Status of LHCb Upgrade I

CERN-RRB-2022-038

LHCb collaboration

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Contents

1 Introduction

The LHCb experiment is expected to have three major phases of detector technology. The original detector completed data-taking at the end of LHC Run 2 in 2018. Physics results arising from the analysis of data collected in this phase are described in this document. The LHCb Upgrade I has been installed during LHC Long-shutdown 2 (LS2) 2018-2022. The status of its construction, installation and commissioning of its hardware and software systems provide the bulk of the material in this document. The LHCb Upgrade II is planned to be primarily installed in LS4, with some smaller modifications foreseen in LS3. Progress on the R&D for this detector is also described in this document.

A total of 10 fb^{-1} were delivered to LHCb in Run 1 and Run 2 data taking periods, with 9 fb^{-1} recorded. The LHCb Run 1 and 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 experiment's unique gas injection system. Exploitation of Run 1 and Run 2 data is progressing very well with, at the time of writing, a total of 609 papers published or submitted, with 49 having been submitted in 2021. Physics highlights since the last report are discussed in Sect. 2. LHCb is particularly designed to measure matter anti-matter asymmetries (CP Violation) and rare decay processes sensitive to new physics. These include a new combination of fifteen measurements of the *CP* violation parameter γ, which dominates the world average. Measuring γ with high precision was one of the key aims of LHCb. Neutral particles that contain charm quarks (D mesons) can oscillate between particle and anti-particles by the fascinating quirks of quantum mechanics. We have measured one of the two the parameters that control this mixing a factor four better than the previous world-average. LHCb has made many discoveries of new particles, bound states of quarks, over the last years. Two new excited beauty baryon (Ξ_b^0) states have been observed. We have again published additional results on the intriguing anomalies seen in tests of lepton flavour universality. Two of these are in the same type of rare decay quark processes that we have discussed in recent meetings ($b \to s\ell\ell$), and show a combined tension with the standard model of around 2σ. While another is the first test of semi-leptonic decay anomalies ($b \to c\ell\nu$) to use a decay of a baryon (Λ_b^0).

The LHCb Upgrade I is one of the largest particle physics detector projects to be installed since the completion of the LHC. It is being completed on-budget. The detector is based on a novel trigger system 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 up to $2 \times 10^{33}\,\text{cm}^{-2}\text{s}^{-1}$. Flavour-physics measurements will be performed with higher precision than was 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 I detector 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) were written for all systems [3–11] and approved by the Research Board. This was followed by their construction period. Installation of most systems has been completed during LS2.

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.

The operational aspects of the detector are covered in Sect. 3. This includes information on the commissioning status of the Upgrade I detector as well as computing and data processing operations concerning Run1 and Run 2 data and simulation. Several of the Upgrade I detector systems, as well as the online system, successfully took data during the pilot beam test in October 2021. Additional full event systems test weeks have been held for commissioning of the experiments software systems.

In the next part (Sect. 4, 5, 6, 7, 8, 9) an update on the status of the LHCb Upgrade I is given, summarising progress since the previous RRB. Nearly all systems have completed primary installation and started commissioning. The RICH1 system, large-scale SciFi tracker system and luminometer systems have all completed installation since the last meeting. The VELO has installed the first half of the detector facilitating the detector commissioning. The assembly of the second-half is being completed, with an early installation in the next period planned. This will complete the system required for initial commissioning, operations and early physics measurements. The UT has mounted the first staves in their assembly room at the surface and completed all planned work on services in the cavern. Installation of the UT detectors is expected to be completed in the year end shutdown at the end of 2022.

The LHCb Upgrade II detector was proposed in the Expression of Interest [14] in 2017 and the Physics Case described in [15]. Its main components, cost-envelope and descopes are defined in the Framework TDR [16] which has recently been reviewed by the LHCC. Some key elements of this document and the next steps are described in section 10.

2 Physics

In 2021 the LHCb collaboration submitted in total 49 new publications, with a futher 6 in 2022. This brings the total to 610 papers at the time of writing, of which 589 have been published. A further 21 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. All papers submitted in this period are listed in table 1.

2.1 CP violation and mixing in beauty and charm

CP violation and mixing are phenomena at the heart of flavour physics. In particular the decays of the type $B \to DK$ are governed by interfering amplitudes with couplings V_{cb} or V_{ub} with a relative weak phase γ. This CKM angle γ is crucial to probe the consistency of numerous flavour measurements through the unitarity of the CKM matrix.

Recently LHCb has combined fifteen $B \to DK$ CP violation measurements with eight D mixing measurements to obtain a new determination of the angle γ [17]

$$\gamma = (65.4^{+3.8}_{-4.2})^o$$

which is the most precise determination by a single experiment, and which is dominating the world average. This includes seven new and updated inputs from

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

Title	arXiv
First measurement of the $Z \to \mu^+\mu^-$ angular coefficients in the forward region of pp collisions at $\sqrt{s} = 13$ TeV	2203.01602
Measurement of the charm mixing parameter $y_{CP} - y_{CP}^{K\pi}$ using two-body D^0 meson decays	2202.09106
Observation of the doubly charmed baryon decay $\Xi_{cc}^{++} \to \Xi_c^{\prime +}\pi^+$	2202.05648
Study of charmonium and charmonium-like contributions in $B^+ \to J/\psi\eta K^+$ decays	2202.04045
Search for the decay $B^0 \to \phi\mu^+\mu^-$	2201.10167
Observation of the decay $\Lambda_b^0 \to \Lambda_c^+\tau^-\overline{\nu}_\tau$	2201.03497
Observation of the $B^0 \to \overline{D}^{*0}K^+\pi^-$ and $B_s^0 \to \overline{D}^{*0}K^-\pi^+$ decays	2112.11428
Constraints on the CKM angle γ from $B^\pm \to Dh^\pm$ decays using $D \to h^\pm h^{\prime\mp}\pi^0$ final states	2112.10617
Precision measurement of forward Z boson production in proton-proton collisions at $\sqrt{s} = 13$ TeV	2112.07458
Observation of $\Lambda_b^0 \to D^+p\pi^-\pi^-$ and $\Lambda_b^0 \to D^{*+}p\pi^-\pi^-$ decays	2112.02013
Searches for rare B_s^0 and B^0 decays into four muons	2111.11339
Measurement of the photon polarization in $\Lambda_b^0 \to \Lambda\ \gamma$ decays	2111.10194
Angular analysis of $D^0 \to \pi^+\pi^-\mu^+\mu^-$ and $D^0 \to K^+K^-\mu^+\mu^-$ decays and search for CP violation	2111.03327
Study of B_c^+ decays to charmonia and three light hadrons	2111.03001
Tests of lepton universality using $B^0 \to K_S^0\ell^+\ell^-$ and $B^+ \to K^{*+}\ell^+\ell^-$ decays	2110.09501
Search for massive long-lived particles decaying semileptonically at sqrt(s)=13 TeV	2110.07293
Observation of two new excited Ξ_b^0 states decaying to $\Lambda_b^0K^-\pi^+$	2110.04497
Simultaneous determination of CKM angle γ and charm mixing parameters	2110.02350

B-meson decays and eight inputs from D-meson decays. It is the first time that the charm mixing parameters are determined at the same time [17],

$$x = (0.400^{+0.052}_{-0.053})\% \qquad \& \qquad y = (0.630^{+0.033}_{-0.030})\%.$$

LHCb continues to provide new measurements that will be included in future combinations, such as [18]

$$y_{CP} - y_{CP}^{K\pi} = (6.96 \pm 0.26 \pm 0.13) \times 10^{-3}$$

which signifies a four times improvement of this charm mixing parameter over the previous world average. In addition, a new measurement to constrain γ has been performed with $B^{\pm} \to Dh^{\pm}$ decays using $D \to h^{\pm}h'^{\mp}\pi^0$ final states [19].

2.2 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.

Two new excited Ξ_b^0 states decaying to $\Lambda_b^0 K^- \pi^+$ have been observed [20] with masses $m(\Xi_b(6327)^0 = 6327.28^{+0.23}_{-0.21} \pm 0.08 \pm 0.24$ MeV and $m(\Xi_b(6333)^0) = 6332.69^{+0.17}_{-0.18} \pm 0.03 \pm 0.22$ MeV. The double heavy baryons Ξ_{cc} provide ideal systems to test effective theories of quantum chromodynamics (QCD). Recently LHCb has discovered the new decay mode $\Xi_{cc}^{++} \to \Xi_c'^{+}\pi^+$.

The system of excited charmonia is studied in detail in the rich 'laboratory' of $B^+ \to J/\psi\eta K^+$ decays [21], with first evidence for the decay $\psi_2(3823) \to J/\psi\eta$ decay through $B^+ \to (\psi_2(3823) \to J/\psi\eta)K^+$ with a significance of 3.4 standard deviations. Furthermore, the doubly heavy B_c^+ meson has been studied with in B_c^+ decays to charmonium with three light hadrons [22], which led to the first observation of four new decay modes of the B_c^+ meson.

2.3 Rare decays and Lepton-Flavour-Universality test

The intriguing flavour anomalies in $b \to s\ell\ell$ and $b \to c\ell\nu$ transitions keep drawing large attention in the community, due to the coherent picture of experimental signatures and its potentially large implications for particle physics.

LHCb has published two new results in both areas. First, LHCb measured new ratios of the decay rate of $B \to K\mu^+\mu^-$ over $B \to Ke^+e^-$ decays, where the K is either a K_S^0 or a K^{*+} meson [23],

$$R_{K_S^0} = 0.66^{+0.20}_{-0.14}(stat.)^{+0.02}_{-0.04}(syst.) \qquad \& \qquad R_{K^{*+}} = 0.70^{+0.18}_{-0.13}(stat.)^{+0.03}_{-0.04}(syst.),$$

which are consistent with the SM at 1.5 and 1.4 standard deviations, respectively, given the standard model expectation of unity with an uncertainty of about 1%.

Secondly, LHCb has for the first time observed the semileptonic decay $\Lambda_b^0 \to \Lambda_c^+ \tau^- \bar{\nu}_\tau$ [24], with a branching fraction of $(1.50 \pm 0.16 \pm 0.25 \pm 0.23)\%$. Using external information for $\Lambda_b^0 \to \Lambda_c^+ \mu^- \bar{\nu}_\mu$, the lepton-flavour-universality ratio has been determined

$$R(\Lambda_c^+) \equiv BR(\Lambda_b^0 \to \Lambda_c^+ \tau^- \bar{\nu}_\tau))/BR(\Lambda_b^0 \to \Lambda_c^+ \mu^- \bar{\nu}_\mu)) \\ = 0.242 \pm 0.026(stat) \pm 0.040(syst) \pm 0.059(BR),$$

which is about one standard deviation below the standard model expectation of (0.324 ± 0.004).

In addition, LHCb has measured the polarization in the flavour-changing-neutral-current $b \to s\gamma$ process using $\Lambda_b^0 \to \Lambda\gamma$ decays [25], performed the first full angular analysis of $D^0 \to \pi^+\pi^-\mu^+\mu^-$ and $D^0 \to K^+K^-\mu^+\mu^-$ decays [26], and searched for the rare $B^0_{(s)} \to \mu^+\mu^-\mu^+\mu^-$ decay [27].

2.4 Z-boson production

LHCb remains an important contributor to the electroweak sector. Recently LHCb has measured the double differential cross section of Z boson production in the forward direction with a sample of about $800,000$ $Z \to \mu^+\mu^-$ decays [28]

$$\sigma(Z \to \mu^+\mu^-) = 195.3 \pm 0.2(stat) \pm 1.5(syst) \pm 3.9(lumi)pb,$$

which will provide strong constraints on the parton density functions of the proton at low and high Bjorken x, given the unique angular coverage of the LHCb experiment.

