Status of LHCb Upgrade I

CERN-RRB-2021-094

LHCb collaboration

27$^{\text{th}}$ October 2021

Contents

1 Introduction

The LHCb experiment completed its data taking at the end of 2018 and the installation phase of the Upgrade is highly advanced. 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 [3–11] and approved by the Research Board.

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 [12] and sub-system items [13], 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 are organised in a Data Processing and Analysis Project. Recently a simulation Project has been formed, replacing a previous working group, recognising the growing importance of this area and providing a more formal structure for institute participation.

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 592 papers published or submitted, of which 37 have already been submitted in 2021. Computing operations have proceeded well, with a restripping being performed of Run2 data to add additional physics channels of interest.

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 observation was made of the mass difference which controls the oscillations between the neutral particle and anti-particle containing the charm quark, a major milestone in the field. Following from our measurement of R_K that we discussed at the last meeting we released further results that strengthen the intriguing hints of flavour anomalies. These results analysed the branching fraction and angular distributions of another related rare decay process. A new tetraquark containing two charm quarks (not a charm and anti-charm quark) was discovered, the first of its type.

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. Several subdetector systems are already commissioning, others are highly advanced and expect to move into commissioning in the next months. Two systems (VELO, UT) remain on the critical path for completion by the cavern closure for Run 3 in February 2022.

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 Upgrade-II Framework TDR is now under review by the LHCC.

2 Operations

2.1 Data processing and computing

A campaign for the partial re-processing of the Run 2 proton collision data was started in summer 2021, profiting from available computing resources. The goal of this campaign is to add selection lines to further extend the LHCb physics programme. The processing of 2017 data was finished in August, that of 2018 data is currently ongoing. The processing of 2016 data will follow, the plan being to complete this activity by the end of 2021.

The usage of computing resources (see Fig. 1) is dominated as usual by the production of simulated data samples, needed to fully exploit the full Run-1 and 2 datasets for LHCb physics analyses. Fast simulation techniques account for two thirds of the total number of simulated events, thus mitigating the required compute work. They are based on two approaches: simulating 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 [14]). Efforts are ongoing in developing further fast simulation methods, based on *e.g.* the parameterisation of calorimeter showers and the usage of machine learning algorithms, which will allow to greatly reduce the CPU usage while still generating large samples.

The collaborations work on simulation has been reorganised into a simulation project, comprised of a number of work-packages. This formalisation of the activities has allowed to attract additional institute contributions to this area.

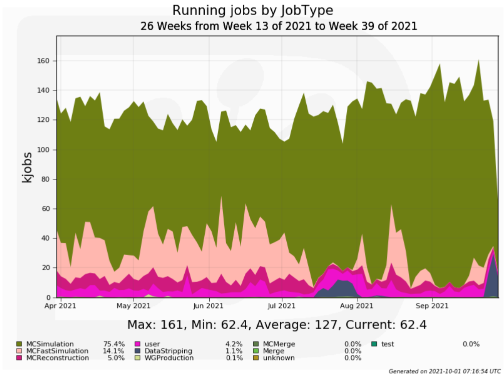

Figure 1: The number of cores used in the computing resources made available to LHCb: the light-pink area indicates Monte Carlo jobs using a fast simulation technique, the green area Monte Carlo jobs using the full event simulation. The blue area corresponds to the re-processing of Run 2 data.

3 Physics

In 2021, the LHCb collaboration has so far submitted 37 new publications, giving a total of 592 papers at the time of writing, of which 566 have been published. All recently submitted papers are listed in table 1. A further 11 publications are being processed by the LHCb Editorial Board and are close to submission. In the following sections some selected results from recent publications are highlighted.

Table 1: Full list of LHCb publications submitted for journal publication since April 2021.

Title	arXiv
Precise determination of the B_s^0-$\overline{B}_s^0$ oscillation frequency	2104.04421
Search for the doubly heavy baryons Ω_{bc}^0 and Ξ_{bc}^0 decaying to $\Lambda_c^+\pi^-$ and $\Xi_c^+\pi^-$	2104.04759
Search for CP violation in $\Xi_b^- \to pK^-K^-$decays	2104.15074
Measurement of CP asymmetry in $D^0 \to K_S^0 K_S^0$ decays	2105.01565
Angular analysis of $B^0 \to D^{*-}D_s^{*+}$ with $D_s^{*+} \to D_s^+\gamma$ decays	2105.02596
Search for time-dependent CP violation in $D^0 \to K^+K^-$ and $D^0 \to \pi^+\pi^-$ decays	2105.09889
Branching fraction measurements of the rare $B_s^0 \to \phi\mu^+\mu^-$ and $B_s^0 \to f_2'(1525)\mu^+\mu^-$ decays	2105.14007
First measurement of the CP-violating phase in $B_s^0 \to J/\psi(\to e^+e^-)\phi$ decays	2105.14738
Observation of the Mass Difference Between Neutral Charm-Meson Eigenstates	2106.03744
Observation of excited Ω_c^0 baryons in $\Omega_b^- \to \Xi_c^+K^-\pi^-$ decays	2107.03419
Observation of a $\Lambda_b^0 - \overline{\Lambda}_b^0$ production asymmetry in proton-proton collisions at $\sqrt{s} = 7$ and $8\,\text{TeV}$	2107.09593
Angular analysis of the rare decay $B_s^0 \to \phi\mu^+\mu^-$	2107.13428
Measurement of prompt charged-particle production in proton-proton collisions at a centre-of-mass energy of 13 TeV	2107.10090
Study of J/ψ photo-production in lead-lead peripheral collisions at $\sqrt{s_{\text{NN}}} = 5$ TeV	2108.02681
Evidence for a new structure in the $J/\psi p$ and $J/\psi\bar{p}$ systems in $B_s^0 \to J/\psi p\bar{p}$ decays	2108.04720
Search for the radiative $\Xi_b^- \to \Xi^-\gamma$ decay	2108.07678
Measurement of the $B_s^0 \to \mu^+\mu^-$ decay properties and search for the $B^0 \to \mu^+\mu^-$ and $B_s^0 \to \mu^+\mu^-\gamma$ decays	2108.09283
Measurement of the nuclear modification factor and prompt charged part. prod. in pPb and pp coll. at $\sqrt{s_{\text{NN}}} = 5\,\text{TeV}$	2108.13115
Updated search for B_c^+ decays to two charm mesons	2109.00488
Study of the doubly charmed tetraquark T_{cc}^+	2109.01056
Measurement of the W boson mass	2109.01113
Observation of an exotic narrow doubly charmed tetraquark	2109.01038
Measurement of the lifetimes of promptly produced Ω_c^0 and Ξ_c^0 baryons	2109.01334
Observation of the suppressed $\Lambda_b^0 \to DpK^-$ decay with $D \to K^+\pi^-$ and measurement of its CP asymmetry	2109.02621
Search for the doubly charmed baryon Ξ_{cc}^+ in the $\Xi_c^+\pi^-\pi^+$ final state	2109.07292
Measurement of $\chi_{c1}(3872)$ production in proton-proton collisions at $\sqrt{s} = 8$ and 13 TeV	2109.07360
Study of Z bosons produced in association with charm in the forward region	2109.08084

3.1 CP violation and constraining the CKM triangle

We have reached an historic milestone with the first observation of a non-zero mass difference between the two mass eigenstates in the neutral D meson system [15]. This mass difference,

$$x_{CP} = (3.97 \pm 0.46(stat) \pm 0.29(syst)) \times 10^{-3} \tag{1}$$

corresponding to about 6μeV is responsible for short-range interactions in $D^0 - \bar{D}^0$ oscillations. In addition, LHCb published the legacy measurement of the mass difference Δm_s in the B_s^0 system [16],

$$\Delta m_s = 17.7656 \pm 0.0057 \mathrm{ps}^{-1}. \tag{2}$$

Together with a new combination of the analyses sensitive to the CKM angle γ, enormous progress is made on the knowledge of charm mixing and CKM unitarity observables.

