Status of LHCb Upgrade I

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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 [3–9] and approved by the Research Board. An additional document describing our recent decision to adopt the innovative and cost-saving technology of Graphical Processing Units in the first level of the trigger has also been supplied to the LHCC this year [10].

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 533 papers published or submitted, of which 27 were submitted in 2020. Data processing is also proceeding smoothly, with a full Run 1 + Run 2 data reprocessing having been completed in the last period.

Physics highlights since the last report are discussed in Sect. 3. LHCb is designed to measure matter anti-matter asymmetries (CP Violation). LHCb has reported the world's best measurement of one of the key *CP* Violation parameters, the CKM angle γ, testing the Standard Model theory. LHCb has discovered a number of new particle in this recent period, these new particles are excited states of the Ω_b^-, Λ_b^0 and Ξ_c^0. In addition to these conventional particles, LHCb has furthered our understanding of additional particles that are "exotic" , that is not composed of two or three quarks as in conventional particles. Notably LHCb announced the discovery of the first tetraquarks, four-quark states, containing four charm quarks (the X(6900)) and open charm (the X(2900)). Another key element of the LHCb programme is the study of rare decay processes, we have continued our investigations on processes where hints of discrepancies with the Standard Model have been seen, with a number of further publications. Analysing with a larger data sample the angular distributions in $B^0 \to K^{*0}\mu^+\mu^-$ decays a slightly smaller deviation with respect to the Standard Model is seen than previously but one that fits better with a possible New Physics scenario.

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. In most cases the progress was heavily disrupted by pandemic lockdowns in the CERN region and in many of the 18 contributing countries. Progress then picked up from July onwards, with our teams quickly adapting to the new ways of working. However progress is now being further impacted by the increasing number and rapidly evolving travel and quarantine restrictions.

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.

2 Operations

2.1 Data processing

In 2019 a full data re-processing campaign started, benefitting from the improved Calorimeter calibration. The Run 1 and 2 re-processing for proton-proton collision data was completed in Spring 2020. Three heavy ions data re-processing campaigns have now been delivered (p-Ne, Pb-Pb and Pb-Ne) thus completing the re-processing of the full data set acquired by LHCb in Run 1 and 2.

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. In general, when generating Monte Carlo simulation samples, the main contribution to the time needed to simulate full events is given by the simulation of the detector response. Figure 1 (left) shows the simulated events in the past 365 days where the fast simulations are dominating the split of the resources. 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 or simulate only part of the events under study (e.g. see ReDecay [13]). Moreover the employment of new technologies and accelerators is under study for future applications.

In order to further speed up the Monte Carlo 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 (right): at the moment almost 90% of the resources are devoted to MC production, 10% to jobs submitted by users and about 1% has been used by data processing.

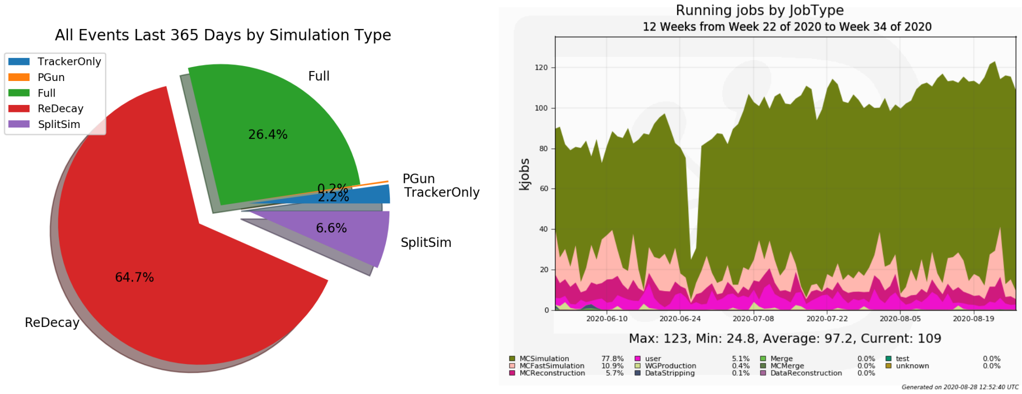

Figure 1: Left: The events simulated by LHCb split by simulation type. The usage of fast simulation techniques is growing allowing a better exploitation of the computing resources. Right: The number of running jobs on the online-farm during the past months: the light-pink area indicates Monte Carlo jobs using a fast simulation technique, the green area Monte Carlo jobs using the full event simulation, the dark blue shows the usage by the heavy ions data re-processing.

2.2 Computing

The usage of computing resources for 2019 [14] is discussed in a separate document. 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, 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 [16].

3 Physics

Since the start of 2020, the LHCb collaboration has submitted 27 new publications (see Table 1), for a total of 533 papers at the time of writing, of which 519 have been published. A further 17 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

Measurements of CP violation remain a cornerstone of the LHCb physics programme. Apart from the search for CP violation in the charmless decays of the Ξ_c^+ baryon, $\Xi_c^+ \to pK^-\pi^+$, multiple analyses of $B^\pm \to DK^\pm$ have been finalized. The number of $B^+ \to DK^+$ decays are compared to the CP-conjugate mode $B^- \to DK^-$. If the D meson subsequently decays into a CP-eigenstate then two amplitudes contribute to the total amplitude which in turn leads to a sizeable CP asymmetry in $B^\pm \to DK^\pm$ decays. This difference in the number of $B^+ \to DK^+$ and $B^- \to DK^-$ decays is directly related to the CKM angle γ. The precise determination of γ is a key element of the LHCb physics programme in testing the Standard Model by comparing numerous precise observables. In 2020 LHCb has published and shown $B^\pm \to DK^\pm$ results with $D \to K_S^0 K^\pm \pi^\mp$ [17] and $D \to K_S^0 \pi^\pm \pi^\mp$ decays, respectively. The use of $D \to K^+K^-$ decays is in the final stages of internal LHCb review. The world's most precise single measurement of $\gamma = (68.7^{+5.2}_{-5.1})^o$ is reported.

3.2 Conventional Spectroscopy

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, which energy levels manifest themselves as

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

Title	arXiv
Search for CP violation in $\Xi_c^+ \to pK^-\pi^+$Apart decays using model-independent techniques	2006.03145
Measurement of the branching fraction of the decay $B_s^0 \to K_S^0 K_S^0$	2002.08229
Strong constraints on the $K_S^0 \to \mu^+\mu^-$ branching fraction	2001.10354
Measurement of $\vert V_{cb}\vert$ with $B_s^0 \to D_s^{(*)-}\mu^+\nu_\mu$ decays	2001.03225
First observation of excited Ω_b^- states	2001.00851
Search for the lepton flavour violating decay $B^+ \to K^+\mu^-\tau^+$ using B_{s2}^{*0} decays	2003.04352
Measurement of CP observables in $B^\pm \to DK^\pm$ and $B^\pm \to D\pi^\pm$ with $D \to K_S^0 K^\pm \pi^\mp$ decays	2002.08858
Observation of a new baryon state in the $\Lambda_b^0\pi^+\pi^-$ mass spectrum	2002.05112
Measurement of the shape of the $B_s^0 \to D_s^{*-}\mu^+\nu_\mu$ differential decay rate	2003.08453
Search for the Rare Decays $B_s^0 \to e^+e^-$ and $B^0 \to e^+e^-$	2003.03999
Measurement of CP-averaged observables in the $B^0 \to K^{*0}\mu^+\mu^-$ decay	2003.04831
Precision measurement of the B_c^+ meson mass	2004.08163
Observation of New Ξ_c^0 Baryons Decaying to $\Lambda_c^+ K^-$	2003.13649
Measurement of the $\Lambda_b^0 \to J/\psi\Lambda$ angular distribution and the Λ_b^0 polarisation in pp collisions	2004.10563
Measurement of the branching fractions for $B^+ \to D^{*\pm}D^\mp K^+$ and $B^0 \to D^{*-}D^0K^+$	2005.10264
Study of the lineshape of the $\chi_{c1}(3872)$ state	2005.13419
Study of the $\psi_2(3823)$ and $\chi_{c1}(3872)$ states in $B^+ \to \left(J\psi\pi^+\pi^-\right)K^+$ decays	2005.13422
Observation of enhanced double parton scattering in proton-lead collisions at $\sqrt{s_{NN}} = 8.16$ TeV	2007.06945
Observation of structure in the J/ψ-pair mass spectrum	2006.16957
First observation of the decay $\Lambda_b^0 \to \eta_c(1S)pK^-$	2007.11292
Searches for low-mass dimuon resonances	2007.03923
Search for the doubly heavy Ξ_{bc}^0 baryon via decays to D^0pK^-	2009.02481
First observation of the decay $B^0 \to D^0\overline{D}^0K^+\pi^-$	2007.04280
First branching fraction measurement of the suppressed decay $\Xi_c^0 \to \pi^-\Lambda_c^+$	2007.12096
Observation of multiplicity-dependent prompt $\chi_{c1}(3872)$ and $\psi(2S)$ production in pp collisions	2009.06619
A model-independent study of resonant structure in $B^+ \to D^+D^-K^+$ decays	2009.00025
Amplitude analysis of the $B^+ \to D^+D^-K^+$ decay	2009.00026