In addition, the transverse momentum distributions of the parton densities will be constrained with a new LHCb result in the angular coefficients of Z boson production [29].

3 Operations

3.1 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 was to add selection lines to further extend the LHCb physics programme. Data from three years have been reprocessed: 2016, 2017 and 2018. The campaign was successfully completed by the end of 2021.

The exploitation of the full Run 1 and 2 data set for LHCb physics analyses requires large simulation samples to be able to validate measurements and evaluate systematic errors accurately. The computing operations are dominated by the production of large simulation samples. These requests are constantly growing and are using the largest fraction of the total computing power. The LHCb collaboration is devoting a lot of effort in developing fast simulation techniques which allow to greatly reduce the CPU usage while still generating large samples. Two approaches are followed by the LHCb collaboration to speed up the simulation: simulate only the elements of the detector essential in a particular measurement, *e.g.* TackerOnly, or simulate only part of the events under study, *e.g.* SplitSim and ReDecay [30]. The breakout by type of the events simulated by LHCb is shown in Figure 1 (left).

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 result 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 more than 90% of the resources are devoted to MC production. The significant component of fast simulations is clearly visible. The usage of computing resources

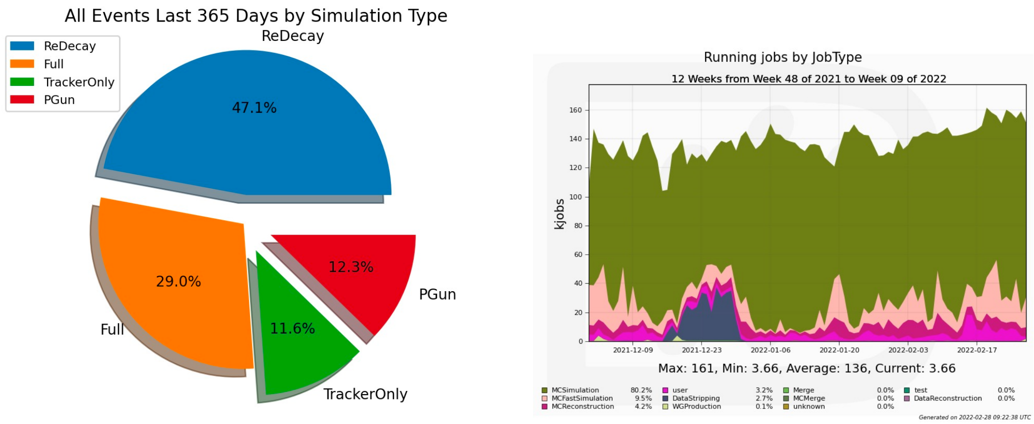

Figure 1: Left: The events simulated by LHCb split by simulation type: the growing usage of fast simulation techniques, with respect to full (detailed) simulation, allows a better exploitation of the computing resources. Right: The number of running jobs on the online-farm during the past months: the light-pink area indicates Monte Carlo jobs using a fast simulation technique, the green area Monte Carlo jobs using the full event simulation and the dark blue one corresponds to the last part of the Run 2 data reprocessing.

for 2021 [31] is discussed in a separate document. A dedicated document [32] has also been prepared to present the estimates for the computing resources in 2023. The LHCb Computing Model for the Upgrade era and the associated computing requirements are presented in [33].

3.2 Preparation for Run3

A plan of complementary tests to validate the Run 3 dataflow has been carried out in 2021. While each sub-detector was being installed and started its commissioning programme, a system of global validation has been set in place to anticipate the commissioning of the data taking and processing infrastructure. These tests have been carried out through Full Experiment System Test (FEST) campaigns. The philosophy of FEST is to inject simulated data through the whole Online and Offline chain to validate its readiness. Each campaign lasts one week, involves all software groups in LHCb together with the Online team and is run in the control room as a regular commissioning week. Various FEST weeks took place starting from June 2021, each with increased level of complexity and automation, aimed as tests of the elements of the system and their interaction rather then of their performance.

In October 2021 LHCb took part in the LHC beam test, this was a short period of data taking with a small number of bunches in the LHC machine that were collided at injection energy. LHCb took part with the sub-detectors installed at the time and whose commissioning was well advanced: the electromagnetic and hadronic calorimeters (ECAL and HCAL) , the Muon detector (MUON), the downstream Ring Imaging Cherenkov detector (RICH2) and the first elements of the Probe for LUminosity MEasurement (PLUME). All sub-detectors managed to successfully take data, aligned with the collisions provided by the machine. The new run control prepared by the Online ensured a successful and stable data taking, together with the first test of the new Event Builder on actual data. The new system to protect LHCb against adverse beam conditions, the Beam Conditions Monitor (BCM) system, was also included in the beam test and operated successfully, providing the beam interlock to LHC during the collisions period, as expected during Run3. Further monitoring of the beam conditions is provided by the Radiation Monitoring System (RMS), installed upstream of the collision point. The newly refurbished RMS was able to detect LHC activity starting from the first injection on 19 October, observing the first LHC "splashes". More details on the successful beam test are reported in the following sections of this document for the individual subsystems.

The commissioning is progressing in parallel for all sub-detectors with common check points organised as weeks to centrally acquire data with cosmic rays. FEST weeks are regularly taking place preparing for the start of the Run 3 collisions.

4 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 is an innovative silicon pixel detector. It has completed installation of the first-half of the detector and this is commissioning. The mounting of all modules in the second half has been completed and testing is starting. An early installation is planned before the LHC scrubbing run, which will ensure minimal disruption to the machine or experiments.

The UT is a silicon strip detector with a crucial role for the trigger in high luminosity running. It is nearing completion of all detector components. The installation of infrastructure in the cavern has been completed. The assembly of the detector is advancing with the first stave having been mounted. The full detector is planned to be installed for the 2023 physics run. The commissioning and data-taking of the LHCb detector will proceed in 2022 without significant disruption from the absence of UT. The operating luminosity for physics data taking will likely be reduced in 2022 with limited impact during this year of early data-taking.

The SciFi is a first-of-its-kind large scale tracking system based on scintillating fibres and Silicon Photomultipliers. The installation of all modules has been completed. The full system has been connected to its services. The detector is now commissioning.

4.1 Vertex Locator (VELO)

4.1.1 System overview

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.

4.1.2 Construction & installation

With the easing of COVID restrictions and the focus of the project moving to two major sites; CERN where the first half is currently being commissioned, and the University of Liverpool where the modules from the University of Manchester and Nikhef are being assembled onto the remaining half, the project has been able to move forward more smoothly. However the advent of Omicron and the associated travel bans in December led to an incompressible delay which has had a knock on effect for the VELO installation. The status of the project is summarised below.

Module Production

The tile production for the VELO was completed, including spare production in December 2021. A total of 26 VeloPix wafers, comprising more than 3276 ASICs were fully qualified, and after bump bonding 430 tile electrical tests were carried out, including IV scans to high voltage in vacuum. A total of 325 installation quality tiles were provided to the module assembly sites, with consistent quality shown throughout gluing, wire bonding and thermal cycling. The microchannel project was extended into October 2021 for a final yield of 81 installation quality coolers, plus eight coolers in reserve which may be used with rework. The module production has been completed for installation modules, but will continue until all spare components are consumed. In total 56 production-quality modules have been assembled, they have been transported in bespoke transport frames in batches of four to the University of Liverpool from the University of Manchester, while from Nikhef the transport is achieved in bulk in a specially constructed crate. In addition to the 52 which have been transported to Liverpool and assembled onto VELO halves there are four spares, with an anticipated further seven modules yet to be assembled. More than 31 extremely detailed steps and quality assurance procedures for each module have been meticulously recorded and tracked in the database (with resultant automatic grading) including metrology, noise, IV scans, thermal performance, photo inspections, thermal cycling, bonding and so on. The entire cohort has been tested for performance in terms of thermal figure of merit, defined as the temperature drop divided by the power density. The cooling performance, illustrated in figure 2 is remarkably efficient and consistent for all modules, and good enough to demonstrate a correlation with the thickness of the glue layer which is known from the metrology analysis.

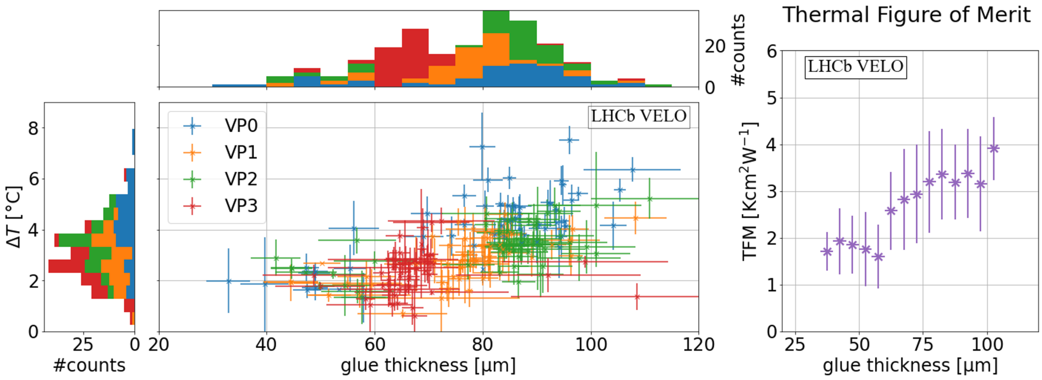

Figure 2: Left plot: change in temperature of the four tiles on the modules (VP0 to VP3), when going from zero to full power ($26W$). The x-axis gives the metrology measurement of the glue thickness for each tile. Right plot: Thermal figure of Merit (TFM) for all ASICs, plotted as a function of glue thickness. All errors represent standard deviation of the measurements.

Assembly and Transport

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, most recently in December. The procedure consists of equipping each half 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. After being fully equipped each half rehearses the VELO movements to check for the integrity of the cables and cooling circuits under full extension and compression. This was followed for the C side by the installation of four pilot pre-production modules. The installation and de-installation procedures were rehearsed and the coolant flow was tested in the most extreme powering and module failure scenarios. For the C side production module mounting then began. For the A side this initial commissioning period was not necessary and the production modules could be mounted directly.

Following module installation a series of tests verify the electrical performance and connectivity, the leak tightness of each individual cooling circuit, and the stability and flow characteristics of each individual cooling loop. For the C side, this was followed by a multi-module system test, focusing on the shortest and longest cooling loops, and electrical performance of adjacent modules, as this was the first opportunity to check for cooling and electrical stability of the system as designed. For the A side, this test could be reduced using the commissioning experience from the C side. When each half is fully qualified, a safety check ensures the correct operation of the safety system to shut off and contain any remaining CO_2 in case of a leak. This is followed by a metrology step, which surveys the module tips at temperatures between room temperature and the final cooled operational temperature to characterise any movement in z. Once complete, each half-tonne detector half is packed for transport into a frame that is specially designed to damp out vibrations for the 1800 km road and rail journey to CERN. The detectors are equipped with telemetry (3D shocks, pitch, roll and yaw) to allow the VELO group to monitor and catalogue events during the trip. The entire transport procedure was rehearsed with a dummy transport in December from the University of Liverpool through to the VELO tank inside the LHCb experiment using the real transport pieces and mockups of all VELO elements.