The analysis of the B_s^0 mixing phase ϕ_s has been performed for the first time with $B_s^0 \to J/\psi(\to e^+e^-)\phi$ decays [17], yielding consistent results with previous measurements, and confirming the understanding of electron reconstruction in LHCb.

3.2 Exotic Hadrons and 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 different mass values of observed resonances. For example, LHCb has confirmed five excited Ω_c^0 baryons, with a study of their quantum numbers [18].

The study of heavy baryons was particularly fruitful in 2021, with studies on doubly charmed $\varXi_{cc}^+$ [19], the Ω_{cc}^+ [20] and Ω_{bc}^0 baryons [21], and the confirmation of the large Ω_c^0 lifetime [22],

$$\tau_{\Omega_c^0} = 276.5 \pm 13.4 \pm 4.4 \pm 0.7 \mathrm{fs}. \tag{3}$$

The highlight in spectroscopy this summer was the discovery of the T_{cc}^+ tetraquark [22,23]. This has the quark content $(cc\bar{u}\bar{d})$, only the third case of a tetraquark content that uniquely identifies the state as manifestly exotic. This new state implies the discovery of a new class of hadrons, the doubly-heavy tetraquarks. The mass of the new T_{cc}^+ state is remarkably close to the D^0D^{*+} threshold, and determined with remarkable accuracy,

$$m_{Tcc} - m_{D^0} - m_{D^{*+}} = -0.273 \pm 0.061(stat) \pm 0.005(syst)^{+0.011}_{-0.014}(J^P)\mathrm{MeV} \tag{4}$$

if determined using a Breit-Wigner lineshape.

3.3 Rare Decays

The area of rare decays has shown a number of intriguing results, commonly referred to as the flavour-anomalies. In the last few months further significant progress has been made. The legacy analysis of $B_s^0 \to \mu^+\mu^-$ has been published this year [24,25]. New results have been shown on the decay rate and angular asymmetries of $B_s^0 \to \phi\mu^+\mu^-$ decays [26,27]. Excitingly the decay rate is $1.8(3.6)\sigma$ below the Standard Model prediction using Light-Cone-Sum-Rules (with lattice QCD), and a Wilson-Coefficient fit to the angular asymmetries shows a best fit value for C_9^{NP} of $-1.3^{+0.7}_{-0.6}$, compatible with that seen in our other recent measurements on related decays.

3.4 Electroweak Physics

LHCb is an important contributor to our knowledge in the electroweak sector. With only the 2016 data, LHCb has measured the W-mass [28] with a precision better than was obtained at LEP,

$$m_W = 80354 \pm 23(stat) \pm 10(exp) \pm 17(theory) \pm 9(PDF)MeV. \tag{5}$$

The statistical uncertainty is comparable to the theoretical uncertainty from the knowledge of the p_T distribution of W production (from angular coefficients and from the parton density functions). When theoretical progress will be made and with the analysis of the full LHCb data set, a further large improvement is foreseen.

A second landmark result this summer was the analysis of Z-bosons, in association with charm [29], where a D meson is identified in the associated jet. This analysis is directly sensitive to the presence of valence-like $< c\bar{c} >$ component in the proton wave-function, consistent with a charm contribution of about 1% to the proton, which was also favoured by low-Q data.

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 VELO group has completed manufacture and testing of 44 of the required 52 modules. An issue was discovered with some vacuum feedthrough boards potted into flanges, and a repair is being made. The mounting of modules onto the first half of the detector system is now underway. The schedule for completion of the second half before cavern closure in February has limited contingency but appears realistic. Mechanical systems and electrical infrastructure are highly advanced.

The UT completed production of all types of hybrids and the module production is highly advanced. The staves, containing the modules, are being assembled with the most complex very inner ones currently under assembly. The mechanical box is assembled. The mounting and test of the first stave in the box is a critical milestone, which will provide a key test of the system readiness. Work on the detector cabling and services is advancing significantly. The system is on the critical path and its progress is followed closely.

The SciFi reached a major milestone with the installation of the first half of the detector in July 2021. The completion of the connections of this half of the detector is underway, with in-situ commissioning starting. The assembly of the second-half is proceeding well, and the final installation is expected in January 2022. This leaves limited time though for the connection and commissioning before the LHC cavern closure.

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 and additional components were ordered. Each of the 52 VELO Upgrade modules 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 microchannel project has proceeded to qualify and solder the processing run with imperfect dicing, for a final total of 78 A grade fully qualified microchannel plates. This completes the soldering activity, however there are an additional 9 plates which were put aside due to various issues during reconstruction which are currently beeing evaluated and safety checked as potential spares. A fresh sensor run was launched in 2020 in order to cover the additional need for tiles, and the corresponding ASIC wafers have been thinned. The freshly produced tiles are of good quality, however a problem occured at the bump bonding stage where an unexpected bow of the diced ASICs was discovered due to a change of procedure at the wafer thinning company. This was swiftly addressed and a new bump bonding procedure with a support wafer is now being used in order to ensure full bump bonding efficiency. The additional 50 pieces, together with an additional run which was launched for the front end hybrids, ensures that the component production is adequate for the module production needs.

4.1.2 Module Production

The module production has proceeded smoothly. At the University of Manchester assembly site a total of 38 installation quality modules have been produced with a further 5 of lower grade and 2 modules currently in process. Three modules exhibited problems with a readout of a VeloPix internal voltage, which was traced to a common failure and two of these modules could be recovered. Using the accumulated performance parameters a robust automatic grading procedure has been implemented based on 7 assembly processes, 9 metrology steps and 7 electrical tests, with each module assigned a quality number in addition to the grading, to allow a fine distinction and to plan the installation pattern. At the Nikhef assembly site the the team was partially changed at the start of 2021 due to planned departures. The assembly procedures were requalified, in particular to address issues on the fragile signal chain infrastructure and feedthroughs which had led to glitches in the electrical testing. The site is now fully qualified for series production and so far 6 installation modules have been produced, including modules which have been recovered by the regluing of the GBTx hybrids and electrical debugging. One module was exchanged between production sites, verifying in detail the equivalence of the QA procedures. The assembly sites are on track to complete the module production by the end of October. Batches of four modules are being regularly transported to the University of Liverpool in transport frames from the University of Manchester (see Figure 2, while from Nikhef there will be bulk transport in a specially constructed crate, which has already been successfully used for a test transport of two pre-production modules.