different mass values of observed resonances. Many new excited hadron states have been reported in 2020, filling some of the remaining gaps in the expected pattern of hadrons.

In particular, LHCb reported excited Ω_b^- states (quark content ssb) for the first time [18], observed the first radial excitation of the Λ_b^0 baryon (quark content bud (the $\Lambda_b^0(2S)$ resonance) [19], and discovered new Ξ_c^0 baryons (quark content csd) decaying to $\Lambda_c^+ K^-$ [20]. Furthermore, searches for the Ξ_{bc}^0 baryon (quark content bcd) was performed [21], and the world's most precise value for the B_c^+ meson (quark content $\bar{b}c$) was determined, $m_{B_c} = 6274.47 \pm 0.27(stat) \pm 0.17(syst)$ MeV/c^2. [22] with a relative precision as small as 5×10^{-5}.

3.3 Exotic Spectroscopy

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, in 2001 the Belle collaboration reported the *"observation of a narrow charmonium-like state in exclusive $B^\pm \to K^\pm \pi^+ \pi^- J/\psi$ decays"*. This famous exotic hadron, now known as the $\chi_{c1}(3872)$ state, is thought to be composed of four quarks (quark content $c\bar{c}q\bar{q}$). However, the exact nature of these states remains a mystery and various models aim to describe the dynamics, ranging from strongly bound 4-quark states, to weakly bound molecule-like states of two mesons.

LHCb measured the exact mass and width of the $\chi_{c1}(3872)$ [23, 24]. This includes precious information on the lifetime of the $\chi_{c1}(3872)$, which in turn is determined by the binding mechanism of the constituents. The mass of the $\chi_{c1}(3872)$ is reported to be remarkably close to the sum of the D^{*0} and D^0 masses ($\delta E = 0.12 \pm 0.13$ MeV), which sheds light on the role of D^{*0}, D^0 rescattering in the appearance of the $\chi_{c1}(3872)$ resonance. In addition LHCb reported how the $\chi_{c1}(3872)$ seems disrupted by traversing busy medium, suggesting a weakly bound state [25].

Two real highlights were reported by LHCb in 2020, the first one being the observation of the first 4-quark state consisting of four heavy quarks, $T_{c\bar{c}c\bar{c}}$ [26]. Although such a state was predicted by some models, this longly awaited observation came as a pleasant surprise to the community. This state was observed in the invariant-mass spectrum of two J/ψ mesons, and was dubbed the $X(6900)$, with a mass of $m(X(6900)) = 6905 \pm 11 \pm 7$ MeV or $m(X(6900)) = 6886 \pm 11 \pm 11$ MeV, depending on the assumptions of the description of the background and its interference with the signal.

The second surprise was the observation of a resonance in the $D^- K^+$ invariant-mass spectrum [27]. Such a state necessarily contains $\bar{c}s$ quarks, but cannot be descibed by excited D_{sJ}^+ states due to its electric charge. The structure is dubbed the $X(2900)$ (with quark content $\bar{c}s\bar{d}u$) with a mass of $m(X_0(2900)) = 2866 \pm 0.007 \pm 0.002$ MeV and $m(X_1(2900)) = 2904 \pm 0.005 \pm 0.001$ MeV for the spin-0 and spin-1 state respectively [28]. This is the first observation of an open-charm exotic hadron.

3.4 Rare Decays

The area of rare decays has shown a number of intriguing surprises, commonly referred to as flavour-anomalies. Most attention is drawn to the $b \to s\mu^+\mu^-$ transition, which in the Standard Model can only occur at loop-level. On the one hand the angular distribution of the muons deviates from expectations, and on the other hand the absolute rate of decays with muons seems low, with respect to predictions.

This year LHCb reported an update of the angular distributions in $B^0 \to K^{*0}\mu^+\mu^-$ decays using 2015 and 2016 data. The data show a smaller deviation with respect to the Standard Model, but remarkably this shows a better agreement with the New Physics scenario where only the vector coupling C_9 is affected.

The models that aim to describe the flavour-anomalies include lepton-flavour-universality-violating (LFUV) mechanisms to distinguish between electrons and muons. This feature goes hand-in-hand with lepton-flavour-violation (LFV), which has been searched for in $B^+ \to K^+\mu^-\tau^+$ decays, which are forbidden in the Standard Model [29]. Interestingly, the missing information from the escaping neutrinos from the tau decay is compensated by using $B_{s2}^{*0} \to B^+K^-$ decays as the source of B^+ mesons. In addition upper limits have been set on the highly suppressed $B_s^0 \to e^+e^-$ and $B^0 \to e^+e^-$ decays [30].

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. Over the last six months the tracking system has progressed at a reduced pace, mostly due to the Covid-19 pandemic side effects. The VELO project has restarted module serial production and the construction of mechanical structures is complete. The UT project has also been impacted by the pandemic. The production of instrumented staves with detector modules has continued at a reduced pace. Four-chip hybrids have been produced in large quantities and batches of hybrid panels with bonded SALT chips have been sent to the module-production site. The SALT chips for the 8-chip hybrids have been produced, wafer-tested and diced. The 8-chip hybrid is currently being produced. The assembly work of the SciFi at CERN, in the surface building, has been severly slowed down during the last 6 months by covid-19 restrictions. However, construction of the first six C-frames (one half of the detector) is very advanced and the second half has been started. A more detailed summary of recent progress and plans for the next half year are 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 Microchannel Production

Each VELO Upgrade module has a backbone of a silicon plate within which tiny microchannels circulate evaporative CO_2 which directly cool the hybrid pixel tiles and power consuming electronics on the module. The production of the microchannel plates, which is achieved in industry, is complete, and the focus is now on the final assembly of the plates together with the CO_2 input/ouput manifold and supply pipes, a process which is achieved with fluxless soldering. The manifold and pipes, referred to as the "connector", are assembled partially in house (Oxford University). The challenge is the robustness of the welds and the quality of the connector surface, which must be perfectly planar to achieve uniform metallisation for soldering wettability without the presence of voids. A new quality control, inspection and grinding procedure has been introduced and 78 connectors are currently available assuring sufficient numbers for production. The soldering step involves a number of procedures, requiring specialist participation at each stage as well as access to dedicated labs, clean rooms and services at CERN. These steps are the connector polishing, the microchannel planarity inspection, the connector metalisation, the formic acid vacuum soldering step, and the X-ray inspection. A procedure has been put in place to assure regular availability of these personnel and services while respecting Covid working practices. This has meant developing new tooling and storage to be able to process multiple items in parallel to match the less frequent availability of slots in the chemical labs. Some of these procedures are illustrated in Figure 2. In addition, a packing and shipping procedure was developed to account for the fact that transport by hand is no longer practical. The production was resumed after lockdown, and several weeks were taken to implement the new procedures and produce the first microchannel. After this the production could speed up and currently 40 Grade A microchannels have been produced (of these nine were used to assemble modules before the investigation of glueing issues after September 2019). A new shipping box has been designed together with a shipping procedure with the use of shock logs; this was tested with multiple trips with dummy plates before shipping production microchannels, and no issues have arisen.