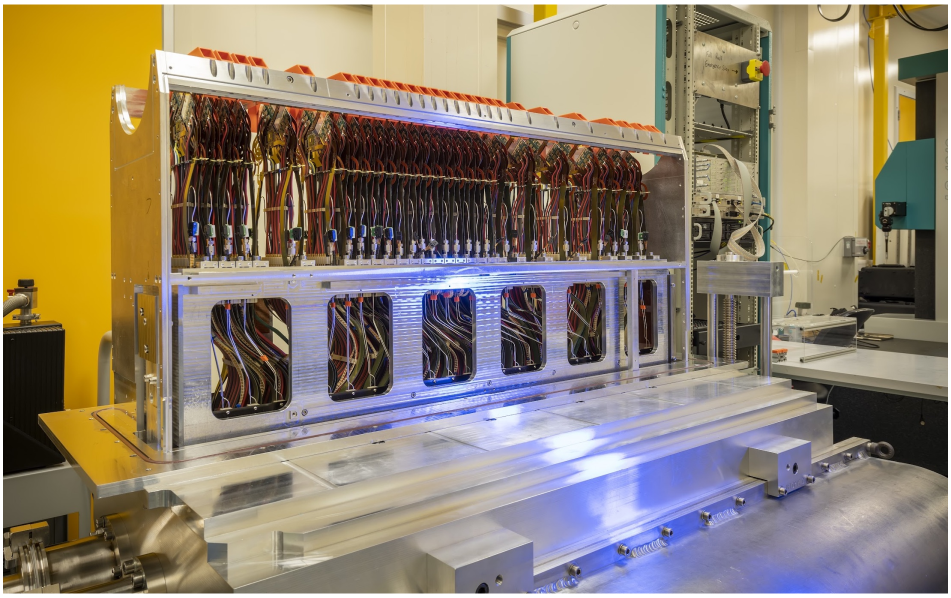

Figure 3: Fully assembled and qualified VELO C side before transport from University of Liverpool.

The C side assembly was delayed in December as the support team for the multimodule test were barred from travel to Liverpool. Instead, the procedures were reversed, focusing first on the metrology and then defining a reduced system test which could be completed at Liverpool in the first months of the year. A photograph of the fully assembled C side in the Liverpool clean room is shown in figure 3. The 26 modules can be seen, with the assembly tooling in place, including the frame which is used to guide the mounting of each individual module, the sacrificial base plate which is used to protect the flange which will communicate with the VELO tank, the umbilicals below the modules and the top of the tertiary vacuum tank.

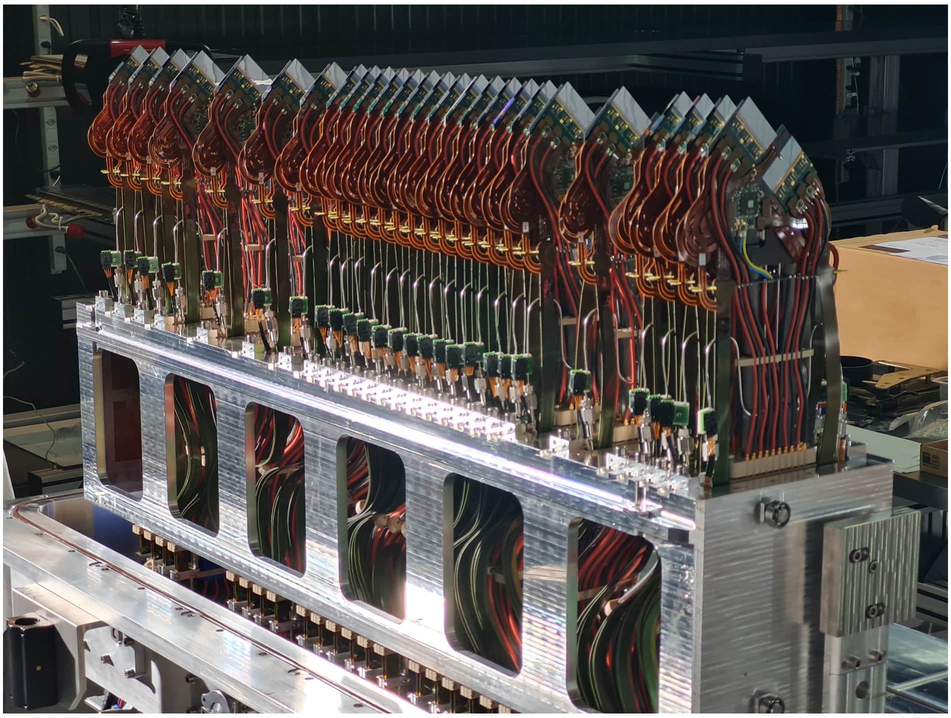

Figure 4: VELO C side after dismount of tooling.

The C side VELO half was shipped to CERN on 24th – 26th January. On reception each module undergoes a rapid electrical test without cooling, designed to check for no loss of connectivity, and a leak tightness check is carried out. In addition work was undertaken on arrival to address some issues which had been flagged before transport, including the replacement of one module with a suspect leak and the connectivity of various tertiary and secondary vacuum services. Finally the external tooling was removed and the VELO C side was rotated into the installation position in order to carry out a full 3D metrology scan with an absolute arm laser device; a measurement which can be completed in a few hours. Following analysis of the metrology data of the modules and RF boxes it was decided for safety to insert removable shims into the VELO base, so that the final module positions will be offset by 1 mm for the initial LHC runs. Following initial data taking and reconstruction of the material distribution with hadronic interactions, the shims will be removed and the VELO moved to the final position. The

VELO was then rotated again and inserted into the protective vacuum trolley to be stored for installation. Figure 4 shows the exposed modules after the dismount of the tooling.

The VELO installation was carried out on March 2nd, in close collaboration with the CERN TE-VSC vacuum group. The installation benefitted from the dummy transport rehearsal described above, with the crane and platform access having been upgraded following issues observed during that transport. The installation proceeded smoothly with one overnight break introduced due to the necessity of machining an installation rail which had been previously exposed to radiation; this step along with other small issues has been also addressed in anticipation of the A side installation. Following installation a pressurised helium leak check confirmed the module integrity, and the commissioning of the C side could start.

At the University of Liverpool assembly of the A side proceeded after the C side shipment. Two problems were encountered which introduced a delay. Firstly, a few very small leaks were discovered in the cooling manifold and loops. These could be partially addressed with VCR fitting and gasket refurbishment, however one loop in particular presented problems and the spare units and had to be remanufactured and replaced. Secondly, there were some issues which cropped up during the final steps of the feedthrough flange assembly. This is a complex process which includes the testing of all signal paths, and on the sixth and final flange to be tested some faults were discovered in the mechanical dimensions and data cable connectivity. This could be finally addressed with the loss of one signal line (out of 1120 for the full VELO). At the time of writing this report the A side has been fully populated with modules and is under test. The VELO group is planning to install this side before the scrubbing run of the LHC.

4.1.3 Commissioning

The first step of the VELO commissioning consisted of the connection of all inputs to the safety system, which communicates with the VELO, the cooling plant, the vacuum system and the LHC beam permits. Each line was independently tested before any operation was undertaken on the VELO half, before CO_2 cooling system, data and monitoring could proceed. The scheduled pump down of the entire system started on March 22nd, with a satisfactory vacuum level of 7×10^{-7} mbar currently achieved inside the detector volumes. The next step was to achieve the connection with the MAUVE cooling system, which is a major milestone for the VELO. The entire system was put under vacuum for a protracted period before first filling with CO_2 at room temperature, checking the correct boiling points within the modules and finally achieving the first cool down, to an initial temperature of -25C°. One module demonstrated a cooling anomaly and investigation is underway; an intervention in the tertiary vacuum may be required for the operation of this module, which can be done in parallel with the A side installation. All other modules passed basic electrical checks, and a more detailed commissioning is underway at the time of writing this report, starting with the ECS module configuration and continuing with the first application of HV and pixel readout and equalisation.

4.1.4 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 SMOG2 [9] allows to inject a low rate of gases giving the unique opportunity to study proton-nucleus and nucleus-nucleus collisions on various target types and at different center-of-mass energies. With SMOG2 new kinematic domains, poorly explored, will be accessible providing measurements relevant for both HEP and astroparticle physics.

SMOG2 has been installed during LS2. The main element of this target system 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 high effective areal densities (and thus luminosities) with low injected gas flow. This makes the system transparent to the LHC operations keeping the beam lifetime unchanged and without interfering with the beam-beam LHCb data taking. A detailed physics

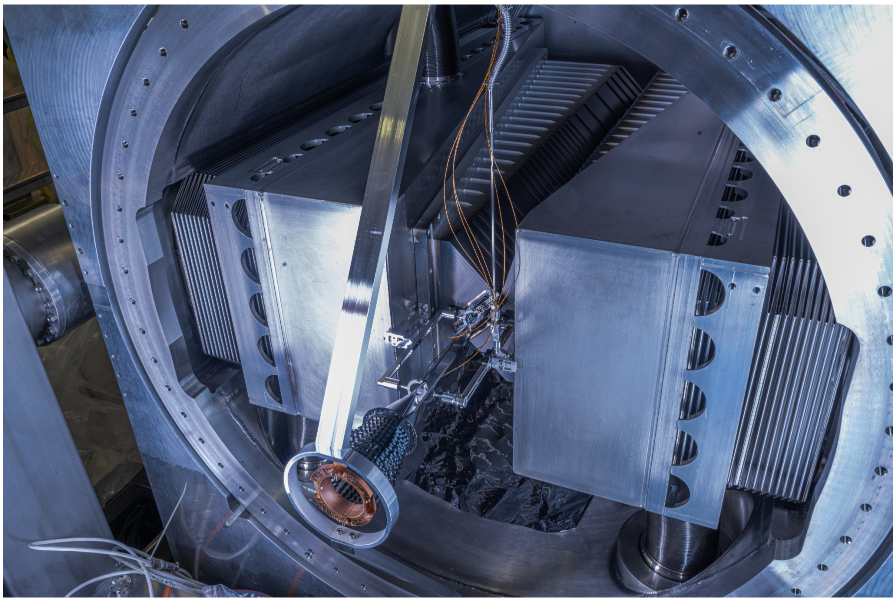

Figure 5: The installed SMOG2 storage cell with wakefield suppressor, attached to the VELO RF box in the VELO vacuum vessel at IP8.

program with a fixed target at LHCb has been presented in a dedicated report of the Physics Beyond Colliders study group in Ref. [34].

In August 2020 the storage cell was successfully installed inside the VELO vacuum vessel, see Fig. 5. 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 a 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 (GFS) installed and commissioned in March 2022. Using this system it is possible to inject precise fluxes of gas, from hydrogen to heavy noble gases. The uncertainty of the luminosity measurement has been calculated by simulations and a ∼2% has been evaluated, independently on the injected gas type or flux.

The storage cell is equipped with five temperature probes and their readout implementation into the LHCb system, together with their publication on the LHC OP page, is ongoing.

Software and trigger implementations in the Real Time Analysis framework have been completed and dedicated triggers in HLT1 have been developed too. 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. 6. In this case the oveerall data throughput increases by only up to 3% with respect to the running conditions with the p-p collision mode only. In addition, an efficient PID method using a Machine Learning technique has been developed and published for the fixed-target collisions [35].