4.1.3 Assembly

The mechanical assembly of the modules onto the VELO halves was 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 brought travel to a standstill. The installation team has successfully addressed many issues, in particular problems with the delivered cooling system which required a specialised cleaning procedure to recover from silicon oil contamination, replacement of failing relief valves, and recovery from the breakdown of an internal chiller fan, which required a major intervention on the system to gain access for replacement. Following from this the focus moved to the equipping of the first half, the C side, with all the necessary services, most importantly the cooling circuits, the feedthrough flanges fully assembled with data, temperature, HV and LV cables, and the tertiary vacuum and safety system. This was followed by the installation of four pilot pre-production modules. The installation and deinstallation procedures were rehearsed and the coolant flow was tested in the most

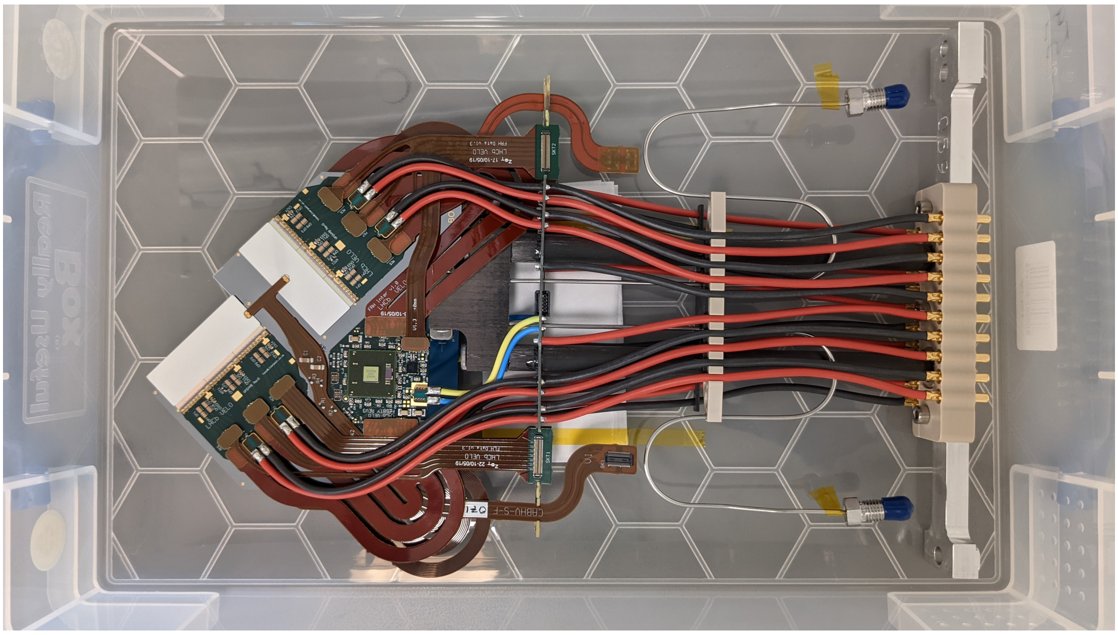

Figure 2: Final photo inspection of finished module before transport to assembly site

extreme powering and module failure scenarios. The feedthrough flange assembly is a complex process which includes the TDR testing of all signal paths, and on the sixth and final flange to be tested a production issue was tracked down which caused the failure of two signal lines. This was traced to a production issue which also affected two flanges on the A side. The faulty flange was swapped with a good flange from the A side, and returned to CERN for repair. This procedure will be followed with the remaining flanges once the repair procedure has been verified.

Following this preparation a module mounting review took place on 28th September. The main purpose of the review was to establish that the infrastructure is in place for safe module mounting on qualified mechanics. The qualification and vacuum tests on the C half were scrutinised, as well as the cooling and electrical performance of the first two modules to be mounted on the base. The assembly sequence, which centres around the batch mounting and testing of four modules at a time, was checked, and the database infrastructure was put in place. Following these preparations the referees approved the launch of production speed module mounting (see Figure 3), following the final approval of the full electrical results of the first two modules. This is a significant milestone for the VELO and marks the start of a well debugged final assembly procedure. During the assembly of the C side a multi module test will be carried out to check for joint electrical operation, and there will be a final metrology step before transport to CERN.

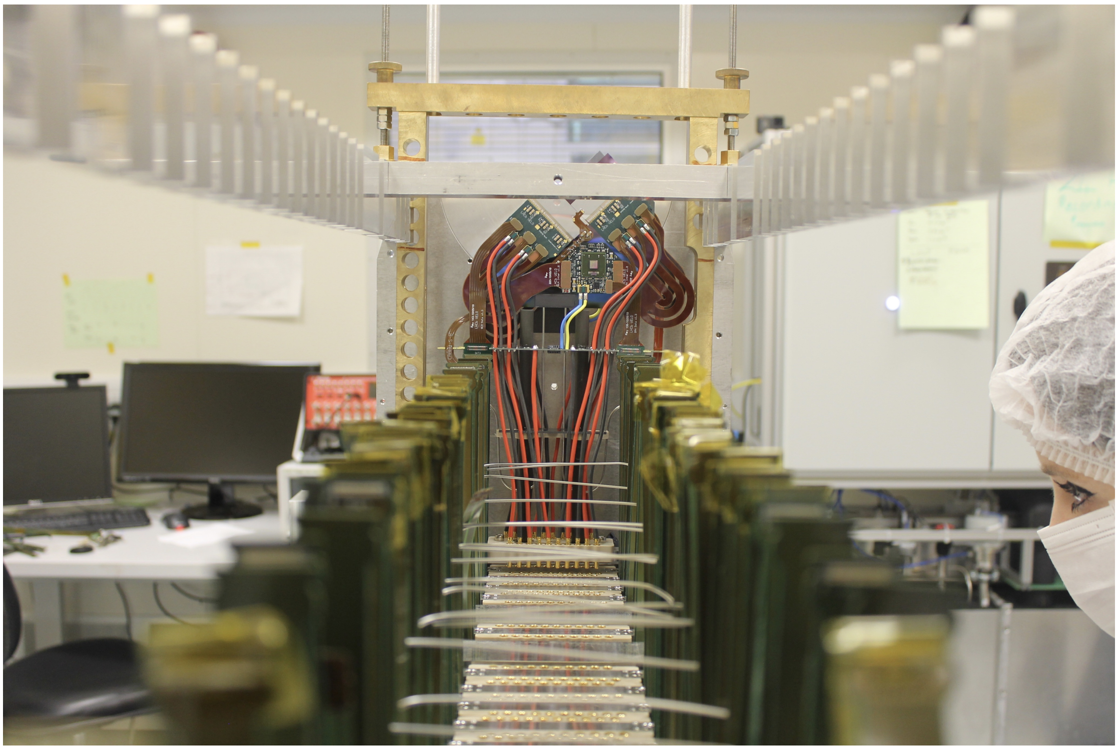

Figure 3: Photograph from the VELO assembly site at the University of Liverpool, showing the first production module to be mounted on the C side

4.1.4 Electronics, Installation, Commissioning

Following the installation of the VELO foils and downstream wakefield suppressors the VELO system was for the first time fully evacuated and the system underwent bake out, to a maximum temperature of 150°C. The evacuation and venting procedures functioned smoothly, with the correct control of the primary and secondary pressures and a maximum stress of 10 mbar on the foils. After the wakefield suppressor installation, inspections and movement tests were carried out, and it was seen that due to a small deformation in the shape as installed, the two halves lightly touch on one finger when the VELO is fully closed. In order to ensure that the surface quality of the wakefield suppressors would not be impacted, as well as to check that the gold plated fingers could not become entangled or form a cold weld in vacuum, a dedicated test stand was constructed. This consisted of foil mockups and a spare wakefield suppressor, mounted exactly as in the final experiment, able to open and close more than a thousand times via an air piston (see Figure 4). In addition it was possible to close the VELO in vacuum for five days, which greatly exceeds the expected fill time duration, in order to check that no macroscopic cold weld could form. Following these tests it is considered safe to leave the wakefield suppressors in place, and to continue to inspect the system during access periods.