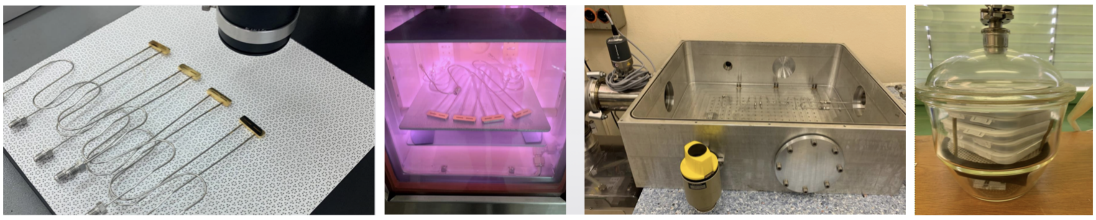

Figure 2: Some of the microchannel procedures developed to deal with Covid-19 working practice. From left to right: optical inspection of connectors, plasma cleaning of multiple connectors, new vacuum tank for storage of multiple connectors before metallisation, new vacuum storage of multiple solder foils.

4.1.2 Module Production

The module production was halted in September 2019 after it was found that in certain circumstances the glue joints may be thermally unreliable. After a long campaign the decision was taken to modify the gluing process, with the major change being the choice of a different catalyst (Stycast + 23 LV) and and improved procedure to mitigate any effect which can have an impact on the extremely thin glue joint, in particular the possible accumulation of humidity on the glue surface, which is counteracted with the use of a heating procedure before assembly. The module production was relaunched just before the pandemic shutdown of spring 2020. During the shutdown there was limited access to the laboratories and a reduced effective of personnel. The opportunity was taken to improve various procedures, including optimisation of the jigs, improvements to the inspection, wire bonding, and data base procedures, and the design of customised heat guns for the heat treatment. As soon as reopening allowed, tests were run at the two assembly sites followed by the relaunch of production. After completion of one module at each site, photographed in figure 3, a pause was taken in order to evaluate the performance and to validate all new procedures. At one assembly site (Manchester) the full set of tests was achieved on the post lockdown production module. A period of two weeks were spent on these tests in order to refine the procedures and prepare for production. The module met or exceeded all targets with respect to assembly, and is production quality with the exception of one faulty ASIC. Based on this, the assembly procedure at Manchester is considered to be fully commissioned and production is continuing. At Nikhef a problem occurred during recomissioning with contamination of the vacuum tank. For this reason, all assembly tests were performed on the module with the exception of the electrical tests in vacuum. The tests showed very good results, however out of precaution, the assembly will only proceed after the complete electrical tests and thermal cycling in the decontaminated vacuum tank. It is estimated that approximately half of the production will be complete by February 2021, and the remaining complement of modules by May 2021.

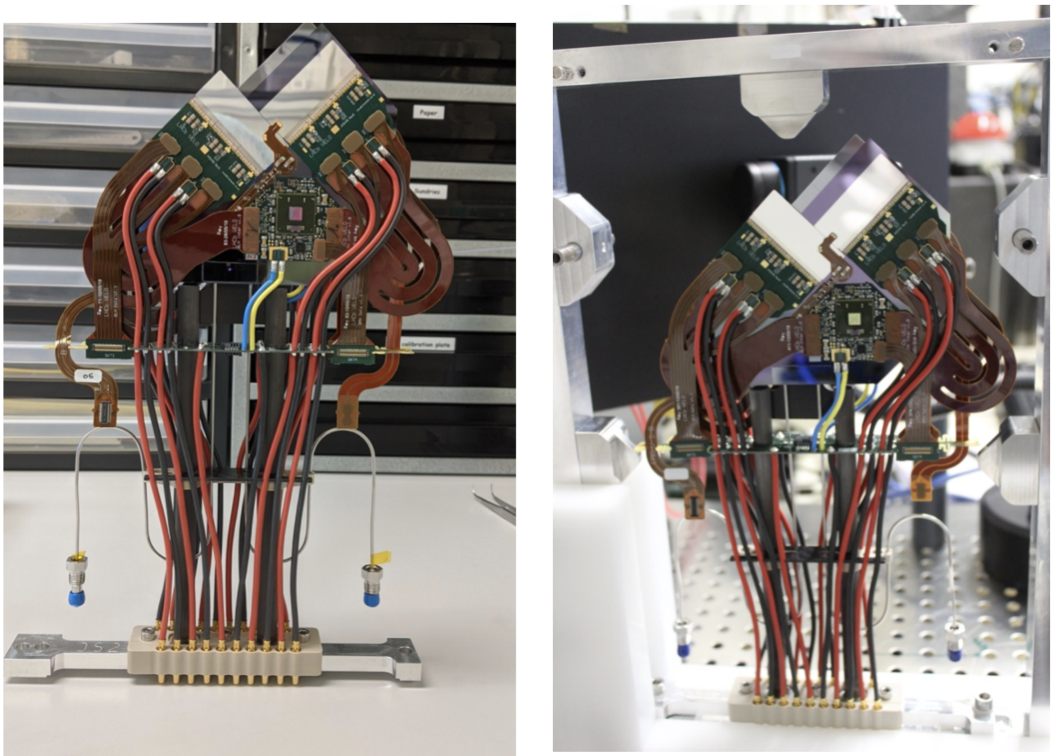

Figure 3: The first post lockdown modules to be produced: M82 (Manchester) on the left; M13 (Nikhef) on the right

4.1.3 Assembly

The mechanical assembly has been heavily impacted by the lockdown and the complete closure of the laboratory at Liverpool, followed by restrictive quarantine regulations which have brought travel to a standstill. The work of the decontamination of the LUCASZ plant, originally planned as part of the global decontamination of all the CO_2 cooling units at CERN and external institutes, has been transferred entirely to Liverpool personnel, requiring the construction of additional tooling and CO_2 traps. The pressure sensors were successfully shipped to CERN for decontamination and the rest of the unit was treated at Liverpool. Prior to the lockdown, all cooling runs were available apart from two faulty ones, and special covid compliant arrangements were made to have the new ones manufactured together with the cooling runs for the A side. The cooling runs of the C side of the VELO have now been completely installed, and the leak, flow and pumpdown tests have been successfully accomplished. The half, photographed in figure 4, has undergone a movement check to ensure that the cooling loops can absorb the VELO movement around the beams. The low voltage cable looms have been completed, and work is now proceeding on installing the wiring, in particular of the

PT100 measurement system of the cooling system followed by the insertion of the looms and feedthrough boards. A new schedule has been constructed, taking into account the long lockdown, the covid working conditions in the laboratory and the need to work in small bubbles. The main changes from before are that the services on the C side are now expected to be completed by the end of October 2020, and the module mounting of the C side will take place between November 2020 and May 2020. The A side will then follow.

Figure 4: VELO C side base and hood, fully installed with cooling runs and tertiary vacuum system

4.1.4 Electronics, Installation, Commissioning

The VELO Engineering Change Request has been fully approved and installation of all services in the cavern as well as the commissioning activities are on schedule. The major items to be installed in the base other than the modules are the data cables and vacuum feedthrough boards. These have been fully assembled, tested, and shipped to the assembly site. The remaining infrastructure is making good progress; the long cabling is underway and a solution has been found for the HV short cable assembly which originally relied on personnel travelling from the UK. The patch panels (a total of 14) for the low voltage cables have been fully assembled and installed in the cavern. The vacuum installation and pump replacements have been completed and the vacuum commissioning is underway. The most severe impact of the covid-19 travel restrictions concerns the preparation of the VELO temperature readout modules, for which the production has been frozen since March. The commissioning preparation is focused on the assembly of a complete block for the readout of one module, which will be shipped to the assembly site. This consists of a crate with the final low voltage system, an interlock board using a combination of items from the old VELO and the new readout boards, a high voltage system and a CO_2 interlock. In addition, safety tests are ongoing for the pressure sensors which will be used for the cooling. The complete system will be shipped to the assembly site by week 44 and is on schedule. After this the system will be upgraded to multi-module readout.

