adapting the tools that set up the LHCb software environment to access non x86_64 resources, an example being the release of those tools for the PowerPC architecture.

In the distributed computing domain, LHCb has successfully moved from Castor to CTA as an archival solution at CERN. LHCb has been using for a few months multi-processor (MP) queues at selected Tier2 sites. The utilisation and investigation of High Performance Computing centres (HPC) continues : the Marconi/A2 KNL partition at CINECA was used until it got dismantled at the end of February 2021. Four more HPC centers are being used, or prepared to be used: SantosDumont in Brazil, NERSC in USA (for which LHCb was awarded an allocation grant), MareNostrum in Spain, and the Marconi/100 partition in Italy. Each of them have different characteristics and pose different challenges.

A new shifter role has been established, in charge of monitoring the distributed computing infrastructure, thus relieving experts from time-consuming daily chores. Shifts started on February 15th. They will be gradually extended to monitor the quality of real data and simulation productions.

The recently established Data Processing and Analysis (DPA) project addresses the challenges for offline data processing and analysis due to the very large increase in data volume with respect to Run II. It does so in two main domains: (i) centralised skimming and trimming (Sprucing) of a significant fraction of HLT2 outputs, and (ii) centralised analysis productions for physics working groups and users. The Sprucing application and selection framework are shared between HLT2 and offline. Sprucing performs the offline data selection and streaming for data that cannot go (initially) to the compactified Turbo stream. The analysis production system has been recently implemented for Run 1 and Run 2 analyses, and its daily use by the collaboration constitutes an excellent test and validation of the system in view of Run 3. The offline analysis software and application will share as much as possible with their online counterparts, focusing on modern design techniques and on user-friendly configuration. A work package on innovative analysis techniques has provided a first proof-of-concept on Quantum Computing techniques for b-jet tagging, while the work package on legacy data and software is preparing for an incremental re-stripping of Run 2 data (see section 2). A new work package has been established for analysis preservation and open data activities, focusing at present on the release of Run 1 data to the CERN Open Data portal, on guidelines and tools for analysis preservation.

8 Status of upgrade: infrastructure

8.1 Infrastructure

The general infrastructure up to the detector distribution panels is completed and commissioning well under way for most of the systems, but still without subdetectors connected. This liberates some of the technical coordination team and members are focusing on the support of the detector teams as travel restriction due to the pandemic has considerably decreased the number of collaborators present at CERN.

For the SciFi detector all necessary work for the near detector service installation has been completed. The structures are ready for the integration of cables and cooling pipes and the first service chains are filled allowing to start the installation of the first SciFi C-frames in the second half of April.

The installation of the clean room that is required for the assembly of the UT detector here at CERN has finally been completed. This was possible only as the technical coordination team took over this work from the UK company that were prevented from coming by travel restrictions. The required infrastructure inside the clean room for the UT assembly has been completed as well.

8.2 Installation

The LHCb dipole required a major consolidation and repair work as two out of 32 supporting clamps had broken during the LHC Run 2. All this work, including the installation of a systems of monitoring has been completed. The monitoring system registers the stresses on the support structures and clamps of the yoke. The magnet was successfully ramped up, followed by a complete magnetic field-map measurement early this year.

The Tungsten beam plug that will reduce the background for the Muon detector behind the HCAL is in place on both sides, A and C. Furthermore, the new electronics for the Muon systems is in place and under commissioning since a few weeks.

The RICH 1 gas enclosure has been successfully installed and the upper quartz window is in place. RICH 1 has been sealed with a huge bellow to the VELO and leak test were performed, showing an acceptable low leakage rate. The next step is the installation of the RICH 1 exit window which is on its way from the UK to CERN.

The first section of the beam pipe has been installed and its tightness successfully tested. The Wake-field suppressor is in place and connecting the first section of the beam pipe to the Velo RF boxes.

RICH 2 MaPMT columns are installed on side A and are being commissioned. RICH 2 columns on side C will follow shortly.