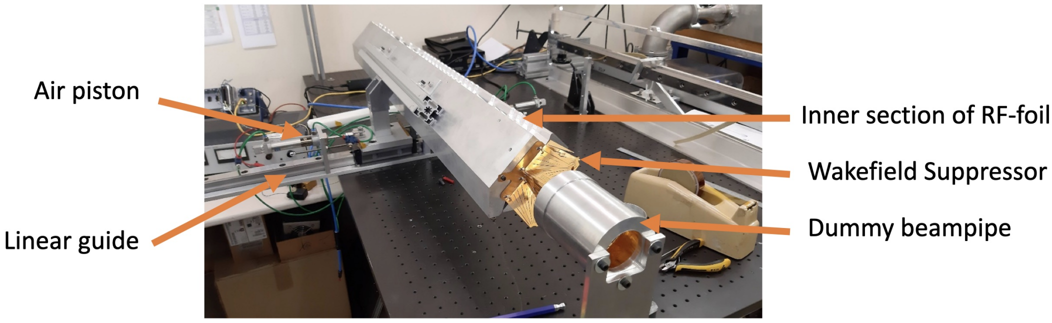

Figure 4: Wakefield Suppressor movement test stand

The remaining mechanical preparations at Point 8 are proceeding smoothly. All supporting Bosch profiles have been built and installed, creating the VELO frame to support the cables and services. A suitable fan system has been selected and installed for the OPB system and the CO_2 switch system, safety panel and local box have been installed and cabled.

The electronics 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. The OPBs have been fully tested and partially shipped to Liverpool where each readout board will be matched with a module during the assembly process. The VSS rack is in the final stage of development and installation to provide the full temperature readout and interlock to the power supplies. All elements are currently on schedule for installation.

4.2 Upstream Tracker (UT)

The UT project has now successfully transitioned from the assembly of individual components to the integration and commissioning stage.

4.2.1 Instrumented staves and near detector electronics

All the flavours of hybrids needed to construct the modules to be mounted on the instrumented staves have been fabricated, including the components needed for the spare staves. Moreover we are currently assembling the so-called “type-C” staves, needed for the innermost portion of the detector planes. Fig. 5 shows the first of such detector elements, which has already undergone electrical tests. Currently 1 type B and 24 type A staves are stored in the assembly area. A shipment containing 2 type C staves and 3 type D staves is imminent.

All the readout and power boards to be installed in the near detector region are currently at CERN, undergoing the quality assurance tests to validate the performance prior to installation in the experiment.

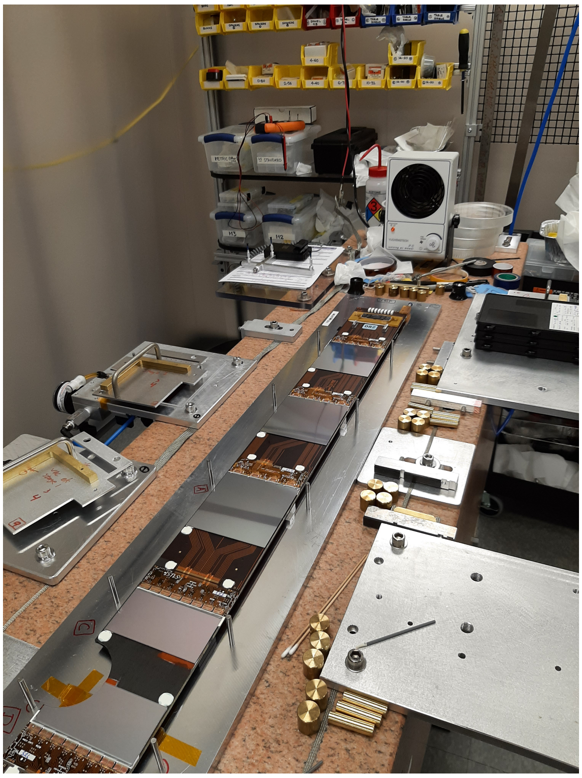

Figure 5: First inner ("type-C") stave of the UT in production.

4.2.2 Mechanical infrastructure and cooling

The UT boxes have been assembled and the C-side box is currently in the UT assembly laboratory, after having been tested with dummy loads and surveyed to assess whether the top and bottom plates met the required tolerances. Fig. 6 shows the C-side half-box in the clean room. Note the associated CO_2 cooling local distribution box assembled on the side. In the back, one can see the manifold that will be mounted inside the box, with the capillary tubes that will be connected to individual staves. These manifolds have been already over-pressurized and tested for leaks.

Currently, the infrastructure needed on the bottom and top near detector region is being assembled.

4.2.3 Integration in the experiment

The UT team is currently working on the assembly and commissioning phase. A team of fourteen scientists, working with the support of a CERN technical team, is attending to the many delicate tasks needed to get the detector ready for installation and commissioning in the experiment.

Currently the assembly and test of the detector at the surface is structured in three phases: mounting and test of the first stave, completion of C-side 1/2 box, and completion of A-side 1/2 box. The first milestone, of the first mounted stave test, will be a critical validation of the project.

In parallel, the complex cabling and services infrastructure is being prepared and commissioned so that the installation of the detector in the experimental area will be completed in a timely manner when the detector is deployed in the experiment.

Overall, significant progress has been made but the project is on the critical-path for completion by the LHC cavern closure. A significantly strengthened team is now working on the assembly and services preparation. The assembly and commissioning strategy of having two different teams devoted to stave installation in the surface and commissioning of services in the experiment facilitates the efficient implementation of these plans. Contingency plans are also developed for if it is not possible to install both sides prior to cavern closure in February 2022.

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 consists 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 are 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 arranged in 12 stereo layers. The detector layers are 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 impacted the progress of the SciFi project significantly. The assembly of the C-frame was suspended for several months and in March 2021 the SciFi groups resumed regular travels to CERN and have restarted the assembly work at CERN. The project has advanced very well since then. Half of the detector has already been installed underground and the assembly of the remaining detector layers is progressing well.

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 PACIFIC carrier boards and cluster boards were completed 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 were performed at CERN. The tests were interrupted by the first Covid-19 lock-down, were resumed in summer 2020 and completed. The quality of the assemblies is high and no major problems have been found. For a fraction of ROBs an exchange of bad components is necessary. This repair is currently underway.

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 were 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 in 2020 during the Covid-19 lockdown.

The cold-boxes are mounted on both ends of the fibre modules before installation. The flex-cables of the SiPMs are later connected to the front-end electronics. The module finishing, i.e. the mounting of the cold-boxes onto the modules, was stopped during the first Covid-19 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 were already equipped with cold-boxes and had been tested. The module finishing was resumed at the end of March 2021 and was finished in May 2021.

4.3.4 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 close around the beam-pipe to 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

Workpackage	C1	C2	C3	C4	C5	C6	C7	C8	C9	C10	C11	C12
Mechanics	ok	ok	ok	ok	ok	ok	ok	ok	ok	ok	ok	ok
Cabling	ok	ok	ok	ok	ok	ok	ok	ok	ok	ok	ok	ok
Services:									ok	ok	ok	ok
Water	ok	ok	ok	ok	ok	ok	ok	ok	ok	ok	i.p.	i.p.
Novec	ok	ok	ok	ok	ok	ok	ok	ok	ok	ok		
Dry-Gas	ok	ok	ok	ok	ok	ok	ok	ok	ok	ok		
Modules	ok	ok	ok	ok	ok	ok	ok	ok	ok	ok		
Heating	ok	ok	ok	ok	ok	ok	ok	ok	ok	ok		
Electronics	ok	ok	ok	ok	ok	ok	ok	ok				
Optical Fibres	ok	ok	ok	ok	ok	ok	ok	ok				
Commissioning	ok	ok	ok	ok	ok	ok	i.p	i.p.				

Table 2: Status of the assembly and commissioning of the C-frames as of calendar week 39 (2021). *ok* means concluded, *i.p.* means in progress.

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 were delivered to CERN. The assembly of the mechanical structures of all 12 C-frames (C1 to C12) has been completed in July 2021.