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 COVID19 pandemic. They include new protocols and restrictions to the number of people allowed to work in the construction laboratories involved in the project, new protocols to be followed to ensure safe practices in all the laboratories, and two significant delays associated with COVID19 impact on industrial partners that we will discuss below.

4.2.1 Instrumented staves

The instrumented stave components that are needed to construct the majority of the detector planes are in advanced production status, as shown in Fig. 5. The production and test of the hybrids hosting the SALT ASIC is 56% completed and is running smoothly in Milano, with weekly shipments to the module production site in Syracuse foreseen until production is completed.

The UT project has recently achieved a significant milestone: the first fully instrumented stave assembled with the fixtures designed for precise positioning of the modules on the staves and following the final construction protocol has been assembled and tested and it is ready to be shipped to CERN to be mounted on the UT frame. The completed stave on a construction bench in the assembly laboratory at Syracuse is shown in Fig. 6. The stave shipment to CERN is organized in five stave installments. The first one is anticipated for late October, contingent upon the readiness of the clean room assembly discussed below.

There is a last component that needs to be validated, namely the eight-chip hybrid. The first iteration did not meet the performance specifications, although there is strong evidence that the shortcomings are related to the implementation of the design with a sub-optimal stack-up, with rigid printed circuit board technology rather than the flex stack-up that optimizes the impedance properties of the power planes to achieve the best SALT performance. A design was available in late spring, but the finalization of the project with the chosen company was delayed by difficulties partially due to limited staffing due to COVID 19 restrictions. The

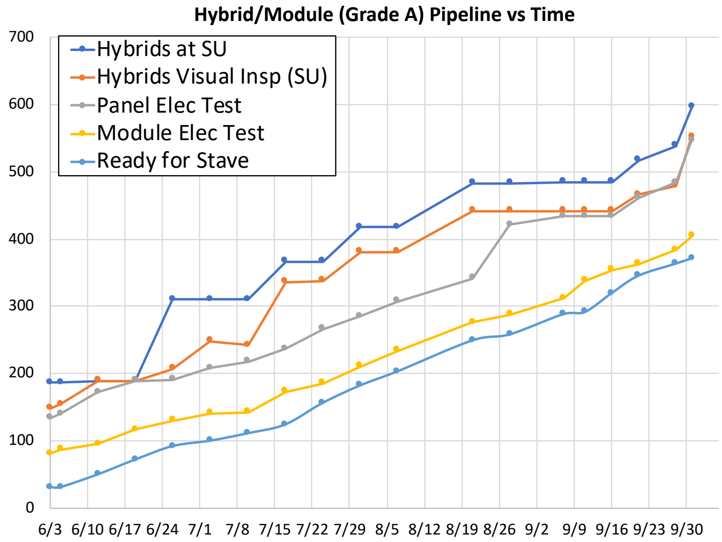

Figure 5: Trending plots of the number of hybrids and modules at different stage of readiness to be mounted in type-A instrumented staves. The finished modules are sufficient for 1/3 of the total number of instrumented staves, including spares.

production is currently under way and the first panels are expected in Milano in the second half of October. This is the first critical path item in the project: a successful outcome of the quality assurance of these devices is critical to the completion of the project in a timely schedule.

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 their burn-in prior to shipment to CERN from Maryland. A shipment this month is expected to include the components necessary to assemble and test the first detector half (C side).

4.2.3 Mechanical infrastructure and cooling

The UT detector will be assembled in a laboratory close to the experiment at P8 in two phases: the first one encompasses the construction of the so-called C-side, followed by the other detector half (A side). The detector box is comprised of two parts: the C-side box is shown in Fig. 7, Each half is mounted on a movable transport element (chariot) which will be used in the assembly clean-room and then transported in the experimental area, where the box with the assembled and tested detector will be slid in place.

Figure 6: First completed stave with final construction procedure.

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 be assembled in April. Due to COVID restrictions, the company responsible for this installment has not been able to complete this task. A tentative completion date of mid-November is now scheduled, and is on the critical path. In order to be able to test staves in the final infrastructure, the PEPI electronics needs to be assembled and tested in situ, and the team's goal is to assemble this infrastructure and validate the performance of the first few staves in 2020, which can be accomplished only if the clean room is available on the expected time scale.

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 will be 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 support bridge as well as the service infrastructure need to be adapted.

Figure 7: UT C-side assembled frame and box.

The CERN Covid-19 lock-down in the spring and the current travel restrictions in several European countries are impacting the progress of the SciFi project significantly.

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 have been 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 the course of 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 of 24 assemblies the remaining ROBs have been assembled by an industrial producer. The last batch of assembled ROBs arrived at CERN in week 10 of 2020. Figure 8 shows a finished ROB. Detailed tests of the assembled front-end electronics have been performed at CERN and have been interrupted by the CERN lock-down in March 2020. However, these tests were amongst the first activities which were relaunched after the reopening of CERN. The ROB tests have now 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 some 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 already been produced.

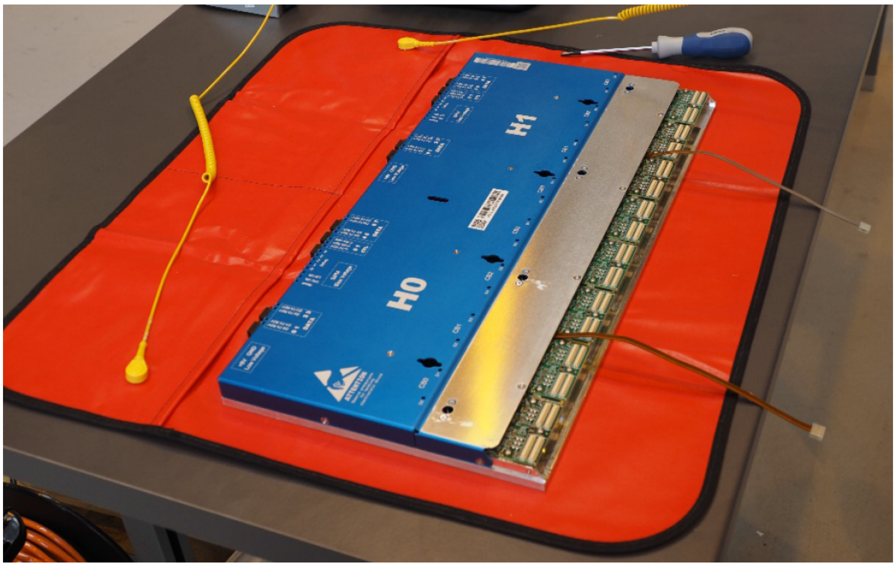

Figure 8: Photograph of a finished readout box (ROB) containing 8 PACIFC carrier boards, 8 cluster boards and 2 master boards

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 up is provided by the cold-box enclosure. The mass production of the cold-boxes at Nikhef has been completed during the Covid-19 lock-down.

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, is progressing well. More than 90% of the detector modules have already been equipped with cold-boxes and have been tested. The remaining ones were supposed to be finished by the end of October 2020. This date will change due to the current Covid-19 related travel restrictions in Europe, with consequences also for the repair of broken components which will not be possible after December 2020.