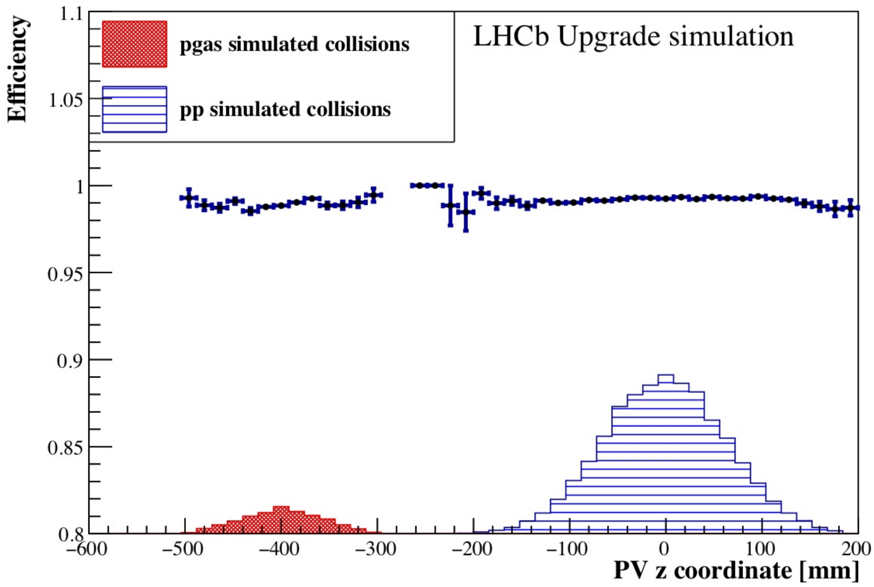

Figure 6: Velo tracking efficiency as a function of the z of the primary vertex. The simulated distributions for p-gas (left side of the plot) and p-p (right side of the plot) collisions, normalized to fit the picture, are super-imposed.

4.2 Upstream Tracker (UT)

4.2.1 System overview

The Upstream Tracker (UT) is a tracking system comprising four planes of silicon microstrip detectors and is located between the RICH1 detector and the dipole magnet. It is a crucial component of the tracking system, especially important for the software trigger at high luminosity, because it exploits the magnetic field at its location to allow a first determination of the track momentum with moderate precision.

Figure 7 shows the geographical location of the various UT components. This detector encompasses 968 silicon sensors, 80 of which are implemented with different designs to maximize the acceptance near the beam pipe and cope with the higher occupancy in the innermost region. They are read out with a dedicated front end ASIC (SALT), which provides fast analog signal shaping, digitization, common mode suppression and sparsification, and data formatting. Sensor and hybrid circuits hosting the SALT chips are mounted on stiffeners which provide mechanical support and thermal coupling to form modules. The UT modules are arranged on mechanical elements called staves. The staves provide mechanical support and cooling (CO_2 evaporative cooling). DATAFLEX circuits glued on both faces provide electrical connectivity with the near detector electronics. The UT comprises 68 staves, 52 of type A, covering the majority of the detector surface, 8 of type B, including some detectors with higher segmentation near the beam plane, and 8 of type C, featuring detectors specially designed to maximize acceptance near the beam pipe.

The near detector electronics distributes power and control signals to the front end and receives data to be transmitted to the processing boards (TELL40) at about 10 meter distance from the detector box, 4 stations host the low voltage regulator boards that provide well regulated power to the detector.

The four planes are enclosed in a thermally insulating, light and airtight box that fits around the beam pipe. The box is split into two halves and mounted on rails, so that the detector can be opened for maintenance or during beam pipe bake-out. Connectivity with ancillary systems (high voltage, low voltage, safety, control) is provided by cables and fibers routed to cable chains that allow the opening and closing movement of the two half-boxes.

4.2.2 Construction & installation

The construction of the UT components is nearly completed, the only components being processed are a few “swap staves” that will be available during the assembly phase to expedite the assembly process. Currently 40 instrumented staves have been received at CERN and are ready to be mounted on their desired location inside the detector box.

The UT installation plan encompasses three activities: installation and commissioning of services and power in the experiment, installation and commissioning

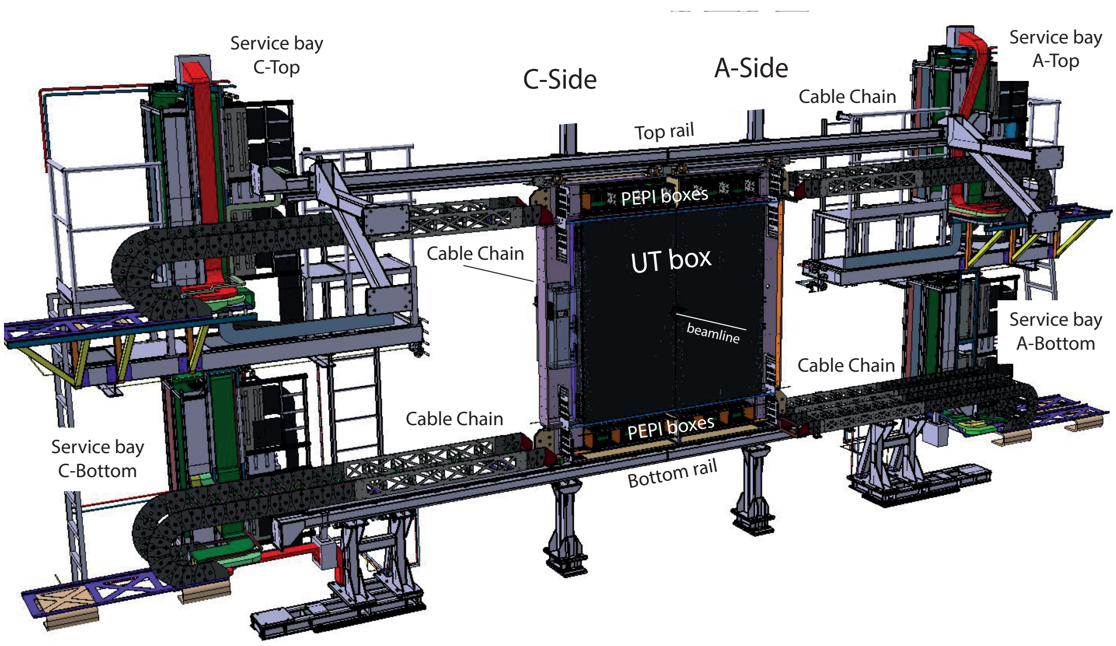

Figure 7: Components of the UT system. The box is split in two halves and mounted on rails to allow maintenance access. Four cable trays allow horizontal movement of the two box halves without putting strain on electronic cables, optical fibers and cooling fluid pipes. The Service Bays host the low voltage boards that power the near detector electronics and the hybrids, and patch panels that distribute the high voltage to the silicon detectors.

of the staves in the detector box in a dedicated clean room, and integration of these two system via the loaded cable-chain structure described below.

A major UT milestone was the assembly of the infrastructure underground in advance of the cavern closing, to be ready for an efficient integration of the detector system. This was achieved recently, and thus the integration task can be implemented according to the plan shared with the collaboration and with the CERN management.

Another important milestone was recently achieved in our assembly work in the UT laboratory at point 8: the first stave mounted at the first location chosen for population has been successfully tested electrically and has shown excellent performance. Fig. 8 shows this stave mounted and connected inside the UT-C box. It is currently undergoing thermal tests to investigate its performance at different temperatures. All the modules have been tested and perform according to specifications.

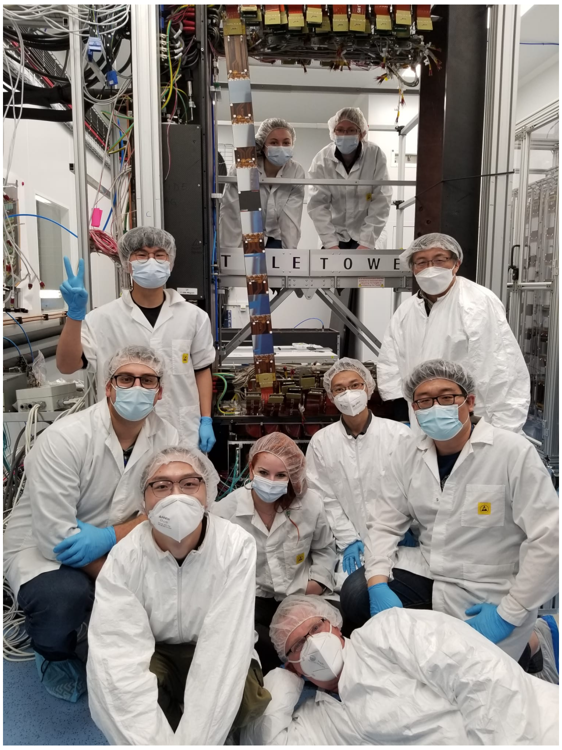

Figure 8: First instrumented stave installed in UT-C box.

4.3 Scintillating-Fibre Tracker (SciFi)

4.3.1 System overview

The technology and the design of the SciFi system is described in the LHCb Tracker Upgrade TDR [5]. The active element of 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 from the outer ends by 128-channel arrays of Silicon Photo-multipliers (SiPMs), which can be cooled to -40°C to limit the dark count rate after irradiation. The SiPM are housed in an insulated box (cold-box) which is a part of the individual modules. Flexible cables connect the SiPMs to the readout electronics: a custom-designed ASIC is followed by digital boards for clustering and further data-processing; Control and data-transmission is ensured by optical links. The readout electronics for the 2048 SiPM channels of a cold-box are mounted into a single unit, the so-called readout box (ROB). Each ROB is connected to 16 optical data links. Two bidirectional links per box allow the slow and fast control (ECS). A power connection provides the 8 V supply voltage.

The modules together with the readout electronics are mounted on 6 m $\times$ 4 m large support frames, the so called C-frames. These frames also provide the necessary service connections(low and bias voltage, optical connections, SiPM cooling) . As the power dissipation per is approximately 100 W, active cooling of the electronics is required. Water cooled mounting plates are therefore embedded into the C-frames. The necessary cooling of the SiPMs to -40°C is achieved with a separated cooling system operated at temperatures as low as $-50°$. Thermal insulation of the cooling pipes requires vacuum insulated supply lines. To avoid water condensation related to the humidity in the cavern, heating wires have been installed around cooling-pipes and cold-boxes. Dry air flushing of the cold-boxes complements the humidity management.

A C-frame comprises 2 stereo-layers of modules (x and u/v layers) mounted to it. In total 6 C-frames are installed on both sides of the beam-pipe and result into 12 stereo-layers for the track reconstruction. The 12 C-frames are installed on a support bridge between the magnet opening window and RICH2. A survey system based on BCAMs will be used to monitor the movements of the C-frames.

4.3.2 Construction & installation

All 12 C-frames have been successfully assembled, tested and installed into the LHCb detector before the experimental cavern was closed on March 24th. Since the last RRB in October 2021 the 6 C-frames on the A-side of the detector have been installed during installation campaigns in November 2021, January and February 2022. All frames are connected to the services and are ready for commissioning. A photograph of the fully installed and connected C-frames of the A-side is shown in Fig. 9. An important task which also was concluded is the exact survey of the location of the 12 C-frames and their correct closure around the beam-pipe. A reproducibility test showed that after opening, the C-frames come back to their original position within the measurement precision of 0.1 mm. As frequent interventions are expected in the coming weeks, the SciFi C-frames will be fully closed only shortly before the start of the LHCb data-taking.

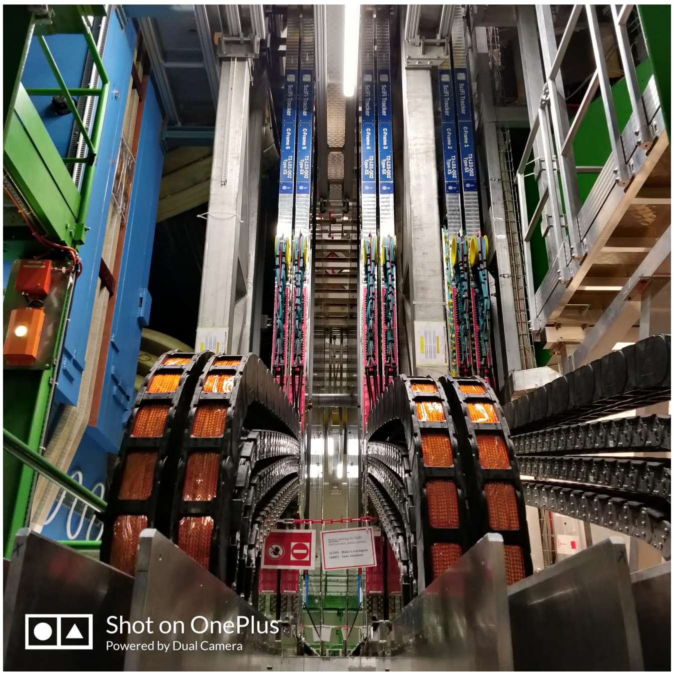

Figure 9: C-frames of the A-side fully installed and connected to services.