8.3 Commissioning

The commissioning of the upgraded LHCb detector has now entered its first phase: the installation of the Online system is almost finalized and its commissioning is well underway, with the goal of completing it by summer 2021. Thanks to this, the first sub-detectors, namely the MUON and the RICH2 systems, were able to start commissioning their installed detectors using the central Online system, which is a major milestone. Particular attention was given to the cleaning of the fibers between the sub-detectors and the LHCb data centre and the integration of the custom-made PCIe40 readout cards in the Event Building servers. Currently, the commissioning of the central control system, readout firmware and tools is where most of the work is being concentrated in collaboration with the first installed sub-detectors. In addition to this, the integration of the HLT1 GPU in the Online system has started as well as the development of the monitoring chain. Moreover, significant progress has happened in the implementation of the HV/LV controls that needs to be ready to power the installed detectors and the integration plans of the newly developed luminometer and beam monitoring systems.

8.4 VTRx Issues

Some failures in a common LHC component of the data transmission, the versatile link Transceiver VTRx, have been reported by other LHC experiments. The issue is under investigation by the CERN Electronic Systems for Experiments group that designed this element. The LHCb Upgrade utilises 1500 of these modules.

9 Status of upgrade: project organization

9.1 Project organization

The upgrade detector construction activity is overseen by the Upgrade Detector Planning Group (UDPG). The UDPG membership consists of an Upgrade Coordinator (chair), an Upgrade Resources Coordinator, an Upgrade Data Processing Coordinator, an Upgrade Electronics Coordinator, as well as the management and a representative of the Physics Coordinator.

The upgrade detector installation activity is overseen by the Technical Coordination team and the LHCb Technical Board. Much of the detector activity has moved from the production to the installation phase. The Technical Board is chaired by the Technical Coordinator and is comprised of all detector project leaders. A number of the subdetectors are also moving into their commissioning phase, this is overseen by the Commissioning coordinator and their deputies.

All the activities concerning the development of the all-software trigger are coordinated by the Upgrade Software Planning Group (USPG). The USPG membership consists of the USPG chair, representatives of the Computing, Online, Real-Time Analysis, Data Processing and Analysis projects and of the Simulation working group, the Operation Coordinator, as well as the management and the physics coordination team.

The various bodies meet regularly to review progress of the projects. Detector and software upgrade activities are organised within the existing Projects and working groups, to ensure efficient sharing of resources between operational needs and Upgrade work.

9.2 Milestones

The overall baseline schedule remains unchanged since the last RRB. Discussions with the other experiments, machine and directorate have recently reconfirmed a schedule of closure of the caverns in February 2022 in readiness for data-taking. This schedule remains tight for LHCb and travel-restrictions, working-condition procedures and delivery delays due to the covid-19 pandemic continue to impact us. The schedule is particularly critical for LHCb given the large scale of the modifications made to the detector system and the strong reliance on personnel being able to travel from institutes to CERN for assembly, installation and commissioning activities. Given the current uncertainties, a close monitoring of the pandemic evolution and its impact on the projects has been put in place and further LHC-wide discussions are planned for June 2021.

9.3 Funding

The status of the M&O Cat.A and B accounts is still affected by the present Covid-19 dominated situation, especially due to difficulties in getting the right collaborators on site. As described in the detector description sections, delays are being reported, therefore we expect minimal or no cash flow issues, providing all members will contribute to the budget. The expenditure on the 2020 M&O Cat.A budget followed well our forecasts. The 2020 year expenditure, the second LS2 activity year, is quite balanced even adding Covid-19 into the equation. According to the financial plan for the M&O Cat.A levels, which we finalised, submitted and got approved by the Scrutiny Group and by the RRB in 2017 and 2018, the proposed and subsequently approved budget for M&O Cat.A is 3,070 kCHF for the year 2021.

A smooth transition is requested by the sub-detectors projects for their M&O Cat.B. This seems to be happening nicely, although of course there is an inevitable difficulty in estimating the resources and technical commitments for the completely new sub-detector projects.

The funding requirements for the LHCb Upgrade construction have been defined in detail in Addendum No. 1 to the Memorandum of Understanding (MoU) for Common Projects [11] and in the Addendum No. 2 to the MoU for the Upgrade of the Sub-Detector Systems [12], which refer to the LHCb Upgrade Framework Technical Design Report [2] and the Technical Design Reports [3–8] for all Upgrade subdetector-systems. These documents define in all details the technical design and cost of the upgraded detector, as well as the sharing of responsibilities among the institutes and Funding Agencies in the construction, installation and commissioning of the upgraded sub-systems. The total cost of the LHCb Upgrade of 57.2 MCHF is divided into a Common Projects for an amount of 15.7 MCHF and Sub-Detector Projects for an amount of 41.5 MCHF.