Workpackage	C1	C2	C3	C4	C5	C6	C7
Mechanics	ok	ok	ok	ok	ok	ok	ok
Services: Water Novec Dry-Gas	 ok ok ok	 ok ok ok	 ok ok ok	 ok ok ok	 ok		 ok
Modules	ok	ok	ok	ok			
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	i.p.	ok	ok			

Table 2: Status of the assembly and commissioning of the C-frames as of calender week 40. *ok* means concluded, *i.p.* means in progress.

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 are mounted on C-shaped support frames. Each C-frame carries 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 was concluded in early 2020 and all parts have been delivered to CERN. The assembly of the first C-frames was started in early 2019 and by February 2020 the mechanical structures of 7 C-frames (C1 to C7) were completed. The construction of the next two C-frames (C8 and C9) was foreseen for September 2020, however this has had to be postponed due to the Covid-19 related travel restrictions.

After the mechanical assembly of the C-frames, cables, services, modules and the readout boxes are 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 not restricted, excellent progress was made. Currently, the existing travel restrictions in several countries are causing significant delays in the C-frame assembly. Table 2 summarizes the status for the first seven C-frames (C1 to C7) at the end of September 2020.

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 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 which have been tested so far, the insulation 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 $-50°$ in the cold-boxes was reached. The cold-spots which have been observed when the first C-frame was cooled down to -40°C in summer 2019 and which led to water condensation have been understood. By stretching the inner part of the vacuum insulated Novec bellows the main cause is removed. Additionally, and as a precaution to guarantee a safe operation of the detector in the experimental cavern, heating wires have been installed on the outside of the cold-boxes and also around the Novec bellows. The new heating system has been extensively tested now for the first four C-frames. It has proven to efficiently avoid any condensation and cold spots when the Novec cooling was operated at -40 degrees 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, C3 and 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 first three C-frames (C1, C3, and C4) are ready for installation. The commissioning of C-frame C2 is well advanced. Figure 9 shows the finished C-frame C1 when being moved into the transport and storage cage.

The Covid-19 lockdown and travel restrictions have significantly delayed the completion of the first six C-frames, which was foreseen for summer 2020. As can been seen from Table 3 a number of different teams of trained technical personnel need to travel regularly to CERN to perform the different assembly steps. The recently imposed Covid-19 travel restrictions will lead to further delays, though we are working hard to mitigate them. It is therefore difficult to provide a completion date at this stage.

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 needs 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 well advanced.

The period of CERN lock-down in spring 2020 was used to progress on two critical components: Flexible cable chains which are compliant with the CERN safety regulations and which fulfil our tight space requirement have been purchased and are now available for installation; A producer for the vacuum insulated Novec transfer lines has been found and the lines have been produced and are now available for installation.

To test the installation procedure, two C-frames (C-frame C7 and the prototype frame) have already been transported to the cavern and have been successfully inserted onto the rails. As a next step they will be equipped with the flexible

Assembly step	Country	Travel/CERN	People
Module preparation	NL	travelling	2
C-frame mounting	D	travelling	3
Crane	CERN	CERN based	2
Water cooling	F	travelling	$2-3$
LV, HV cabling	D	travelling	2
Dry Gas	CERN	CERN based	1
Module instal.	NL	travelling	2
	D	travelling	1
Heating wires	D	CERN based	1
FE Box	F	travelling	$2-3$
Optical Fibres	D	travelling	2
	NL	travelling	1
FE interventions	CH	in region (VD)	1
Survey, photogram.	D	travelling	1
	CERN	CERN based	2
Prepare Installation	CH	in region (VD)	2
	CERN	CERN based	2

Table 3: Trained technical personnel (technicians/engineers, not physicists) required for the different assembly steps of each C-frame. Trips from the different home institutes to CERN are typically of one week duration per visit.

cable chains. In summary, the cavern preparation for the installation of the C-frames is well advanced.

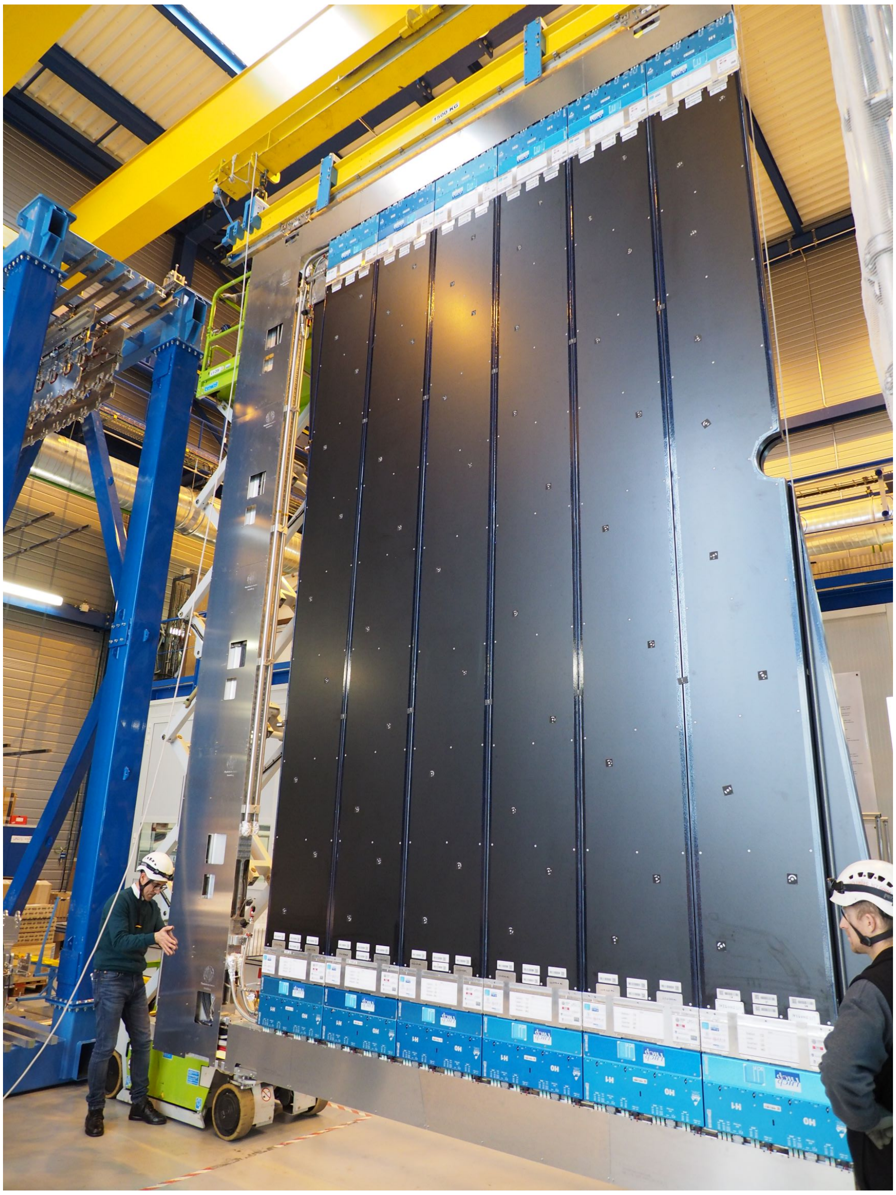

Figure 9: Photograph of the first finished C-frame C1 when being moved to the transport and storage cage.

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 design of the main components of the three sub-systems is complete. Mass production of the detector and front-end electronics components is mostly finished or approaching completion. The projects are focusing on assembling the detector modules and electronics boards, installing in the pit at LHC Point 8 and commissioning. 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 dismantling of the two RICH detectors took place at the beginning of 2019, according to schedule, the radiator gases (CF_4 and C_4F_10) were carefully recuperated, in order not to impact the environment and the preparations for the reception of the new optoelectronic chains, optics and mechanics readied.

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 be similar to that achieved with the existing detector in LHC Runs 1 and 2, albeit at a 10-fold high 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 are now going through 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. It is currently planned that the gas enclosure will be transported back to the pit on the 12^{th} of October to be installed in position together with the upper quartz window.

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 are satisfactory.