4.3.3 Commissioning

The commissioning of the first six C-frames installed on the C-side of the detector started at the end of 2021. The commissioning of the A-side was launched shortly after the installation was completed in February 2022.

As a first step, the Experiment Control System (ECS) via the optical control links was used to configure the front-end electronics. This allowed also the reading of temperatures and voltages. The ECS is operational for all 12 C-frames installed. As the frames are powered, the cooling of the readout boxes needs to be ensured. After initial problems the water cooling of the electronics is working stably.

The C-side frames are currently being prepared for the integration into the LHCb DAQ system. Checks of the mapping of the optical readout links have been performed and a few cabling mistakes have been spotted and repaired. The commissioning tests which were performed during the C-frame assembly before installation are being repeated using the central control and data-taking tools. These tests include timing adjustments and bit-error tests as well as threshold scans using the light-injection system. For the A-side frames the check of the optical fibre mapping has also started.

An important commissioning step was achieved when the SiPMs were cooled down to $-40°C$ at the end of March 2022. The cool-down required a working vacuum insulation of the supply lines (as vacuum better than 5×10^{-4} mbar has been achieved for all frames), an operational heating system, a working dry-gas flushing of the cold-boxes and an operational cooling plant. In addition, the monitoring of the vacuum, of the outer cold-box temperatures and of the dry gas flow through all 256 cold-boxes had to be established before cool-down. The SiPM cooling together with all elements of the condensation prevention is operating stably for all 12 frames since then.

5 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 RICH System, comprising RICH1 and RICH2 is ready to operate with beams. In particular, RICH2 has been taking real event during the pilot LHC run in November with excellent results. CO2 was used as a radiator, providing good data towards our effort to further lower the greenhouse impact for our experiment.

The calorimeter is fully equipped with new electronics systems. The hardware and software of the motion system has been replaced. The system successfully took data during the LHC beam test, and the tests were useful for debugging. The system is now essentially ready for data-taking.

The muon system has redesigned off-detector electronics and additional shielding. The detector has been commissioning since early in 2021 and took data during the LHC beam test. Recent work has been performed on the control system, data acquisition, data decoding and geometry description software in preparation for Run 3.

5.1 RICH system

5.1.1 System overview

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.

5.1.2 Construction & installation

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. New carbon-fibre spherical mirrors and glass flat mirrors for RICH1 were manufactured. 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 installed into the gas enclosure.

The gas enclosure is 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. The RICH1 gas enclosure is ready to host its photodetector cameras.

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 46 RICH1 and RICH2 Columns.

5.1.3 Commissioning

The commissioning and installation of the whole photon detector has been 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 RICHes Photodetector Arrays have now been fully commissioned, readied and installed at the pit.

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 has been successfully operated at the pilot LHC beam test. We took excellent data, which seem to confirm our expectations for the RICH system performance and further prepare for the 2022 Run 3 start (see figure 10). RICH2 was filled with CO_2 (and not CF_4), which provided essential information on the feasibility of running RICH2 with a much more environmentally friendly gas than CF_4.

5.2 Calorimeter system

5.2.1 System overview

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 sends 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.

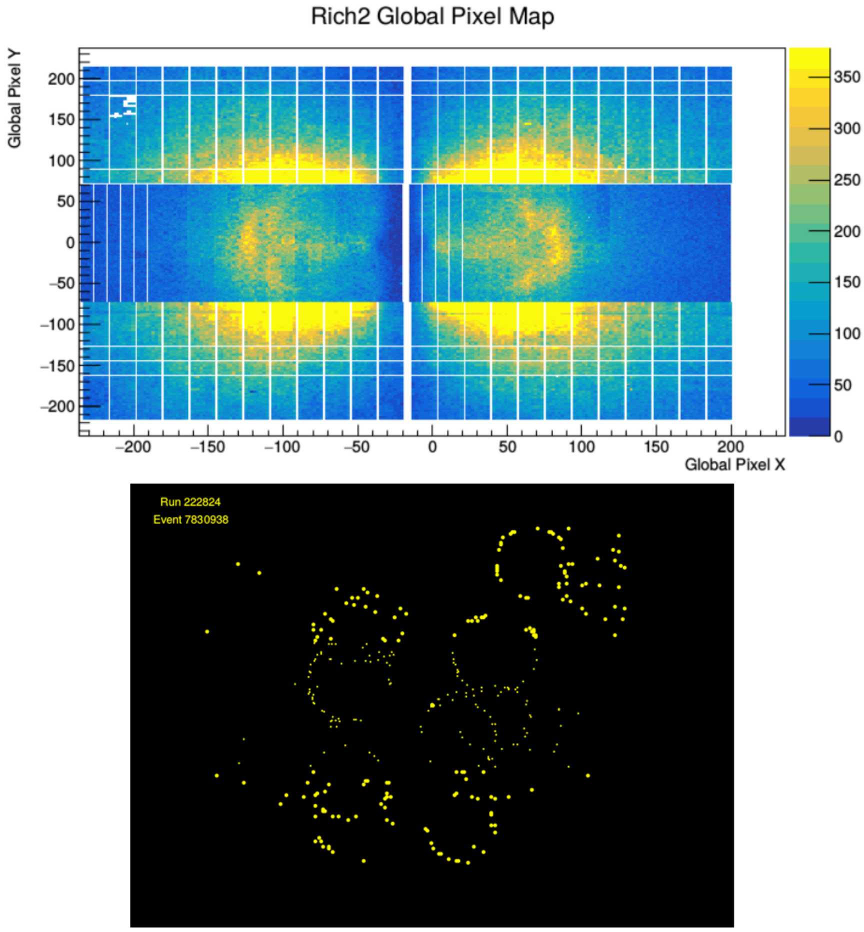

Figure 10: Top: Cumulative hitmap of RICH2 acquired in stable beams conditions; Bottom: Single event display of the Cherenkov rings detected in RICH2.

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.

5.2.2 Production and installation

Front-end electronics The production of the electronics boards was completed a year ago. The 262 FEBs needed were produced and tested at Orsay on a dedicated test bench. They are now installed at CERN in the LHCb cavern. The 18 crates that equip the calorimeter (ECAL and HCAL) have received their control boards (3CU) which are located in the central slots. They are now installed in the crates altogether with the FEBs. The inputs of each FEB have been connected to the photo-multipliers and the outputs to the optical links. The 3CU boards have also been connected to the slow control of the experiment.

High-voltage, calibration and monitoring The work for the high-voltage, calibration and monitoring systems resumed a few months ago after a pause due to the COVID pandemic. It was already well advanced before the pause and is now operational: the boards have been produced, delivered, tested, installed and connected to the control of the experiment.

5.2.3 Commissioning and software

The calorimeter system has been at the commissioning stage already for several months. It took part in the LHC beam test of October 2021 and succesfully acquired data (see Fig. 11). The system performed a first time adjustment of the different parts of the system. The test was useful uncovering some software and firmware issues and allowing them to be corrected. Issues in the decoding of the calorimeter data have been observed and fixed. The data flow at the level of the trigger also had a bug that was solved more recently.

The optical links have been thoroughly monitored and tested during the last months. The system has more than a thousand links. After installation, intermittent signals or no signals were observed on a few percent of them. This was observed during the October 20221 beam test and have been solved either by cleaning the fibers or through inspections that revealed that some ribbons were not properly plugged in its connector. An event builder equipped with several TELL40 boards was also faulty and was recently replaced.

The situation is now much changed, there only five fibers in the full system that are still faulty. By swapping links at different positions along the path between the front-end electronics and the computer farm, it is identified that the faults are localized after the last patch panel before leaving the cavern and before the patch

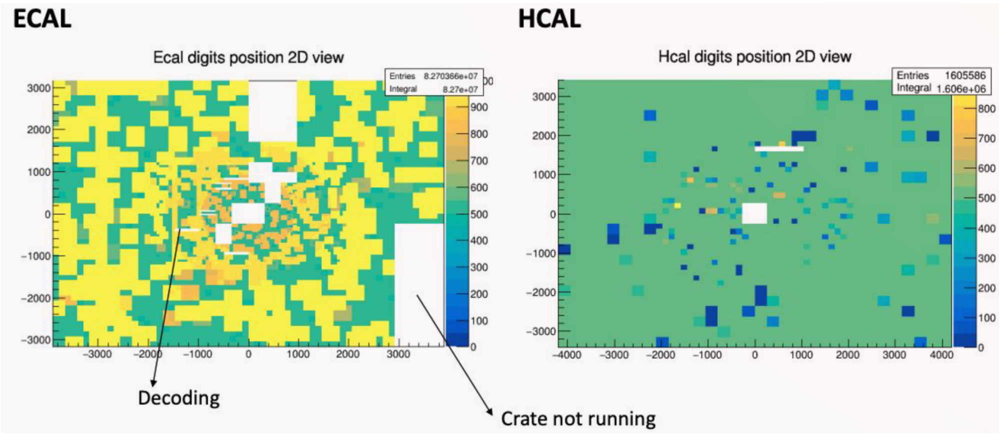

Figure 11: Picture of some events acquired during the Oct. 2021 test beam at CERN. The empty regions correspond to wrong decoding, bad connections, faulty TELL40 boards or an event builder. These have been fixed subsequently and show the importance of these tests for the commissioning .

panel that redirects the signals to the TELL40 on the surface. Spare links will be used and it is expected to soon be in a situation where all the links are operational.

The photo-multiplier cable connections at the input of the FEB were checked by using a pulser implemented on the FEB at the level of the input stage. The reflection of the pulse generated is monitored by taking runs with the central LHCb acquisition and after propagation of the pulse up to the photo-multipliers and back to the FEB. A bad connection would lead to a partial or no propagation and essentially no reflection. After a problem is identified, the connector of the cable is removed and a new one is mounted.

The software for the control of the experiment has been improved in the last months. Many new WINCC panels permit now to control, configure and monitor the electronics of the calorimeter more efficiently.

The high-voltage of the photo-multipliers is operational since October 2021. The ramp up has been improved recently by reducing the time needed from 20 to 7 minutes. Only 70 channels out of the 8000 DAC readouts that follow the HV levels have issues and generate false alarms. The voltages have been checked to be properly set and further debugging is on-going.

The TELL40 programs are now up to date and include the latest functionalities. The latest firmware has been uploaded for the high-voltage, monitoring and calibration systems.

A new version of the firmware of the 3CU and FEB, which is expected to be the final one, has been released a few weeks ago. It provides an improved management of the time and fast control signals from the experiment, a second method for the pedestal subtraction of the electronics channels read out by the FEBs (subtraction that we may use in the regions of the calorimeter with the largest occupancy) and includes some new counters for an efficient debugging of the system in the future. After a long period of tests at Orsay, the firmware has been loaded into the electronics remotely with our WINCC programs. Almost 3000 large FPGAs equipping our FEBs have been smoothly loaded with the firmware during the operation that lasted more than two days.