At present, the LHCb Upgrade project continues to progress. All major contracts have been placed and spending of CORE funds is proceeding for all of the sub-detector components. Most of the remaining funds for sub-detectors construction will have been spent during the year 2021. The majority of the Common Project funds (in particular for the acquisition of the Computing Farm) are expected to be spent in 2020-2021. The Upgrade project continues to evolve within the agreed cost envelope and there is confidence that the funding profile will essentially match the spending profile to ensure a complete and timely installation of the new experiment by the end of LS2. A deficit in the RICH Detector Project, as shown in the Addendum No. 2 to the MoU for the Upgrade of the Sub-Detector Systems [12], has been essentially reabsorbed, thanks to savings, a more aggressive cost policy and a generous extra contribution. No request for further funds has been put forward.

10 Upgrade II

A future upgrade of the LHCb detector capable to integrate up to 300 fb^{-1} throughout the full HL-LHC phase has been proposed in [37], with details on the physics reach discussed in [38]. The project consists of a major change of the detector during LS4, in order to sustain an instantaneous luminosity up to $1.5 \times 10^{34}\ \mathrm{cm}^{-2}\mathrm{s}^{-1}$ starting from Run 5. A series of minor consolidation changes to the detector are also proposed for LS3, with the purpose of staging part of the construction activities during this long shutdown phase, while ensuring better physics performances already during Run 4.

The above plan received strong support in the 2020 Update of the European Strategy for Particle Physics [39], recently approved by the CERN Council. This indicates a clear priority in exploiting the full potential of the HL-LHC, including the study of flavour physics, which will be enhanced with the ongoing and proposed future upgrades of LHCb.

A timescale has been agreed by the LHCC for submission of a Framework TDR for Upgrade II during the second half of 2021, which will be followed by subsystems TDRs describing consolidation in LS3 and later by subsystem TDRs describing the Upgrade II for LS4. The RRB will be kept informed about the preparation of these documents. The Framework TDR will describe the detector and computing that demonstrate we have technological feasible options to deliver our physics case, with projections of costs and national interests. The preparatory work is now in advanced state, with all subsystems engaged in drafting their baseline scenarios. A collaboration meeting will be held at the beginning of May, with the purpose of finalising the discussion and starting the document review process.

One of the key ingredients for success of the project will be to develop highly innovative technological solutions, for which a vigorous R&D is being carried on in all the areas of interest for Upgrade II, with strong support from the contributing nations. Some examples include developing state-of-the-art sensors and readout electronics with picosecond timing capability, extreme radiation hardness and unprecedented data throughput capabilities, or exploiting heterogeneity advances in CPU/GPU/co-processor technologies to boost the performances of the data acquisition system. All these aspects are also central in the ongoing discussion within the ECFA in order to define a roadmap for future detector R&D. Under this respect, the LHCb upgrade II, with its technological challenges, can be seen as a bridge towards experiments at future accelerator facilities.

The HL-LHC project also established an organisation for the accelerator studies for Upgrade II, and a detailed plan to adapt the beam optics and the operation scenarios is being prepared. The HL-LHC team will present a Conceptual Design Report for the machine modifications on the same timescale as the Framework TDR. In the meantime, plans are also being prepared in order to upgrade the infrastructure in the LHCb cavern to protect the relevant LHC machine cryogenic equipment from the radiation environment foreseen at Run 5. Also in this case, construction activities could be staged in LS3, in order to make an efficient use of the prolonged period of shutdown.

11 Collaboration matters

The collaboration continues to grow, having added two further institutes in this period. The collaboration has 976 authors at the time of writing. The Centre Nacional de Microelectrònica, Institute of Microelectronics, Barcelona (IMB-CNM) has joined as a Technical Associate member group with particular interest in the precision-timing VELO system for Upgrade-II. The Eötvös Loránd University, Budapest (ELTE) has joined the collaboration as an Associate Member group, they have a range of physics, software and detector interests including the precision-timing calorimeter system for Upgrade-II. This is the collaboration's first group from Hungary, which we are pleased to welcome to our community bringing our number of contributing countries to 19. The collaboration has approved changes to the constitution to extend the membership opportunities to those working on software and detector development.

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