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 2 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 and readied to be installed at the pit (see Figure 10). All the mechanics is ready and at hand to be installed. This is currently foreseen to take place at the end of October 2020.

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 soon will be installed in the RICH1 Columns.

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 3.25 ns at present. This would improve PID performance and strongly decrease background.

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 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

Figure 10: Complete photodetector array ready to be installed in RICH2. The two RICHes features four arrays. Those for RICH2 are ready to be installed after having been assembled and commissioned at CERN. The use of both 1" and 2" MaPMTs in the RICH2 design is visible.

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 Boards 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 production of the FEBs should start soon. The green light has been given to the company after the reception and test of a pre-production batch. The production should follow in batches of 22, 32 and 80 boards. In order to cope with the delay accumulated in the fabrication, several batches have been sent to the company that fabricate our systems, to perform the ageing of large samples of boards in parallel. In the same spirit and to organize a faster installation of the boards at CERN, the shipping, installation and commissioning in the pit will start with the validation of the first sample received and will be performed in parallel with the delivery from the company. Finally in order to speed up this validation, two test benches have been mounted recently and will give twice the capacity to test the boards. The delivery of the last sample is planned for March 2021.

The Control Board production has started and should be finished soon. The systems will be ready for installation by the end of the year and will already benefit from the two test benches installed at Orsay for the validation of the FEBs. The installation will be done altogether with the installation of the FEBs, the boards sharing the same crates in the pit.

The high-voltage, calibration and monitoring systems are 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 (mezzanines and GBT fanouts) have been designed and fabricated. Most of those boards have been also validated in functional tests and their firmware is close to the final version. A total of a month of work is still needed and we hope to start the installation before the end of this year.

Figure 11: Test bench of the calorimeter equipped with pre-production FEBs.

5.2.2 Status of the systems in the cavern and latest tests performed

Before the installation of the hardware, which is produced in external institutes, the installation of the infrastructure already started at the LHCb cavern. More than 1000 optical fibres to control and acquire the data of the calorimeters have been pulled and connected to newly installed TELL40/SOL40 DAQ boards that are located on the surface of the site, next to the PC-farm. The other ends of the fibres are now connected to a new general patch-panel first and "local" patch-panels installed on the crates of the calorimeters. The existing crates have been fully adapted and the power supplies have been modified. Everything is now ready at CERN to receive our boards.

A test has been performed at CERN in July 2020. A calorimeter crate in the cavern has been used, filled with 16 pre-production boards and used to validate the system and the modifications.

The software for the control and acquisition of the calorimeter is in good shape. The additional time available due to the delay in the board production has been used to progress on this domain. Thus, it has already been possible to set up the validation, in the labs, of the FEBs and Control Boards with the final programs based on WINCC. Those programs are now running routinely on the Minidaqs that equip our test benches.

5.3 Muon system

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 have to be installed. Taking into acccount the spares, we will produce 190 nODE, 150 nSB and 14 nPDMs.

5.3.1 Status of the nSYNCs

The test and selection of all the needed nSYNCs (760) has been completed; 372 have already been installed on 93 nODEs and the full set is at the company ready to be installed on the remaining nODE boards. Furthermore, about 100 additional spare nSYNCs has been selected for future usage.

5.3.2 Status of the nODE boards

At present a total of 93 nODE boards (including pre-productions) have been produced and tested in LNF, of which 77 are working properly and 16 show some issues that are being investigated.
The boards have been installed in M4 and M5 stations, that are now fully equipped with the new electronics (see fig.12), and on M3 (29 out of 32 boards), for a total completion percentage of 52%. Due to the covid-19 outbreak, the company is experiencing some difficulties with components procurement and board assembly, which at present is causing a two months delay in the production. About 100 more boards have to be produced, and their best estimate to complete the production is the end of October, but the plan might be strongly influenced by how the covid situation will evolve.

5.3.3 Status of the nSB and nPDM boards

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

5.3.4 Commissioning

The commissioning phase will be split in two parts: in the first part we will check the connectivity between the chambers and the nODEs by pulsing the FEBs and reading back the signals on a PCIe40 readout board installed in a movable "commissioning rack" close to the detector. In the second part, once the online farm will be available, the signals will be readout from the data centre using the

Figure 12: The Muon commissioning rack (left) and the Q1M45 Muon rack (right), fully equipped with new readout and control electronics

standard readout chain.
The systematic connectivity test (from the commissioning rack) is starting on M45 side A, which is now fully equipped with new electronics, and will continue on M45 side C afterward. The plan, if the covid-19 situation permits, is to have the detector completely equipped with the new electronics, and have performed the connectivity test on stations M4 and M5, by the end of 2020.

5.3.5 Additional Shielding in front of M2

In parallel, activities related to the addition of material in front of M2 are progressing. This is foreseen to reduce by about a factor teo the low energy background rate in this region. This 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 has been successfully installed and aligned and we are now moving to the installation of the tungsten in the HCAL innermost cells, which will take about two months. The installation of the new M2 beam plugs will follow.

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) [31] 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.

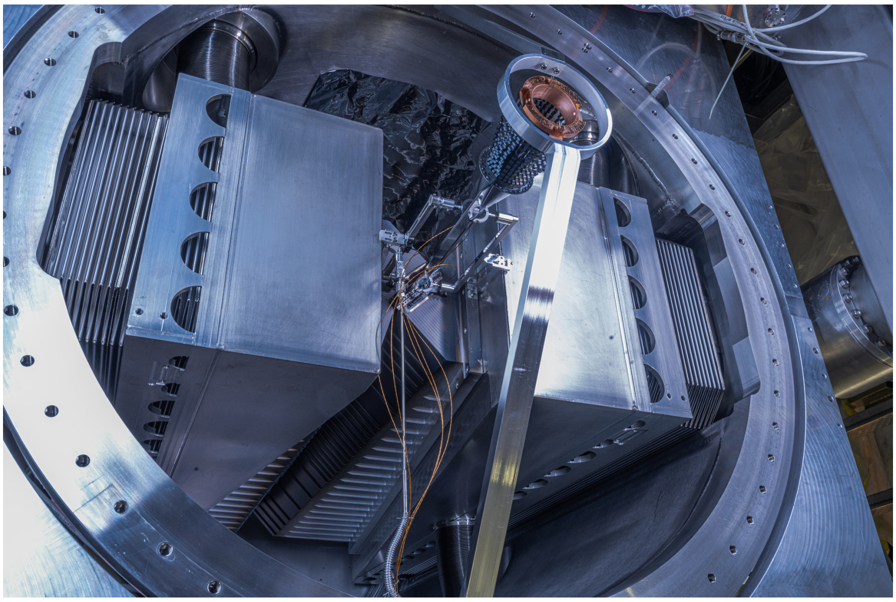

Figure 13: The installed SMOG2 storage cell with wake field suppressor, attached to the VELO RF box in the VELO vacuum vessel at IP8.

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. [32].

The TDR was approved by the LHCC [9] and all machine aspects have been discussed several times in LHC dedicated meetings, in particular within the vacuum group, at the LHC Tunnel Region Experiments Working Group (TREX), at the LHC Machine Protection Panel (MPP), and at the LHC Machine Committee (LMC) meetings.

In August 2020 the storage cell was successfully installed inside the VELO vacuum vessel, see Fig. 13. One of the most important steps to achieve was the alignment of the cell with the beam axis. The physical aperture of 5 mm gives about 2 mm margin to the minimum allowed aperture of the LHC. An overall misalignment ranging from 0.14 to 0.25 mm was reached, which is satisfactory.

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. Together with the input from five temperature probes, installed along the storage cell, this will give a precise measurement of the p-gas instantaneous luminosity. Software and trigger implementations are already well advanced. Preliminary studies show that it is possible to run simultaneously in pp and p-gas mode without losing reconstruction efficiency and without impeding the flow of data to storage.

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 production of 1263 PCIe40 modules is performed via a CERN contract for both LHCb and ALICE Collaborations. The production was launched at the end of January 2019. The last module was delivered in July 2020.