Since the reload of the firmware into the boards, the calorimeter is run most of the time, day and night, by the central control of LHCb in order to gain experience with the acquisition system. The plan is to configure the calorimeter soon in LED calibration mode and perform some acquisitions of the pulses produced.

A lot is being done at present to write the programs to tune the calorimeter system with the first data. The phase adjustment of the 8000 channels cannot be done without particles, but the programs are already in a well advanced stage. Similarly, the programs to tune the analog electronics should be soon ready. The online calibration programs that use the LED pulses and should be updated after each run are being prepared in parallel with the offline calibration algorithms based the π^0 mass reconstruction.

In summary, the calorimeter is mostly ready for data taking. The passive dosimeters have been installed at different positions on the calorimeter in order to monitor the dose accumulated.

5.3 Muon system

5.3.1 System overview

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, the redesign of the off-detector electronics, and the installation of a new shielding in front of the inner region of M2 to reduce by about a factor two the low energy background rate in this region.

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 the 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.

5.3.2 Construction & installation

M1 station has been removed in 2019 at the beginning of LS2. The three parts of the new shielding have been prepared and installed: the new HCAL beam-plug (lead in a steal carcass) which goes closer (up to 1 cm) to the beam pipe has been installed in 2020; the additional tungsten shielding in place of PMTs of the innermost HCAL cells has been installed in January 2021, while the improved M2 beam plug (identical to the old one, but partially made of lead) has been completed at the end of LS2, in March 2022.

All the Muon stations are equipped with the new electronic boards (144 nODE, 120 nSB and 8 nPDMS), and a sufficient number of spare boards as well as spare nSYNC chips is available in case of problems. The faulty boards can now be reworked in Frascati, thanks to the hiring of a technician expert in board processing and the possibility of an immediate test by the experts. The laboratory has been equipped in such a way as to be able to perform all the rework, including the final cleaning. All nODE and nPDM boards now mount cured VTRx components, and a heat sink has also been mounted on the AUX-SCA of each nODE.

5.3.3 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 both the control and data lines has been completed, and all the issues spotted (typically dead or noise channels) have been fixed by the end of LS2. The ECS project is well advanced in all its sub-projects, and 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 successfully took part to the test with the LHC at the end of October 2021. The detector worked perfectly as well as the ECS, while the DAQ required some more effort to get running in the global partition with the other LHCb sub-detectors. By the end of the beam test the Muon was time-aligned to the LHC clock. The whole test was very useful to define the next tests and qualifications without indicating any significant issues for a smooth commissioning at the beginning of Run 3.

A lot of effort has been also put to update the Run 1 and Run 2 Muon software to the Run 3 detector and environment. The readout cabling is much changed and required a new raw data decoding and simulation encoding software. The Muon reconstruction and identification algorithms have been adapted to the tight time constraints of the full software trigger. The removal of M1 and the new shielding required to modify the detector description and all the geometry has been ported in DD4HEP, the new open source toolkit adopted for the LHCb detector description starting with Run 3. Finally an improved modelling of the detector response to low energy background and to spillover is ready to be used in the simulation.

6 Luminometer and beam induced background monitors

During its Upgrade-I phase, LHCb has developed and equipped its interaction region area with dedicated systems whose goals are to continuously monitor luminosity and beam induced background conditions. These systems have been fully installed, commissioned and are now in preparation for first beams.

6.1 System overview

The luminosity and beam/background monitors at LHCb are composed of a set of hardware and software systems.

The PLUME detector is fully dedicated to continuously monitor in real-time the instantaneous luminosity, averaged and per bunch, and to provide a direct measure of the average number of visible pp interactions per bunch crossing (μ). The PLUME detector is synchronized with the LHC clock and in addition it is included in the LHCb Data Acquisition (DAQ) system providing such measurements for offline purposes as well, included in the event bank. The PLUME detector is a brand new detector in LHCb, based on Quartz sensors and utilizing the Calorimeter Front-End readout electronics, specifically developed and adapted for LHCb Run 3.

The Beam Conditions Monitor (BCM) is dedicated to directly measure beam losses around the LHCb interaction region and acts as LHCb primary safety interlock, dumping the beams when such losses are above specified thresholds. The BCM consists of two stations (Upstream and Downstream), each composed of 8 diamond sensors interfaced to Current-to-Frequency Converter (CFC) cards providing continuous running sums (RS) over 40 μs (short RS) and 1280 μs (long RS).

The Radiation Monitoring System (RMS) is dedicated to continuously estimate the amount of beam induced losses observed around the LHCb interaction region. The RMS is composed of 4 stations, with each composed of 2 metal foil detectors connected to charge-to-frequency converters. The change in frequency is linearly proportional to the number of Minimum Ionizing Particles (MIPs) providing an estimate of the amount of particles lost by the beams around LHCb.

PLUME, BCM Upstream and RMS are located around 1.5 m from the interaction point in LHCb, in the zone of the LHCb cavern between the VELO and the cavern wall, commonly referred to as the VELO alcove (Figure 12). The BCM Downstream is located between the Upstream Tracker and the LHCb spectrometer.

The information provided by the detectors are used in real-time to monitor the beam conditions around LHCb, feeding them to the LHCb control room for operations as well as to control the instantaneous luminosity at the experiment's location. This is paramount as LHCb plans to take data at a leveled luminosity throughout the entirety of Run 3.

In addition, each LHCb sub-detector is developing a set of so-called luminosity counters to be included in a dedicated luminosity line of the LHCb software trigger. The counters are selected based on their linearity with respect to mu and stability in time, ranging from low level observables (i.e. number of clusters for SciFi) to high level ones (i.e. VELO tracks), and will be used to determine and monitor the value of μ independently. In this way, a double goal is achieved: the value of mu is monitored online and offline at different stages and locations within the detector as well as providing a continuous monitoring of the stability of each sub-detector.

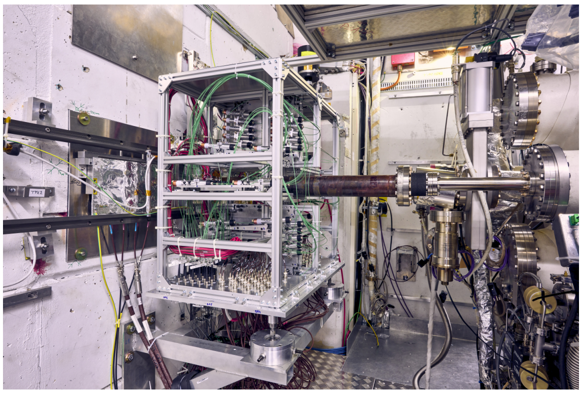

Figure 12: Picture of the VELO alcove showing the PLUME, BCM and RMS detectors.

Finally, these measurements aim at improving the precision of the final absolute luminosity determination.

6.2 Construction & installation

All the systems aforementioned have completed their construction and installation in the LHCb experimental area, as well as their readout systems and are ready for first operations in LHCb in Run 3.

The PLUME sensors are constructed and installed in a lightweight cage supporting each individual sensor. The sensors are aligned with their Z axis tilted towards the interaction point in the VELO, to maximize its Cherenkov effect and efficiency and to allow for cross-calibration with the VELO tracks. HV and LV cables were routed and connected in situ as well as its monitoring system, based on a LED calibration system. The readout system utilizes Front-End Boards from the Calorimeter and the readout cards are located in the LHCb computing data center, interfaces to the final readout acquisition system. The control systems and the readout firmware are fully ready for first beams.

The BCM stations are also fully constructed and installed. While the downstream station is installed in a collar supported around the beam pipe between the Upstream Tracker and the LHCb spectrometer, the upstream station is built on two movable plates located on the wall just behind the PLUME detector. This was done in order to allow the BCM to be reachable for intervention in the very busy space in the VELO alcove. The readout system is also ready, with a dedicated readout control system based on FPGA being finalized in the days before first beams.

The RMS sensors have been constructed and installed on the wall in the VELO alcove, with dedicated supports, LV cables and fibers fully routed. The readout systems of both the BCM and the RMS are located in the LHCb computing barracks underground, on the safe side of the cavern behind the shielding wall.

6.3 Commissioning

The luminosity and beam/background monitoring systems are finalizing their commissioning in view of the first LHC beams in Run 3. A major step was already achieved during the LHC October Beam Test where all detectors were commissioned successfully and operated for the first time, validating the full readout chain.

The BCM and the RMS systems were the first two systems to see real beams in LHCb, observing injection losses and dedicated "beam splashes" (i.e. losses deriving from beams impinging on the tertiary collimators near the triplets) around LHCb. With first beams in the upcoming months, the BCM and RMS plan to calibrate the detector response to the beam losses (expressed in number of particles) to provide real-time estimates of the magnitude of LHC beam losses. In addition, the BCM validated its interlock hardware connections to the LHC Beam Interlock System (BIS).

The PLUME detector also successfully participated in the LHC October Beam Test with a reduced detector. Only a few sensors were used at that time, with the goal of validating the full readout chain and performing its very first time alignment. This was reached within a few days of data taking with collisions as shown in Figure 13 where the detector activity, expressed in raw ADC counts from the available sensors, was time aligned to the collision bunch numbers of the LHC. Since then, the full detector was installed and all sensors have been commissioned and read out. In addition, the firmware and software functionalities have been integrated and interfaced to the central control system of LHCb.

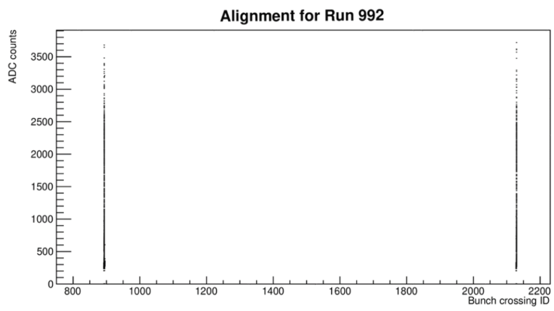

Figure 13: Plot showing the detector response as a function of the bunch identifier.

Lastly, the software and trigger infrastructure for the online and offline luminosity measurement is being completed. The software communication interfaces to the LHC have been tested and developed and the software processes to monitor and control the instantaneous luminosity have been validated. The trigger luminosity line is being finalized and included in the central software LHCb trigger. The plan is to calibrate all detectors and their responses with early minimal Van der Meer scans, as soon as first collisions will take place in the LHC.

7 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, aggregating 40 Tbits/s. It is composed of 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.

The event-builder houses the first stage of the event reconstruction in real-time, running on GPGPU. All A5000 Nvidia cards are installed in PC-servers.

The event-builder software is working well. It is used regularly for test and detector commissioning. It acquired data during the LHC test beam in October 2021.

In the container two of the data centre, the HLT2 farm runs about 1800 nodes from the legacy event-filter farm and nodes given by the IT department. Another batch from IT is under installation in container 6. The farm is currently used for Monte-Carlo production.

Disks and servers buffering data between the HLT1 and HLT2 as well as at the output of HLT2 arrived and were installed. Commissioning is ongoing.

Moving data from HLT2 output storage and to CERN EOS for permanent storage is tested. The performance is promising.

The LHC clock is connected to the online system in the LHCb data centre. It is distributed to readout modules and ECS control boards via a PON network. The throttling mechanism from readout board via PON network is being commissioned.

The Experimental control system is progressing well for sub-detectors, event-builder and HLT system. The run control is operational, allowing to manage all sub-detectors together or several subsets ("partitions") at the same time.

All detectors are fully connected to the central control system (ECS). Some detectors are still finalizing the commissioning of their connection to the readout-system (DAQ) and the Online team is actively supporting them in this.

7.2 Trigger and real-time analysis

The Upgrade trigger [6] consists of a collection of identical software tasks running on GPGPU and 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. HLT1 runs on GPGPU while HLT2 on a farm of CPU.