Cables, services, modules and the readout boxes are being installed on the mechanical structures. The different assembly steps require the presence of trained experts from the different contributing institutes. The assembly procedure was therefore suspended due to Covid-19 travel restriction and was relaunched at the end of March 2021, when the groups resumed traveling to CERN. Table 2 summarizes the status for the 12 C-frames at the end of September 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 vacuum insulation of all Novec lines, and, to prevent icing of the SiPMs, dry air flushing of the inner cold-box volume.

For all C-frames (C1-C8) 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. 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 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 - C6. C-frames C7 and C8 are currently under way. 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 assembly of the remaining C-frames, C9 to C12 , is progressing very well. It is foreseen to finish testing the last frame (C12) in January 2022. This schedule assumes that there are no further Covid-19 related restrictions or other major problems.

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. Flexible cable chains to guide the cables and services to the detector frames have been installed and filled: the C-side was finished in time for the installation of the first C-frames. The A-side infrastructure was concluded in September 2021.

4.3.6 C-frame installation, integration and commissioning

The first 4 C-frames (C1-C4) have been transported and installed in the experimental cavern in early May 2021. Frames C5 and C6 followed in early July and completed the C-side of the detector. Figure 7 shows the 6 frames of the C-side installed in the LHCb-detector and connected to the flexible cable chains. The achievement of this milestone in July was a necessary condition for the installation of the beam-pipe which started at the end of July. In parallel the flexible cable chains with all services have been connected. Water cooling and dry-air flushing of the cold-boxes have been commissioned. The vacuum pump down for the Novec lines has started. Novec has already been circulating at room temperature. Currently (September 2021) the low and high-voltage and the optical fibres are being connected and the in-situ commissioning of the first detector half is starting.

The remaining C-frames (C7-C12) will be installed in several installation campaigns, the first one foreseen for November 2021 (C7-C8). The current schedule assumes that the last frames are installed in January 2021. This installation schedule is tight and leaves only limited time for the connection and the commissioning of the frames before the LHC start-up.

Figure 6: The C-side 1/2 box in the assembly room. The cabinet holding the staves ready to be mounted and the C-side CO_2 manifold ready for installation are visible.

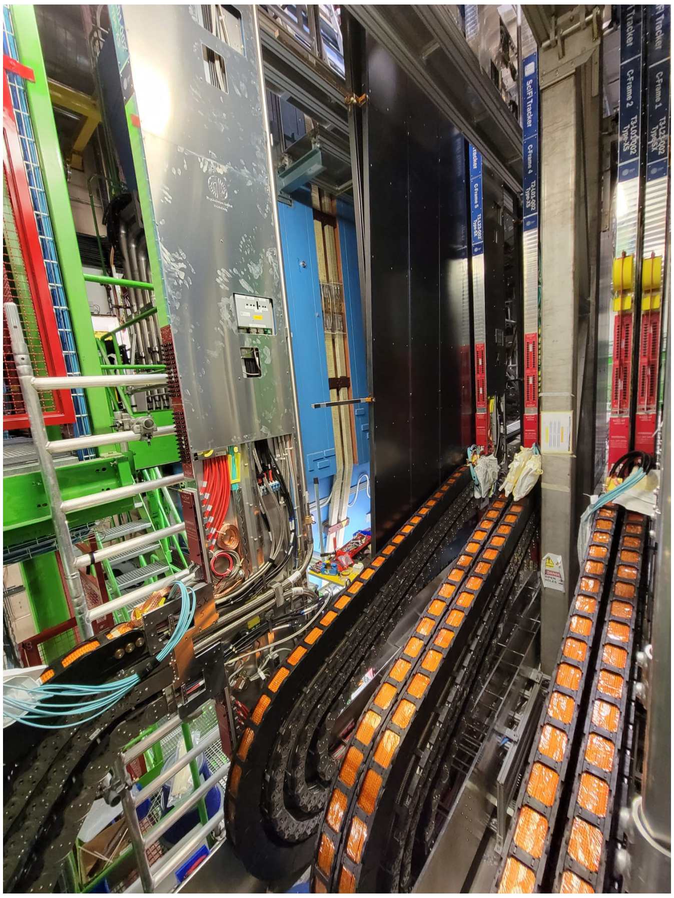

Figure 7: C-frames of the C-side of the SciFi detector installed and connected to the flexible cable chains.

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 system is complete and equipped with its mirrors. The RICH1 columns of photon detectors are being prepared for installation. The RICH2 system is complete and is commissioning. It will be taking data during the forthcoming LHC beam test.

The calorimeter is fully equipped with the new electronics systems. The hardware and software of the motion system has been replaced. The calorimeter system is commissioning and will be taking data during the forthcoming LHC beam test.

The muon system has been commissioning throughout 2021 and will be taking data during the forthcoming LHC beam test.

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 were obtained. Both types of mirrors underwent QA and characterization before being accepted. The quality is excellent. They have 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. These mirrors have now been aligned and were recently installed into the gas enclosure.

After being produced and tested, the new RICH1 gas enclosure was installed on the beam line of LHCb in August 2019. However, shortly after 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 applied that did not disrupt the overall LHC schedule. The gas enclosure is now in position on the beam line and both 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. Having recently been furnished with both spherical and flat mirror arrays, the RICH1 gas enclosure is ready to host its photodetector cameras.

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, are 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. 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 installed at the pit inside RICH2 (see Figure 8). At present, assembly and commissioning work on the RICH1 columns is proceeding as per schedule and the column installation is foreseen for the end of the year.

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.

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.

The RICH2 system is being readied now for the coming LHC beam test. We expect to take data and hope to confirm our expectations for the RICH system performance and further prepare for the 2022 Run 3 start. RICH2 will be filled with CO2 (and not CF4), which will provide essential information on the feasibility of running RICH2 with a much more environmentally friendly gas than CF4.

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

Figure 8: Complete photodetector array ready to be installed in RICH2. The two RICHes features four arrays. Those for RICH2 have 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 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 is 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.

The main ingredients of the upgrade are the new FEBs, the control units and the adaptation of the high-voltage, calibration and monitoring systems. Those systems are now mostly produced and installed in the LHCb cavern.

5.2.1 The Front-End boards

The production of the FEBs is now completed. To equip the calorimeter (ECAL and HCAL), 246 boards are needed (including the boards used by the LED calibration system). The purchase consisted of 16 pre-production boards and 262 production boards, giving the required boards and 32 spare FEBs. At present 271 boards have been delivered. The remaining spares should be shipped to IJCLab (Orsay) at the beginning of October. The delay on the last batch is due to damage of the oven used for the ageing of the boards in the company producing the FEBs. The 271 boards received have been thoroughly tested at IJCLab. Most of the boards were fully functional and a couple have been fixed in our laboratory. Currently, only 15 boards have remaining issues and these are being debugged. 250 FEBs have already been sent to CERN so that the calorimeter is now fully equipped.

The calorimeter electronics has 18 crates (14 and 4 for ECAL and HCAL respectively). They received the FEBs which have been connected to the photomultipliers at the input (signal cables). Each FEB has also been connected to its four readout optical fibres and to the TELL40 of the PC-farm.

5.2.2 Control Units

The 26 control units have all been produced. 18 are needed to equip the calorimeter system and one is required by the Plume luminometer. Hence, 5 spares boards have been foreseen. After the validation tests 2 had to be fixed and the calorimeter system is fully equipped. The problem identified by CERN on the VTRx components (see section 8.4) affected the calorimeter system. The VTRx that were originally plugged on the control unit boards and have now all been replaced by ones that have undergone a heat treatment procedure.