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 order of PC-servers was launched at the end of November 2019 and delivered in June 2020. Two racks were populated in order to validate the installation procedure and to start the commissioning of event-builder hardware and software. The installation of the remaining racks will start in October.

The surface and the underground areas are connected via a backbone of long distance optical cables. The installation of the 19008 long distance optical fibres ended in September 2019. Short distance optical cables interconnect long distance ones to PC-servers within the data centre. The short distance cabling is ready for VELO, RICH, CALO and MUON. It is on-going for SCIFI and UT. It will be finished by January 2021.

The commissioning with detectors will begin in November 2020 for MUON and RICH, starting with the ECS part and a low bandwidth data acquisition network.

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. They are fully operational since November 2019. Two containers are used by CERN-IT since mid 2019. A large part of the old LHCb farm, used during Run 2, migrated. The current power consumption is around 1 MW. Due to the covid-19 pandemic, the maintenance of the containers has been difficult and we hope for smoother operation in the future.

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 *Real Time Analysis* project reached the state where the fast reconstruction can process the full 30 MHz of collisions when running on a thousand reference servers equipped with x86 CPU. The fast reconstruction has also been ported to an heterogeneous architecture in which the CPU uses a GPU co-processor. This *Allen* project is described in the TDR document [10]. In May 2020, the collaboration chose the heterogeneous architecture for its potentially enhanced physics performance through relaxed reconstruction thresholds, for its cost and its attractiveness to developing the skills of younger researchers. In September 2020, the processing rate was increased by more than 60% allowing to populate each event-builder PC-server with only one GPU.

The full reconstruction is working in the new framework. In past months, many improvements were deployed on tracking and track fitting algorithms. The throughput reached 200 Hz per reference server allowing to process an HLT1 output rate of about 0.8 MHz. Additional gains are expected by rewriting the calorimeter reconstruction and by speeding up the track fit.

A first implementation of the HLT2 selections has been put in place during summer 2020. It processes about 100 selection lines from the different physics groups, allowing to benchmark the selection implementation and to test new idea to make it faster.

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.

7.3 Computing

Activities in the core software domain continued in the areas of conditions data and detector description, in order to make them compliant with thread safety and concurrency. Porting the description of detectors to DD4HEP is proceeding at a good pace for all sub-detectors, using tools that have been provided for the migration from the current framework and the validation. The handling of alignment and calibration in DD4HEP requires some software development that is underway. The design and implementation of thread-safe counters and histograms is progressing well in view of the integration of the Gaudi software framework in the online system. The choice of an heterogeneous architecture to run the first stage of the software trigger in Run3, mentioned above, implies some integration work in the core software infrastructure, e.g. in the nightly builds system, that is being organized. The LHCb software stack was recently ported to the ARM architecture. This enables the utilization of computing resources supporting this architecture and helps in limiting architecture-specific instruction sets in the code base. The software trigger applications were also benchmarked on ARM.

During this last period, the LHCb DIRAC team has deployed in production a major DIRAC release that enables an easier exploitation of non-standard Grid resources. The required features include full support for multi-processor jobs and resources, including support for intra-node partitioning. An improvement in the integration of computing resources exposing the SLURM batch system, which is the one typically adopted in HPC centres, is currently under way. The Marconi farm at the CINECA HPC center in Italy, consisting of Xeon-Phi processors, was exercised by producing Monte Carlo events with a multi-process version of the LHCb application Gauss, thus demonstrating the possibility to use this processor class.

The LHCb Collaboration Board approved in September the Data Processing and Analysis (DPA) project, whose goals are to design, implement and maintain the offline analysis infrastructure for Run 3 and beyond. This includes: (i) the selection framework to filter and slim events according to criteria that are analysis-specific, and to stream the output according to the various physics categories; (ii) the reorganization of analysis jobs in terms of centralized productions; (iii) the integration of external analysis packages; (iv) the exploitation of new analysis facilities, including e.g. heterogeneous resources; (v) the maintenance of legacy software and data samples.

8 Status of upgrade: infrastructure

8.1 Infrastructure

The installation of long distance cables finished in July 2020, and a very large fraction of the short distance cables are also already in place. All cables that are under the responsibility of the technical coordination, rather than the subdetectors, will be installed by the end of October 2020. These include 34 km of optical fibre cables and all copper cables with a total length of up to 35 km. The general electrical infrastructure is 90% ready, some minor modifications of electronics racks in the experimental area remain to be done.

All detector cooling plants and transfer lines (up to the near-detector manifolds) are installed. The commissioning of the cooling plants and the new shared primary chiller for VELO, UT and SciFi is in progress, and the cleaning of the CO_2 cooling systems from silicone oil contamination is advancing well. The near-detector cooling and dry gas pipework remain to be installed and will be completed in time for the detector installation.

The clean room that is urgently required for the UT assembly will be installed by a contractor based in the UK and has been considerably delayed due to the covid-19 travel restrictions. It is currently expected that the cleanroom will be in place by early November.

8.2 Installation

The huge shielding wall separating the detector area from the service area has been fully closed again, as the installation of all services that run through the wall is completed.

A major consolidation work is being performed on the LHCb dipole as two broken supporting clamps of the coil were discovered at the start of LS2. The first part of this work, shimming of all supports at the backside, has been completed in September 2020. Additional support structures up- and downstream of the magnet have been manufactured and their installation has started. The consolidation work of the magnet is expected to be completed by the end of October 2020, followed by a final ramp up of the current.

HCAL Beam plugs for the muon system were installed on both sides of the detector in May 2020. The tungsten section that will replace the innermost part of the HCAL will be installed before the end of this year. The SciFi C-frames of side C were planned to go down in the experimental cavern by the end of this year. With the current travel restrictions, due to the increasing covid-19 cases in all the collaborating SciFi countries, it will be very difficult to keep the present schedule. We are working in close collaboration with the SciFi project team in order to reduce any delay to a minimum.

The RICH 1 gas enclosure was sent for modification and mechanical reinforcement back to the UK and will return to CERN at the end of October. Before installing the gas enclosure, leak tests will be performed to verify that no damage occurred during its transport. In addition, the project is facing the same problems as in most other detector projects. The covid-19 related travel restrictions delay the installation, although we are working on solutions. The gas enclosure must be installed before the first beam pipe section is inserted.

A test installation of the RICH 2 mechanics was performed in August and the final installation is foreseen for October 2020.

The VELO RF boxes were installed in May with remote support by the experts at Nikhef. The SMOG II gas storage cell system has been successfully installed in the VELO vacuum in August.

8.3 Commissioning

The commissioning of the online system is currently the priority and it is underway. Online equipment is currently being installed in modules IT3 and IT4, with priority given to the global vertical slice test-stand, the MUON detector and the RICH2 detector. These detectors are expected to be the first to be commissioned with the central online equipment. In parallel, development on the central control system and tools is ongoing.

During the Covid-19 lockdown, the commissioning concentrated on central software aspects, with significant progress made in the monitoring, the firmware, the control and the software. The most recent firmware and software release addresses the current needs for commissioning, in particular including features of data injection, data format interfaces and central readout supervision. These central software aspects will be fundamental to speed up the commissioning once installation of the sub-detectors is concluded.

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 towards 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.

Since the last RRB report, a substantial delay has been accumulated, entirely due to the Covid-19 pandemic. However, the overall planning of the LHC and of the other LHC experiments has also been strongly impacted. Discussions at the highest management level have taken place to revise and adapt the overall LS2 schedule with a restart currently shifted to early 2022 as the baseline, with late 2021 remaining an option. With this new schedule the LHCb detector Upgrade is still on track for completion and installation in LS2. 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, with possible new planning adjustments, will take place regularly. The next discussion will take place at the end of October 2020.