The full chain is tested regularly in FEST campaigns as well as the integration in the online system. In each event-builder 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 the Run Control and monitored by online monitoring tools.

Work is ongoing to integrate sub-detectors decoding optimized for GPGPU as well as sub-detectors geometry described by the DD4HEP library. In addition, we are modifying forward tracking, seeding and matching algorithms to reconstruct tracks without the UT sub-detector for initial operation. Selection lines will be adapted accordingly. All the required no-UT algorithms exist in draft form and will be ready for deployment in time for the start of beam commissioning.

The Allen and Moore software will be frozen at the end of April in order to have a stable running versions for the commissioning with first beams, and subsequently updated for the first stable beam collisions anticipated in June.

7.3 Data processing

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

The data processing centralizes *Sprucing* of a significant fraction of the HLT2 output data, as well as *Analysis Productions* for physics working groups and users. *Analysis and preservation* of legacy LHCb data and related software is also dealt with.

The main developments in the project are on the Sprucing processing step, in order to digest input data and to handle many selection lines from physics working groups, keeping the output bandwidth as low as possible.

The analysis productions are a centralised way to produce ntuples that are subsequently utilised for physics measurements. Jobs are run on WLCG via the LHCb-Dirac software. Work is ongoing to finalise the infrastructure allowing physics working groups to submit their jobs, monitor them and retrieve output data. The system has been in use for analyses on the legacy data since over a year.

On the analysis tools front, modern, thread-safe and flexible tools are in preparation. In particular, a new ntuple making framework has seen the light and a first version is under stress-tests by early consumers such as analysts preparing early measurements.

7.4 Computing and offline processing

The computing and offline processing systems are being commissioned for the start of data taking. The software framework for the detector description with the DD4HEP tool has been completed and validated. The migration to python3 has been completed for both core software and distributed computing. The refactoring of the continuous integration system and a new CMake toolchain are being finalised.

In the distributed computing domain, data transfers from the LHCb online system to the CERN Tier0 tape system (CTA) have been tested at a sustained rate of 16 GB/s, thus exceeding the 10 GB/s nominal rate. Tape challenges have been successfully performed in March together with the other LHC experiment, to verify that the overall throughput for writing to and reading from tape satisfies the required levels.

The use of High Performance Computing centres (HPC) continues to be investigated. The CSCS and SantosDumont centres in Switzerland and Brazil are in production. The allocation at NERSC in the USA has been exhausted. The MareNostrum partition at the Barcelona Supercomputing Center in Spain has been successfully configured for production; a few jobs are currently in execution, with a ramp-up in plan. The Marconi/100 partition at CINECA in Italy has been configured as well, with pilot jobs in execution and a few user workloads running locally.

8 Infrastructure and Installation

8.1 Infrastructure

As the general LHCb infrastructure has been completed since a year now, the technical coordination team has focused their activities on the near detector equipment and structures. All installed sub-detectors are connected to their cooling system, and commissioning is in full swing.

The magnet went through a complete final check together with the EP/DT group and the LHC operation team. The LHCb dipole has been powered to its nominal current several times without any problem. Furthermore, the movements of both coils have been carefully monitored. The monitoring system was installed together with a major consolidation work of the support structures of both coils.

Transport tools for the Upstream Tracker (UT) have been finalized and a test installation of one empty detector box has been successfully completed early this year. The design of access structures around the UT service systems have been completed, constructed and installed.

All materials in the experimental cavern that is not required for the operation of the LHCb detector have been removed and brought to the surface where they will be sorted in a temporary tent. The cavern was closed on the 24 March as scheduled. Before the cavern closure the entire area around the detector was painted.

The floor of the platform close to the magnet on side C has been renewed and modified to properly transport the VELO C-side to the VELO alcove.

The general smoke detection of the cavern has been considerably improved with higher granularity adding two additional sensors.

Work on the Detector Safety system is ongoing and the individual safety matrix of each detector system is being verified with detector groups and tested.

8.2 Installation

All detectors have been installed, except Velo side A and the UT detector. Velo side A encountered some leak problems when assembling. The LHCb management supported the decision that was proposed by the Velo group to plan for an installation after the cavern closure and not compromise any detector efficiency. The final installation is planned for the first weeks in May.

The SicFi group installed the remaining six C-frames on side A on time. All C-frames are now aligned, closed, and cooled down. Extensions of the existing access platforms to the SciFi were mounted. In addition, the BCAMs for monitoring the movements of the detector during operation are now in place.

RICH1 team completed the installation of all MaPMTs and the heavy side shielding has been mounted onto the structure.

To protect the beam pipe from the low temperature of the UT, aerogel patches with heating layers have been wrapped around the beam pipe in the region of the Upstream Tracker. Cables for this system have been pulled up to the controls equipment. Services for side C have been all installed, ready for the installation of the UT C side and its cable chain. The installation is planned once the C side box is fully equipped with detector staves and tested. LHCb is aiming for an installation in September 2022.

A noise reduction shield has been installed on the new Data Center. The noise level was slightly surpassing the new regulation at CERN. A final measurement will be performed during the summer period once the maximum heat load is reached.

Finally, the SAMs (Sample Activation Mateials) have been re-installed all over the LHCb detector. These samples will be checked and compared to the radiation simulation results during a longer technical stop or shutdown.

9 Project organization

9.1 Project organization

The Upgrade I detector is overseen by the LHCb Technical Board. The Technical Board is chaired by the Technical Coordinator and is comprised of all detector project leaders. Day-to-Day detector work is overseen by the technical coordination team. The Commissioning of the Upgrade I detector is overseen by the Commissioning coordinator and discussed at commissioning meetings, with representation from all projects. Operational aspects are overseen by the Operations Coordinator and discussed at the Operations Planning Group, with representation from performance working groups, software projects, and relevant task forces.

Coordination between the software projects are overseen 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 development of the Upgrade II detector design is overseen by the Upgrade II Planning Group.

9.2 Funding

During 2021 the status of the M&O Cat.A and B accounts was only slightly affected by the Covid-19 situation. Difficulties in getting the right collaborators on site has become more manageable, although for some countries the arrangements remained quite complex. As expected no cash flow issues were present, as all members have contributed to the budget. The expenditure on the 2021 M&O Cat.A budget followed well our forecasts. According to the financial plan for the M&O Cat.A levels, which was 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 was 3,070 kCHF for the year 2021. The book closing on the 2021 M&O Cat.A shows sustained activities and a balanced budget. For the year 2022, we foresee important maintenance activities, especially on services, gas and cooling systems and further improvement of safety. The online will see a completely new scheme with a GPU farm side-by-side with the more classical CPU farms and powerful network infrastructure, therefore we expect a certain stress also in this sector. However, we are confident that the budget levels will be respected and no cash flow issues will appear, providing the commitment and help from our Funding Agencies will not falter. We are studying all options to face the new tragic international crisis, with priority on the protection of our experiment and its resources. The contributions of Ukraine and Russia to the experiment are further discussed in section 9.

A smooth transition is requested by the sub-detectors projects for their M&O Cat.B. This is 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 well. Most of detectors have been installed and are in their commissioning phase. Spending of CORE funds is essentially finished. 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 and possibly 2023, in order to achieve the best value for money.

The Upgrade construction project is thus drawing to a close and has been achieved within the agreed cost envelope. No request for further funds has been put forward.

10 Upgrade II

A future upgrade of the LHCb detector capable of integrating up to $300\,\text{fb}^{-1}$ throughout the full HL-LHC phase was proposed in Ref. [14], with details on the physics reach discussed in [15]. The project consists of a major change of the detector during LS4, in order to sustain an instantaneous luminosity of 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 [36], 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. Fig. 14 shows the expected integrated luminosity profile of LHCb throughout the HL-LHC era.

The project components, cost-envelope and options being investigated for descoping are defined in the Framework TDR [16], which has recently been reviewed by the LHCC. The LHCC has recommended to perform "the R&D necessary to complete technical design reports on the proposed schedule". A brief summary is reported in the following sections.

10.1 Detector overview

Performing flavour physics in the forward region at a peak luminosity of 1.5×10^{34} cm^{-2}s^{-1} presents significant experimental challenges. The expected number of interactions per crossing is around 40, producing ~ 2000 charged particles within the LHCb acceptance. Radiation damage also becomes a greater concern for most detectors, with *e.g.* neutron fluences reaching 6×10^{16} 1 MeV $n_{\text{eq}}/\text{cm}^2$ in the innermost irradiated region of the VELO. On the other side, the exploitation of the physics programme assumes that the Run 3 detector performance is maintained

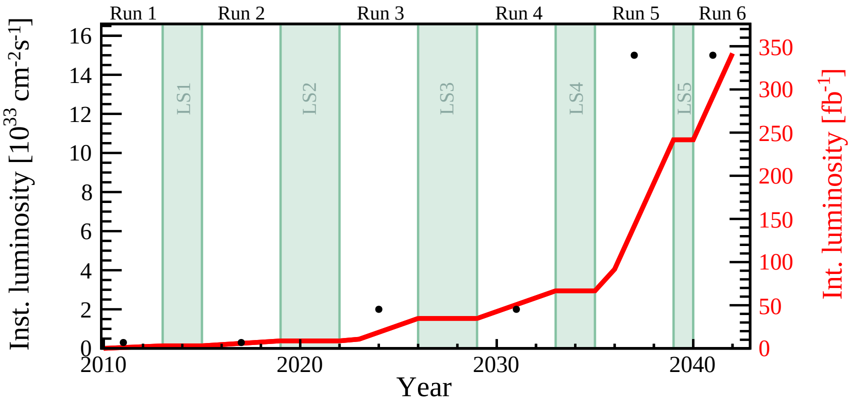

Figure 14: Integrated luminosity profile for the original LHCb, and the one expected for Upgrade I (Run 3 and 4) and Upgrade II (Run 5 and 6) experiments. The points and the left scale indicate the anticipated maximum instantaneous luminosity whilst the solid line and right scale indicate the accumulated integrated luminosity.

also at Upgrade II, and even improved in certain specific domains. The design proposed in Ref. [16] is based on the present spectrometer footprint, with all the detector components being upgraded in order to meet the desired specifications. Among the distinctive features of the new design is the capability of providing fast-timing information with resolution of few tens of ps per particle, which at very high pile-up becomes an essential attribute for suppressing combinatorial background. As an example, a new VELO detector will be designed to provide a similar spatial resolution as the Upgrade I detector, but adding a 50 ps resolution time-stamp per hit, thus becoming the first 4D-tracking device of this type.

For the tracking system, high granularity silicon pixel sensors appear to provide a solution to cope with high particle density in the UT and in the central region of downstream tracker (MT in the following), and to minimise the incorrect matching of upstream and downstream track segments. The emerging radiation hard DMAPS technology is a strong candidate for the above detectors. The outer region of the MT will be still covered by scintillating fibres, as in Run 3, with significant developments required to cope with the radiation damage. As a new feature with respect to Upgrade I, additional tracking stations will cover the magnet side walls, thus increasing the acceptance for low-momentum particles.