The control units have all been installed into the 18 crates of the calorimeter

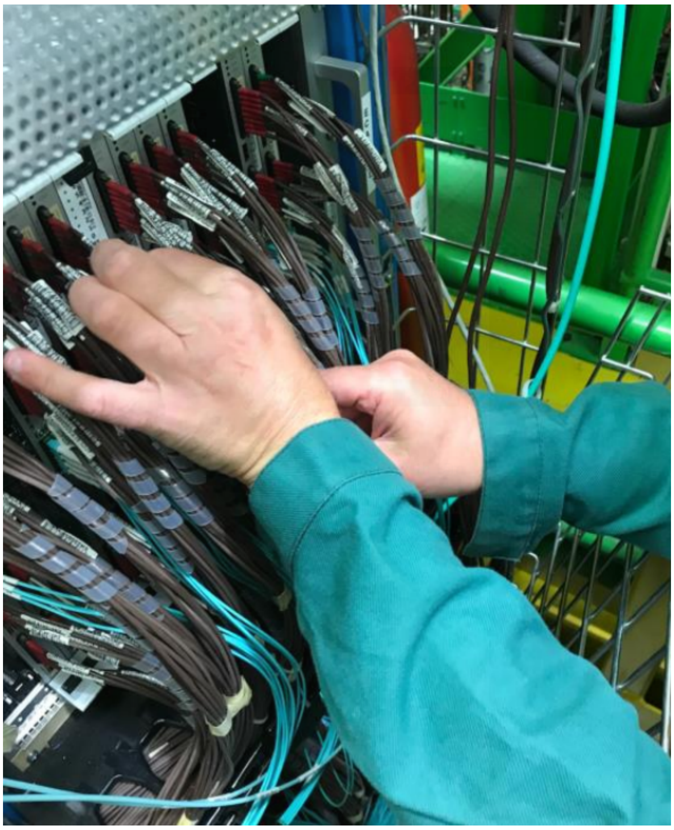

Figure 9: Installation of the front-end boards into the calorimeter crates and connection of the PMT signal cables (brown) and of the optical fibres (blue).

system. They have been connected to the slow-control bi-directional fibres and to the control computers.

5.2.3 High-voltage, calibration and monitoring

Progress on the high-voltage, calibration and monitoring systems was paused for a lengthy period due to Covid-19 travel restrictions. Fortunately, this part of the project was well advanced. Now, all the boards (a total of 144 boards of five types, including mezzanines and GBT fanouts or ELDM boards) have been designed and fabricated. The high-voltage system is validated and already installed on the calorimeter. The LED triggering electronics is mostly tested and the installation is on-going. The Caesium source based calibration system should be installed in November-December. The corresponding firmware is being developed and is close to its final version.

5.2.4 Infrastructure

The infrastructure of the calorimeter system is essentially in place. The crates, backplanes, power supplies and turbines for the cooling have been either adapted or replaced before the FEBs and control units were delivered to CERN.

The installation of the Low-Level-Trigger cables is on-going and will be achieved in November together with the installation of the calibration systems.

The electromagnetic and hadronic calorimeter motors for the movement of the A and C sides of the detector have been replaced. The hardware and software of the control system of the motors have also been upgraded and provide much more reliable operations. The new software implementing a convenient interface is now completed.

5.2.5 Commissioning and software

The calorimeter system is mostly at the commissioning stage. The crates are powered and the configuration of the system is now a routine operation. The control software is almost ready and is being debugged. We start to use the online infrastructure of the experiment in order to perform data acquisitions at the full calorimeter scale in the PC farm. This will soon permit to perform an overall validation of the signal cable and optical fibre connections.

The PCie40 firmware is mostly operational and we are now working on the decoding software in order to provide the data with the correct format to the trigger and the fast analysis programs in the farm.

The plan is to participate to the October LHC beam test and take data in order to check the behaviour of the detector, gaining some real experience before the LHC start-up in 2022 and perform a first time alignment of the crates.

5.3 Muon system

The Muon detector has performed exceptionally well in Run 1 and Run 2 of the LHC. The main changes for 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 need for spares, 190 nODE, 150 nSB and 14 nPDMs boards in total have been produced.

All the nSYNCs required are installed on the 185 complete nODE boards and about 100 additional spare nSYNCs are ready for future usage.

After difficulties with component procurement and board assembly due to the Covid-19 pandemic, the producing company sent the final batch of boards at the end of 2020. At present a total of 185 nODE boards have been produced and tested at LNF (with final 5 out of 190 still to be produced). In January 2021 all the muon stations were fully equipped with the new electronics. The situation at CERN is now the following: 144 boards are installed (100% completion) of which five temporarily accepted with degraded BER (<1E-12); 2 more boards are available as spares.

Failed boards were sent back to the company for reworking but the success in their recovery was not too satisfactory (5 recovered out of 18). Instead the hiring of a technician expert in board processing and the possibility of an immediate test by the experts, has enabled the rework of the faulty boards in Frascati. A high success rate has been achieved so far (9 recovered out of 10). The laboratory will be equipped to be able to perform all the rework, including the final cleaning.

All stations are also fully equipped with the required nSB (120) and nPDM (8 boards), and spares (30 nSB and 6 nPDM) are available at CERN.

At the end of August 2021 we received the cured VTRx components with which we replaced the ones in all the boards installed (144 nODE + 8 nPDM). During the replacement a heat sink has also been mounted on the AUX-SCA of each nODE. This, together with an improved ventilation of the racks, decreased the working temperature of the SCA.

5.3.2 Commissioning

All the activities needed for the commissioning of the muon system are progressing well. All muon Tell40 and SOL40 boards are connected and in use, and the firmware is updated to the latest version. The connectivity test for the control lines was completed in June, while the one for the data lines is ongoing on side C. Side A will follow closely.

The ECS project is well advanced in all its sub-projects; in particular all the non-DAQ projects (low- and high voltage control, DCS temperature monitor, DCS gas flow and gain monitor) are completed. The muon system is ready to fully profit of the test with LHC beams of 18-31 October 2021.

5.3.3 Additional Shielding in front of M2

In parallel the activities related to the addition of material in front of M2 are almost completed. The additional material 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 (installed in 2020), tungsten slabs in place of the innermost HCAL cells (installed in January 2021), and a new M2 beam plug, partially made of lead (installed in July). The only missing parts are the small end-caps to complete the M2 beam plug; the machining and the installation will happen after the LHC beam test.

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) [30] allows to inject a low rate of noble gases into the vacuum vessel of the 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.

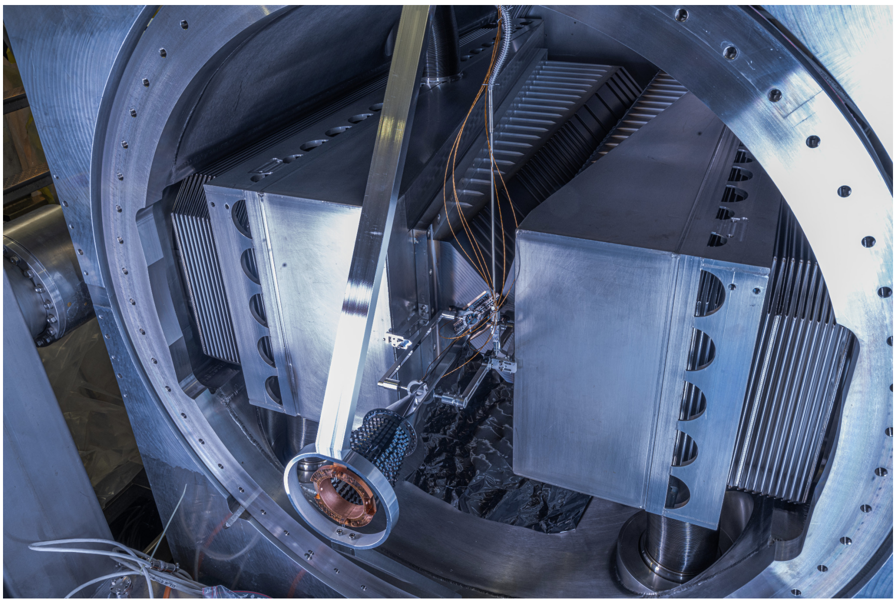

Figure 10: The installed SMOG2 storage cell with wake field suppressor, attached to the VELO RF box in the VELO vacuum vessel at IP8.