Progress has continued, though with varying pace, in the different sub-projects. For the SciFi, RICH, and Muon projects, large fractions of the detectors have been assembled and are ready for installation, though quarantine and travel restrictions are causing difficulties for this phase. The Calo project encountered unexpected delays with production of the main FE electronics boards, but is still expecting to install in time. The VELO module and UT instrumented stave production have started in earnest and risks of delay are mostly associated with the pandemic restrictions (in particular, travel restrictions). The progress of production and assembly is being closely monitored. After installation of the subdetectors, a full detector commissioning will take place. Preparation for this phase is progressing well.

9.2 Funding

The status of the M&O Cat.A and B accounts is affected by the present COVID-19 dominated situation. 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 2019 M&O Cat.A budget followed well our forecasts. The 2019 year expenditure, the first LS2 activity year, is well balanced. This is thanks to the financial plan for the M&O Cat.A levels for the forthcoming LS2 and successive upgrade phase which we finalised, submitted and got approved by the Scrutiny Group and by the RRB in 2017 and 2018. This plan foresaw an increase in the budget for 2019 to 2.725 MCHF plus the use of 0.4 MCHF of pluriannual surplus. For 2020, the approved budget for M&O Cat.A is 2,930 kCHF.

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 as planned. 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 2020. 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.

10 Upgrade II

A future upgrade of the LHCb detector capable to integrate up to $300\,\mathrm{fb}^{-1}$ throughout the full HL-LHC phase has been proposed in [33], with details on the physics reach discussed in [34]. The project consists of a major change of the detector during LS4, in order to sustain an instantaneous luminosity up to 1.5×10^{-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 [35], 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 developing their baseline scenarios.

One of the key ingredients for success 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 example include developing state-of-the-art sensors and readout electronics with picosecond timing capability, and exploiting heterogeneity advances in CPU/GPU/co-processor technologies to boost the performances of the data acquisition system.

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.

11 Collaboration matters

The collaboration continues to grow, having 986 authors at the time of writing. Hunan University, China has joined as an associate member group. Laboratoire Leprince-Ringuet, France has joined as a full member group. Karlsruhe Institute of Technology, Germany has joined as a Technical Associate Group. Unfortunately our group in Constantine, Algeria has had to close due to difficult local circumstances, fortunately the active group members have been able to join other LHCb groups. The collaboration has also introduced additional rules and categories to extend the membership opportunities to those working on software and detector development.

References

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

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

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

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

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

[6] LHCb collaboration, *LHCb Trigger and Online Technical Design Report*, CERN-LHCC-2014-016, 2014.

[7] LHCb collaboration, *LHCb Upgrade Software and Computing*, CERN-LHCC-2018-007, 2018.

[8] LHCb collaboration, *Computing Model of the Upgrade LHCb experiment*, CERN-LHCC-2018-014, 2018.

[9] LHCb collaboration, *LHCb SMOG Upgrade*, CERN-LHCC-2019-005, 2019.

[10] L. Collaboration, *LHCb Upgrade GPU High Level Trigger Technical Design Report*, CERN-LHCC-2020-006. LHCB-TDR-021, 2020.

[11] 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-2012-119A, revised April 2014, 2012.

[12] LHCb collaboration, *Addendum No. 2 to the Memorandum of Understanding for Collaboration in the Construction of the LHCb Detector Upgrade of the LHCb detector Sub-Detector Systems*, CERN-RRB-2014-105, 2014.

[13] D. Müller, M. Clemencic, G. Corti, and M. Gersabeck, *ReDecay: A novel approach to speed up the simulation at LHCb*, Eur. Phys. J. **C78** (2018) 1009, arXiv:1810.10362.

[14] C. Bozzi, *LHCb Computing Resource usage in 2019*, Tech. Rep. LHCb-PUB-2020-002. CERN-LHCb-PUB-2020-002, CERN, Geneva, 2020.

[15] C. Bozzi, *LHCb Computing Resources: preliminary 2022 requests*, Tech. Rep. LHCb-PUB-2020-005. CERN-LHCb-PUB-2020-005, CERN, Geneva, 2020.

[16] C. M. LHCb Collaboration, *Computing Model of the Upgrade LHCb experiment*, Tech. Rep. CERN-LHCC-2018-014. LHCB-TDR-018, CERN, Geneva, 2018.

[17] LHCb, R. Aaij *et al.*, *Measurement of CP observables in $B^{\pm} \to DK^{\pm}$ and $B^{\pm}$ rightarrow $D\pi^{\pm}$ with D rightarrow $K^0_S K^{\pm}\pi^{\mp}$ decays*, JHEP **06** (2020) 058, arXiv:2002.08858.

[18] LHCb, R. Aaij *et al.*, *First observation of excited Ω_b^- states*, Phys. Rev. Lett. **124** (2020) 082002, arXiv:2001.00851.

[19] LHCb, R. Aaij *et al.*, *Observation of a new baryon state in the $\Lambda^0_b\pi^+\pi^-$ mass spectrum*, JHEP **06** (2020) 136, arXiv:2002.05112.

[20] LHCb, R. Aaij *et al.*, *Observation of New Ξ^0_c Baryons Decaying to $\Lambda^+_c K^-$*, Phys. Rev. Lett. **124** (2020) 222001, arXiv:2003.13649.

[21] LHCb, R. Aaij *et al.*, *Search for the doubly heavy Ξ^0_{bc} baryon via decays to D^0pK^-*, arXiv:2009.02481.

[22] LHCb, R. Aaij *et al.*, *Precision measurement of the B^+_c meson mass*, JHEP **07** (2020) 123, arXiv:2004.08163.

[23] LHCb, R. Aaij *et al.*, *Study of the lineshape of the $\chi_{c1}(3872)$ state*, arXiv:2005.13419.

[24] LHCb, R. Aaij *et al.*, *Study of the $\psi_2(3823)$ and $\chi_{c1}(3872)$ states in $B^+ \to (J\psi\pi^+\pi^-) K^+$ decays*, JHEP **08** (2020) 123, arXiv:2005.13422.

[25] LHCb, R. Aaij *et al.*, *Observation of multiplicity-dependent prompt $\chi_{c1}(3872)$ and $\psi(2S)$ production in pp collisions*, arXiv:2009.06619.

[26] LHCb, R. Aaij *et al.*, *Observation of structure in the J/ψ-pair mass spectrum*, arXiv:2006.16957.

[27] LHCb, R. Aaij *et al.*, *A model-independent study of resonant structure in $B^+ \to D^+D^-K^+$ decays*, arXiv:2009.00025.

[28] LHCb, R. Aaij *et al.*, *Amplitude analysis of the $B^+ \to D^+D^-K^+$ decay*, arXiv:2009.00026.

[29] LHCb, R. Aaij *et al.*, *Search for the lepton flavour violating decay $B^+ \to K^+\mu^-\tau^+$ using B^{*0}_{s2} decays*, JHEP **06** (2020) 129, arXiv:2003.04352.

[30] LHCb, R. Aaij *et al.*, *Search for the Rare Decays $B^0_s \to e^+e^-$ and $B^0 \to e^+e^-$*, Phys. Rev. Lett. **124** (2020) 211802, arXiv:2003.03999.

[31] M. Ferro-Luzzi, *Proposal for an absolute luminosity determination in colliding beam experiments using vertex detection of beam-gas interactions*, Nucl. Instrum. Meth. **A553** (2005) 388.

[32] A. Bursche *et al.*, *Physics opportunities with the fixed-target program of the LHCb experiment using an unpolarized gas target*, Tech. Rep. LHCb-PUB-2018-015. CERN-LHCb-PUB-2018-015, CERN, Geneva, 2018.

[33] *Expression of Interest for the LHCb Upgrade II*, CERN-LHCC-2017-003, 2017.

[34] LHCb collaboration, *Physics case for an LHCb Upgrade II — Opportunities in flavour physics, and beyond, in the HL-LHC era*, arXiv:1808.08865.

[35] European Strategy Group, *Deliberation Document on the 2020 update of the European Strategy for Particle Physics*, CERN-ESU-014.