The excellent performance of the PID detectors of the current experiment will be maintained for Upgrade II, and in some cases enhanced. The RICH system will be a natural evolution of the current detectors, with SiPMs considered for replacing the multi-anode PMTs due to their higher granularity and excellent timing performance. In particular, a single photon time resolution of a few tens of picoseconds is required to obtain a significant suppression of the combinatorial background. In addition, to meet the required performance it will be also necessary to achieve a Cherenkov angle resolution of ~ 0.2 mrad, a factor of three better than Run 3. As an additional feature to boost the PID performance at low momenta, a time-of-flight detector (TORCH) is proposed, to be installed in front of RICH2. The new ECAL baseline implements a SpaCal design for the innermost highly irradiated region, while keeping Shashlik modules for the outer part. For SpaCal, a combination of tungsten absorber and novel very radiation hard crystals fibres or lead and polysterene fibres will be used for expected doses above and below 200 kGy, respectively. A double readout with longitudinal segmentation of the modules could be used on the whole calorimeter, in order to achieve a timing resolution of the order of few tens of ps, which will guarantee the needed background reduction. The baseline design will replace the hadron calorimeter by additional shielding in front of the muon detector. Finally, for the muon system itself new detectors will be needed to replace MWPCs in the innermost region of all stations, with a design possessing both high granularity and high rate capability. A promising candidate for this purpose is the $\mu-$RWELL, a new type of Micro-Pattern Gaseous Detector based on the same principle as the GEM and exploiting a very similar manufacturing process.

10.2 Project timeline and R&D phase

The detector challenges described above will require a dedicated R&D effort in the next ~ 4 years, in parallel to the Run 3 of LHC, to develop new technologies for tracking and particle detection, front-end electronics and data acquisition systems. Between the end of Run 3 and the beginning of LS3 the TDRs of the subdetectors will be issued, and an MoU for the Upgrade II project will be submitted for approval. The construction phase will then start, which will cover the following ~ 6 years, spanning over LS3 and Run 4. This timeline has sufficient margins to guarantee a timely delivery of the detector components for installation at beginning of LS4.

The R&D programme, which has already started in many areas, is extensive, and requires proper planning and a strong support in terms of resources. However, the technological developments needed to face the very challenging experimental conditions of HL-LHC in the forward direction will represent a bridge towards projects based at future accelerators, so that synergies between the different initiatives in this field will be highly beneficial. A few key points are highlighted below (more details in Ref. [16] and references therein):

- For the VELO, candidate sensor technologies such as LGADs and 3D are being pursued to deploy 4D tracking with the required space and time resolutions, and respecting the extreme radiation hardness requirements. In particular, promising results have been obtained by a few different groups especially with 3D devices. For the ASIC, the direction is towards exploring the 28 nm CMOS technology, which is the candidate for next generation ASICs in HEP.

- For the UT and MT silicon pixel detectors, the goal is to develop DMAPS designs capable of being realised in modules at scale, facilitating the first major radiation-hard detectors to be constructed from this technology. This is a very promising and cost effective option for large area pixel detectors, with many solutions developed in recent years.

- For the outer part of MT detector, work is needed to extend the limits of usage of scintillating fibers coupled to SiPMs in regimes of high irradiation by testing new scintillators based on nano-organic luminescence (NOL) materials, by exploiting the cryogenic cooling to decrease the SiPM dark counting rate, and by implementing the concept of micro-lens enhanced SiPMs to improve the light yield.

- For the ECAL, an intense activity is ongoing to characterise in test beams the prototypes of the SpaCal modules equipped with novel very radiation hard crystal fibres for the central region of the calorimeter, and to evaluate the timing performance of SpaCal modules equipped with polystyrene fibres and of Shashlik modules.

- For RICH detectors the photon sensor candidates are SiPMs, which will need to operate at fluences for single photons in excess of $10^{11} n_{\mathrm{eq}}/\mathrm{cm}^2$, for the first time and at cryogenic temperature. The TORCH project, which has a similar time performance target, is instead developing novel MCP-PMT sensors for photon detection. In addition, for both projects a specific ASIC is being designed (FASTIC+TDC), with the goal of implementing a first version already for Run 4.

In addition to the R&D programme, another aspect to be considered in connection with the project timeline, is the infrastructure preparation. Indeed, given the extended duration of the LS3, which needs to accomodate the ATLAS and CMS phase II upgrades, it is optimal for LHCb to profit to prepare the infrastructure of Upgrade II to facilitate a shorter LS4 and thus less disruption to the ATLAS and CMS operations. The major machine infrastructure factor on the schedule is identified as the construction of the shielding wall needed to protect the LHC cryogenic facilities which are housed in the UX85 cavern, just beside the LHCb detector. This construction work, will necessitate the relocation of bulky and sensitive equipment in the close proximity of LHCb, and will require ~ 21 months of work. A detailed estimate of the interference between the construction of the shielding wall and of the Upgrade II detector installation still needs to be made, but very likely ~ 1 additional year would be needed to carry on both operation in parallel during LS4 as compared to detector-only installation. To conclude, we reiterate the importance of performing the above shielding wall installation during LS3, to optimise the duration of LS4.

10.3 Detector scenarios and financial envelope

The detector design proposed as a baseline for this project is to operate at a peak luminosity of 1.5×10^{34} cm^{-2}s^{-1}, collecting 300 fb^{-1}, and taking full benefit of the potential of the HL-LHC for flavour physics in the forward region, within the bounds of the detector technology evolution that can be reasonably expected in the next years. The capability to function at high occupancy will facilitate the collection of the largest possible data sample, while the new detector's attributes will expand its sensitivity to a wider range of physics signatures. The cost estimates for the baseline design of all subsystems are listed in Tab. 2. The total cost envelope

Table 2: Cost estimates for all subsystems to be installed at LS4 in baseline scenario.

Detector	Baseline (kCHF)
VELO	14800
UT	8900
Magnet Stations	2300
MT-SciFi	22400
MT-CMOS	19500
RICH	15600
TORCH	9900
ECAL	34800
Muon	7100
RTA	17400
Online	8900
Infrastructure	13500
Total	175100

for the baseline design amounts to $\sim$ 175 MCHF. This is significantly larger than for the previous version of the detector.

Descoping options are also being considered, with the purpose of significantly reducing the overall budget by removing important features of the detector. A common theme for the scenarios under study is the assumption of a substantial reduction of peak luminosity, $\sim$ 30% at least, which would be accompanied by a similar decrease of detector occupancy and data throughtput. This would help in reducing the detector complexity and cost, a relevant example of this being *e.g.* the reduction in size of the online farm, but still not sufficient for a substantial budget reduction. Directions of investigations for all subsystems are described in Ref. [16], with a couple of examples given below. The first is driven by technology, and consists of significantly reducing in the MT detector the area covered by silicon pixels, which essentially relies on developing radiation-hard scintillating fibres to cover a larger fraction of the acceptance, and to implement a cryogenic cooling for the SiPMs. The second is driven by physics performance, and consists of relaxing the constraints on the background rejection in the ECAL, and keeping a large fraction of the present Shashlik modules, which are not equipped for longitudinal segmentation and dual readout, in the outer region of the calorimeter.

When considered all together, the descoping options could bring down the total cost of the experiment by ~ 25 % to ~ 130 MCHF. However, the final reach will depend on the results of the R&D on technology and on dedicated physics performance studies, which is where the future activity will concentrate, in order to better define the content and scope of the descoped scenario.

11 Collaboration matters

The collaboration continues to grow, having added a further institute in this period. The collaboration has 1056 authors at the time of writing. Lanzhou University has joined as an associate member group with particular interest in the Upstream tracker for Upgrade I and a CMOS-based replacement for Upgrade-II. They have physics interests in charm baryon decays and hidden charm exotic hadrons.

11.1 War in Ukraine

LHCb supports the statements of the CERN Council on the war in Ukraine:

"CERN condemns, in the strongest terms, the military invasion of Ukraine by the Russian Federation and deplores the resulting loss of life and consequent humanitarian impact. CERN wishes to express solidarity with our Ukrainian colleagues, their families and the entire Ukrainian people. Our thoughts are with everyone whose life has been disrupted by the war."

The LHCb Collaboration has institutes in Ukraine and in Russia. The contributions from Ukraine will inevitably and regretably be much affected by the situation. For Russia, the CERN Council has said that its session in June 2022 may consider the suspension of the international cooperation agreements and requested information to inform its deliberations. The contributions from these countries are described below.

11.1.1 Ukranian institute contributions to LHCb

LHCb has 15 registered members at the Ukrainian institutions and a further 12 Ukrainian nationals at CERN and other institutions in the collaboration.

LHCb has four institutes from the Ukraine. Two are founding members of the collaboration:

- Institute for Nuclear Research of the National Academy of Sciences (KINR), Kyiv, Ukraine

- NSC Kharkiv Institute of Physics and Technology (NSC KIPT), Kharkiv, Ukraine

And two joined recently as technical associate members (for Upgrade I luminometer (plume) and Upgrade II ECAL):

- Taras Shevchenko National University of Kyiv, Kyiv, Ukraine
- Institute for Scintillation Materials, Kharkiv, Ukraine

The total outstanding Ukranian M&O A contribution is 356 kCHF at the end of 2021. We will be considering a proposal to cancel this debt at the forthcoming LHCb Collaboration Board. If this were recommended, we would consult the RRB at our meeting. We would not be requesting additional funds from the RRB for this.

For LHCb Upgrade I they have provided a new radiation monitoring system (see section 6). This system was entirely designed and produced in Ukraine. They have taken a leading role in the design, testing, installation and commissioning of the Plume luminometer.

11.1.2 Russian institute contributions to LHCb

The LHCb collaboration counts 148 active members from 11 Russian institutes.

- Institute for Nuclear Research of the Russian Academy of Sciences (INR RAS), Moscow, Russia
- Institute of Theoretical and Experimental Physics NRC Kurchatov Institute (ITEP NRC KI), Moscow, Russia
- Institute of Nuclear Physics, Moscow State University (SINP MSU), Moscow, Russia
- National Research Centre Kurchatov Institute, Moscow, Russia
- Budker Institute of Nuclear Physics (SB RAS), Novosibirsk, Russia
- Petersburg Nuclear Physics Institute NRC Kurchatov Institute (PNPI NRC KI), Gatchina, Russia
- Institute for High Energy Physics NRC Kurchatov Institute (IHEP NRC KI), Protvino, Russia, Protvino, Russia
- National Research Tomsk Polytechnic University, Tomsk, Russia
- National Research University Higher School of Economics, Moscow, Russia
- National University of Science and Technology “MISIS”, Moscow, Russia

- Yandex School of Data Analysis, Moscow, Russia

The balance of Russian M&O contributions is:

- Outstanding from 2021: M&O A: 200 kCHF, M&O B: 135 kCHF
- Expected contributions for 2022: M&O A: 220 kCHF (institutes) 83 kCHF (universities), M&O B: 135 kCHF
- Total outstanding 2021/22: 773 kCHF

In the LHCb collaboration we have registered as based at CERN 19 members of Russian nationality working for a Russian institute.

LHCb operations and technical coordination during Run 3 rely on a core resident team of approximately 15 people with Russian institute affiliation, plus additional staff visiting on a regular basis. The Technical Coordination relies on 6 resident technicians and technical engineers and 1 resident engineer for design and project management. Their current tasks include support for the construction and installation of the Upstream Tracker, data centre server installation and cabling, consolidation of detectors and tooling and the dismantling of the detectors removed during LS2.

On the detector side, the Russian teams are involved in the muon, calorimeters, scintillating fibre (SciFi), and vertex detector (VELO), and computing operations. They have project leadership roles in the calorimeters (ECAL and HCAL) and Muon systems, which rely heavily on the Russian teams for maintenance and calibration during Run 3, including some elements where all knowledge currently resides in the Russian teams. A further small number of individuals play key operational roles in the VELO, offline data management and online data monitoring. Institutes are currently constructing muon chambers in Russia for insertion during a year end technical stop in Run 3, as this project moves towards installation the number of people from the team present on the CERN site will increase. The Russian team produced fibre mats for the SciFi detector, where it is considered that inner modules may need to be replaced LS3. The teams are heavily engaged in R&D for the ECAL where it has long been known that replacement of at least the most inner modules will be needed in LS3.

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