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. [31].

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. 10. 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. The original SMOG gas system was removed in summer 202 and is thus not available for the autumn LHC beam test. The installation of the SMOG2 gas system is foreseen before the end of the LS2. 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. Studies on the track reconstruction efficiency show that it is possible to run simultaneously in p-p and p-gas mode without creating interference between the two colliding systems, see fig. 11. In this case the data throughput increases by only up to 3% with respect to the running conditions with the p-p collision mode only.

7 Status of upgrade: online, trigger and real-time analysis, data-processing, 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 event-builder has to aggregate 40 Tbits/s. The architecture relies on 163 PC-servers interconnected through a 200 Gbits/s bi-directional network. The installation of the event-builder is finished, and it is fully connected to the sub-detectors.

Framework and continuous integration processes are used to develop the firmware for the sub-detectors which are loaded in readout boards. The latest firmware release incorporates the distribution of the LHC clock and fast command by using PON technology, the implementation of the GBT6 protocol as well as the generation of event fragments properly formatted for event building.

Dry runs of the event-builder software have been performed with realistic event fragments. They show that an aggregation rate above 30 MHz can be sustained

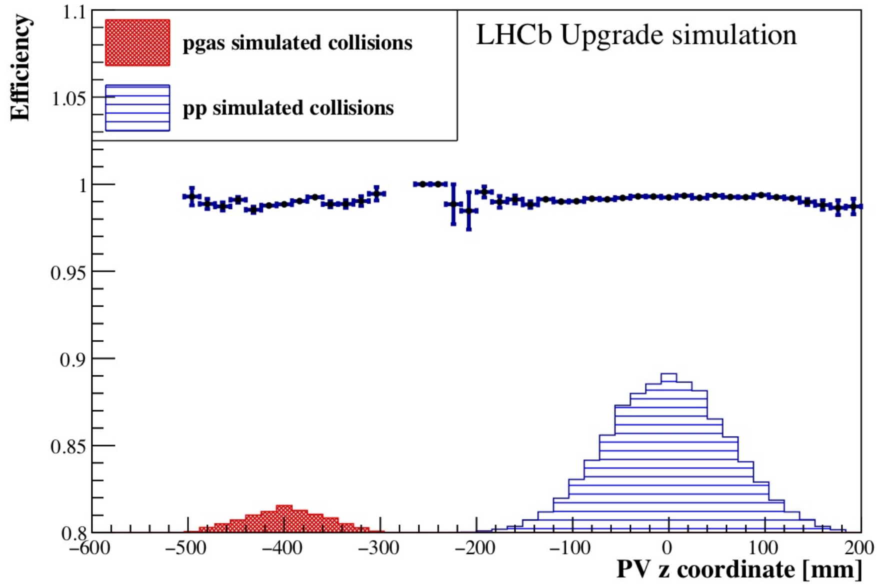

Figure 11: Velo tracking efficiency as a function of the z of the primary vertex. The simulated distributions for p-gas (left side of the plot) and p-p (right side of the plot) collisions, normalized to fit the picture, are super-imposed [Ref: LHCb-FIGURE-2019-007].

between 200 PC-Servers.

In order to exercise the downstream part of the dataflow, Full Experiment Systems Test (FEST) campaigns have been organized. In each PC-server, the aggregation layer is replaced by a software injecting full events which are generated by Monte-Carlo simulation. Events are then propagated to HLT1, disk buffer, HLT2 and the final tape storage. The whole process is controlled via a dedicated version of the Run Control.

The LHC clock has been connected to the online system in the LHCb data centre. The clock is distributed to readout modules and ECS control boards via a PON network. A deterministic latency has been achieved with a jitter of about 80 ps.

The development of software to control the experiment is progressing. Many components are implemented and tested. It is now possible to control the event builder and to monitor the front-end configurations. A first version of the run control is also available.

The commissioning is ongoing for the CALO, MUON and RICH2 systems. The online system should be ready to acquire data during the LHC beam test scheduled in October.

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. A Production Readiness Review was held August. Its aim was to evaluate if the candidate GPU is adequate in terms of performance, cost, and if it can be integrated in the event builder. The A5000 card from NVIDIA was selected and 200 of them ordered. They will be installed in November.

The event model behind all reconstruction algorithms continued to evolve for more reliability and usability. In addition, full reconstruction algorithms improved and can now process about 400 Hz per node allowing an HLT1 output rate above 1 MHz.

A subset of the intended HLT2 selections has been implemented and tested. The performance obtained with around 100 lines implemented shows an impact of below 10% on the output rate. Developments are ongoing in order to handle the full $\mathcal{O}(1000)$ lines without an excessive effect on the event processing rate.

7.3 Data processing

Following the trigger reconstruction and selections, the data is required to be processed before their analysis by end-users. This is performed offline, exploiting WLCG resources.

In mid 2020 the Collaboration set up the DPA (Data Processing & Analysis) project. It addresses the challenges for offline data processing due to the very large increase in data volume with respect to Run II. The project centralizes "Sprucing" (trimming and skimming) of a significant fraction of the HLT2 output data, as well as analysis productions for physics working groups and users. It is organized around six working groups.

A collaboration agreement has been arranged on the sharing of the maintenance and Operation Resources of the DPA project. It will ensure long-term support for the development, maintenance, and operation of the DPA software, covering both personnel and financial contributions.

Currently, the main developments in the project are on the Sprucing processing step, which runs on non-TURBO data containing reconstructed physics objects.

7.4 Computing and offline processing

Work has been continuing on the framework upgrade for Run 3. Progress has been made on the refactoring of the continuous integration system, on a new CMake toolchain, on adding features needed for the detector description with the DD4HEP tool and the conditions database.

In the distributed computing domain, data transfers from the LHCb online system to the CERN Tier0 tape system (CTA) have been successfully tested at the 10 GB/s nominal rate. A first integration test of the LHCb dataflow has been performed in June. Another test is being performed in October, with the goal of automatizing the procedures and extending the data transfer and archival to Tier1 sites.

The use of High Performance Computing centres (HPC) continues to be investigated. The CSCS and SantosDumont centres in Switzerland and Brazil are in production. NERSC in the USA (for which LHCb was awarded an allocation grant) has been recently configured and is currently in production. The configuration of MareNostrum in Spain and the Marconi/100 partition in Italy is under development.

8 Status of upgrade: infrastructure

8.1 Infrastructure

The general infrastructure has now been in place for several months and the commissioning is well advanced. This has allowed the technical coordination team to support detector specific work, assisting on activities that are behind schedule due to the covid-19 crisis.

The high and low voltage power supplies of the muon system have been reconfigured and relocated in their racks. The entire electronics chain of PLUME (Probe for LUminosity MEasurement) is now in place, in good time for its commissioning. The Velo CO_2 cooling infrastructure is completed and the cables are now in place between the Patch Panels and the Local Box close to the detector. The equivalent cabling for the Upstream Tracker will follow soon. More than 80% of the water-cooling pipes in the electronic racks have been exchanged. For the Calorimeter system new air-cooling units are integrated in the electronics racks above the detector. Assistance is provided to the Upstream Tracker group, which is making preparations for the installation of the first staves in the cleanroom. All the cabling work for the monitoring of the cooling system is completed. The new main chiller, providing primary cooling for the VELO/UT CO2 cooling plants and the SciFi Novec cooling plant, is operational. Commissioning of the RICH and SciFi cooling systems has started to accompany the operation of these detector systems.

Most of the lightning in the LHCb cavern has been renewed. As a result the entire experiment is much better illuminated and the electrical power consumption of this has been significantly reduced.

8.2 Installation

Installation work related to the luminosity and beam condition monitors has been performed over the summer. The Radiation Monitoring System is installed upstream of the LHCb detector as well as the supporting structures of the BCM (Beam Condition Monitor). Furthermore, the main infrastructure for PLUME is now in place together with a subset of detecting devices ready for taking first data during the LHC Beam Test in October.

The complete side C of the SciFi detector was installed in July, as discussed in the tracking section of this document, and this enabled the installation of the entire beam pipe. The beam-pipe has been baked out, and with the completion of this work another important milestone has been successfully passed. This paved the way for the mounting of the RICH 1 flat and spherical mirrors inside the gas enclosure. The optical system was surveyed and aligned. Now, the RICH 1 gas enclosure is closed for what is expected to be the final time.

For the Muon system, all the shielding plugs are in place. The HCAL/ECAL displacement system has been upgraded, both in hardware and software.

The lifting tools and platforms have been made ready for the installation of the UT on the side C.

8.3 Commissioning

The commissioning of the upgraded LHCb detector has now entered its integration phase: the central readout supervisor, the central control system and the central timing and clock distribution have been deployed. This is enabling the currently installed sub-detectors, namely Calorimeters, the Muon system and the RICH2 detector to perform regular commissioning of the entire detector chain. The Front-End electronics is being checked and validated as well as the Back-End sub-detector specific firmware. In addition, the central Event Builder and the central monitoring system, including its web-based user interface MONET, have been deployed and tested extensively during the summer. These are now being released in their production versions for usage by sub-detectors.

The entire readout chain, including Event Building, Monitoring and the RICH2, Muon and Calorimeter detectors will participate in the LHC October Beam Test. This will thus enable the first data taking of the upgraded LHCb detector during the first collisions in October. A day-to-day plan aiming at time aligning these three detectors, reading them out centrally and controlling them is made. This plan, supported by detector experts and non-expert central shifts, has already been devised and the commissioning work is currently concentrated towards this goal. The other sub-detectors, which have not yet completed installation, are also being supported in their local commissioning and transition from the labs to the LHCb cavern.

The LHC running conditions in LHCb, in view of 2022 and 2023 and beyond, have been agreed with the machine experts. LHCb has started generating simulated data based on these conditions.

8.4 VTRx Issues

The VTRx is an optical link element that is a common electronic component for all LHC experiments. Failures in this component were understood after extensive investigation. A procedure to mitigate the defects of the VTRx has been developed by the EP-ECE group at CERN. A longterm baking of the VTrx is applied to fully cure the adhesive that was causing the issue. LHCb has started to replace the faulty VTRx components in many of the detectors. All components that are most at risk of failure, due to not being cooled, will be replaced before the end of LS2.

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. Most of the detector activity has moved from the production to the installation or commissioning phase. The Technical Board is chaired by the Technical Coordinator and is comprised of all detector project leaders. A number of the subdetectors are in 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 project, the Operation Coordinator, as well as the management and the physics coordination team.

The various bodies meet 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 has shifted by three weeks since the last RRB as a consequence of two sectors of the machine needing to be warmed up for repairs. Cavern closure for Run 3 is planned for the 21st February 2021.

Discussions with the other experiments, machine and directorate on the schedule occur regularly, with the next meeting planned for the 1st November. The schedule is tight for some LHCb subdetectors, with delays accumulated due to the Covid-19 pandemic being significant. 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. Contingency plans are being put in place should the UT system not be ready for installation prior to cavern closure. This include the advancement of work on detector services, with the assistance of CERN personnel, to enable a later installation of the detector boxes should this be required; and considerations in the trigger system to permit its functionality for commissioning should the UT not be present for the early running.

9.3 Funding

The status of the M&O Cat.A and B accounts is only slightly affected by the present Covid-19 situation. Difficulties in getting the right collaborators on site are becoming more manageable, although for some countries the arrangements remain quite complex. As described in the detector description sections, delays are being reported and 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. Half year marks on the 2021 M&O Cat.A show sustained activities and a balanced expected end-of-year budget.

A smooth transition is requested by the sub-detectors projects for their M&O Cat.B. This seems to be happening, although of course there is an inevitable difficulty in estimating the resources and technical commitments for the completely new sub-detector projects. However, we do not expect large variations of these levels for the coming years.

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 [12] and in the Addendum No. 2 to the MoU for the Upgrade of the Sub-Detector Systems [13], 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. Funds will be utilized at the end of 2021 and beginning of 2022 for the commissioning and M&O activities. The majority of the Common Project funds (in particular for the acquisition of the Computing Farm) have been spent in 2020-2021. However, owing to the present difficult situation in the CPU and GPU market, non-essential acquisitions have been delayed to 2022, in order to achieve the best value for money. 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 [13], 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 of integrating up to $300\,\mathrm{fb}^{-1}$ throughout the full HL-LHC phase was proposed in [32], with details on the physics reach discussed in [33]. 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} cm^{-2}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 improved physics performance already during Run 4.

This plan received strong support in the 2020 Update of the European Strategy for Particle Physics [34], approved by the CERN Council in 2020. 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 upgrade of LHCb.

In September 2021 we entered the review phase of the Upgrade II project, by delivering to the LHCC a draft of the Framework TDR (FTDR). This document describes the detector and computing that demonstrate we have technological feasible options to deliver our physics case. This will be followed by subsystem light TDRs describing minor consolidation work for LS3 and later by subsystem TDRs describing the Upgrade II for LS4. The RRB will be kept informed about the preparation of these documents.

One of the key ingredients for success of the project will be to develop highly innovative technological solutions. A vigorous R&D programme is being carried out for all areas of 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 discussions within ECFA in order to define a roadmap for future detector R&D. In 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 accelerator studies for Upgrade II. A detailed plan to adapt the beam optics and develop 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. If this construction activity can be performed in LS3, it will make an efficient use of the extended period of shutdown.

11 Collaboration matters

The collaboration continues to grow, having added five further institutes in this period. The collaboration has recently passed 1000 authors, having 1003 at the time of writing. The IRFU-CEA Saclay group has joined as a Technical Associate member group with particular interest in a CMOS-based Upstream Tracking system for Upgrade-II, and an intention to become a full member with heavy-ion physics interests in the longer term. The Uppsala University group has joined the collaboration as an Associate Member group, with interests in silicon detector systems for Upgrade-I and Upgrade-II and a physics focus on studies of hadronic states. This is the collaboration's first group from Sweden, which we are pleased to welcome to our community bringing our number of contributing countries to 20. The Cracow University of Technology has joined as an Associate Member group, with interests in the Upgrade-I RICH system, the magnet-side stations of Upgrade-II, and rare decays physics. The Institute for Scintillating Materials (ISMA) in Kharkiv and the Taras Shevchenko National University of Kyiv (TSU) have both joined as Technical Associate Member groups with particular involvement in the PLUME luminometer.

The collaboration board has approved the formation of a new simulation project, providing a more formal structure than the previous working group. This project is organised in a series of working groups, covering aspects such as event generators, simulation framework, simulation sample production, detailed and fast simulations, detector modelling and radiation and environmental background simulation.

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