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Plans and status of the LHCb upgrade

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LHCb (Large Hadron Collider beauty) is a high precision experiment dedicated to searching for New Physics beyond the Standard Model in the heavy flavour sector. Since LHCb is optimised to perform indirect studies and is sensitive to mass scales potentially larger than the LHC energy it is playing a key role in broad searches for New Physics phenomena. This expectation is supported by many intriguing anomalies, especially related to rare decays and lepton flavour universality, observed and reported by LHCb. Thus, it is essential for LHCb to enter the high luminosity phase and continue data taking beyond LHC Long Shutdown 2 (LS2). The LHCb experimental setup will undergo a major upgrade that is being planned for the LHC Run 3. Here we will discuss selected aspects of this project.

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1. Introduction

LHCb (Large Hadron Collider beauty) [1] is an experiment that has been designed to perform precise heavy flavour physics measurements and search for New Physics at the LHC [2]. The LHCb detector is a single arm forward spectrometer that aims at providing measurements that are either complementary to or more precise than those performed by the general-purpose ATLAS and CMS experiments. LHCb features the most precise tracking system at LHC and is designed to operate at instantaneous luminosity[2] of $\mathcal{L} = 4 \cdot 10^{32}$, which is more than one order of magnitude smaller than the luminosity provided by the LHC machine to ATLAS and CMS. The main motivation for that is obtaining much less busy environment (with one visible proton-proton interaction per beam crossing), which allows high precision studies to be performed. A schematic view of the LHCb spectrometer is presented in Figure 1.

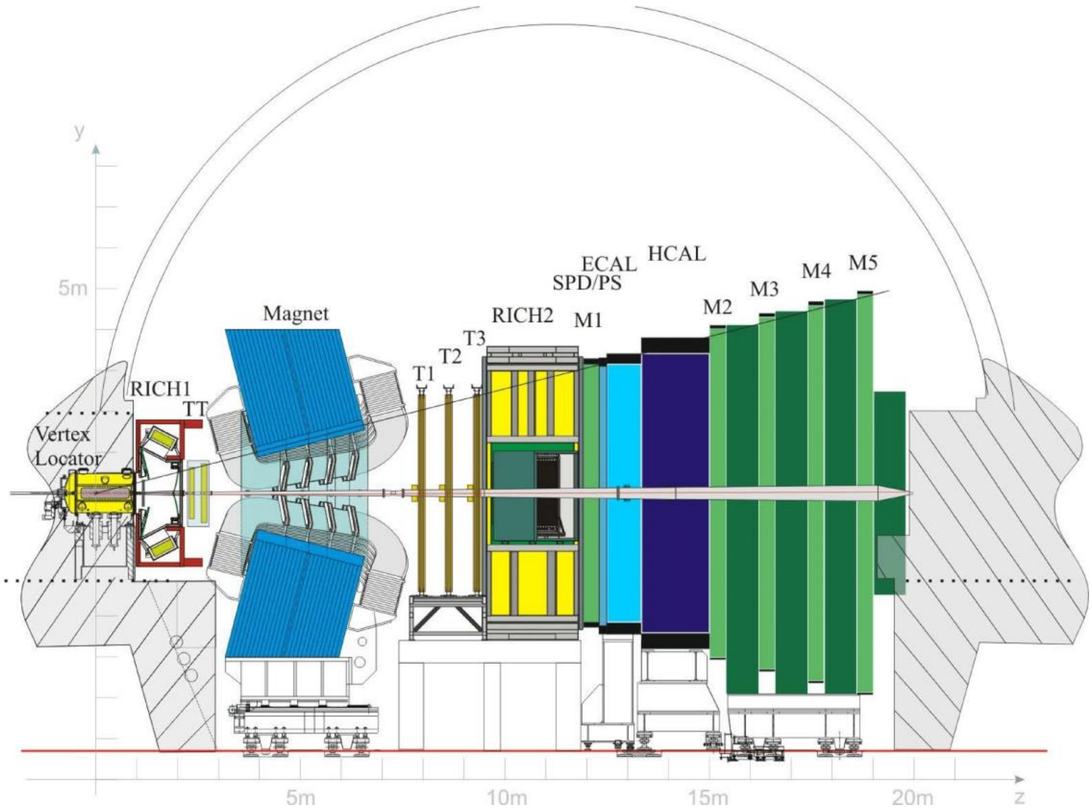

Figure 1. Schematic view (side cross-section) of the LHCb spectrometer. The experimental setup comprises of (starting from the left-hand side): Vertex Locator (VELO), RICH1 (Ring Imaging Cherenkov), TT tracking stations, magnet, tracking stations T1 – T3, RICH2, muon chamber M1, SPD/PS (Scintillating Pad Detector/Pre-Shower), electromagnetic and hadronic calorimeters ECAL and HCAL, muon chambers M2 – M5.

[2] The nominal design luminosity of the LHCb spectrometer was $\mathcal{L} = 2 \cdot 10^{32}$, however, during the initial operation the performance of the tracking system and trigger allowed to push it up. At the end of Run 1 the instantenous luminosity at which the detector performed stably was 100 % higher than the nominal one.

Both the machine and detector performed extremely well, allowing for great improvements with respect to the B-factories, observation of the rarest beauty meson decay into a pair of muons: $B_s \to \mu^+\mu^-$ [3] and discovery of pentaquarks [4]. Also, LHCb reported a number of interesting anomalies related to the flavour sector which caught a lot of attention from theorists. To pursue further these exciting results and fully exploit the flavour physics potential of the LHC, the LHCb detector requires an upgrade. In the following text, we describe the physics motivation and general aspects of the modernization project. Next, we give a short description of changes foreseen for the detector sub-systems.

2. General aspects of the LHCb upgrade

From a technical point of view the LHCb upgrade is driven by two key factors. Firstly, we want to exploit better the machine potential and collect more data. At present the first, hardware based, trigger layer constitutes a barrier which cannot be surpassed and limits the amount of data taken each year to a maximum of about $2\ \mathrm{fb}^{-1}$. Secondly, most of the detector's sub-systems would not be able to cope with higher luminosity due to obsolete readout electronics and the radiation induced damage sustained by them during Run 1 and Run 2 data taking. The initial ideas regarding the upgrade have been formulated already in 2011 [5] and took final shape in 2012 when the Technical Design Report for the LHCb upgrade was released [6]. The most crucial point of the entire project is to build a reliable and robust detector capable of operating at higher luminosity without compromising the excellent physics performance of the current detector. This, in turn, cannot be achieved by redesigning the hardware components of the setup alone but must be followed by an innovative trigger system, as increasing the data rate without ability to accordingly increase the trigger efficiencies would defeat the purpose of the entire project. Another critical part of the modernization process is the new trigger-less front-end electronics capable of reading out the full detector at 40 MHz, i.e., at the machine clock. Completely new and novel chips have been designed and initially tested for the pixel sensors [7], silicon micro-strip tracker UT (upstream tracker) [8] and RICH detectors [9].

The upgraded detector will operate at the instantaneous luminosity of $2 \cdot 10^{33}\ \mathrm{cm}^{-2}\mathrm{s}^{-1}$ which allows to collect more than $5\ \mathrm{fb}^{-1}$ of data per year[3]. To cope with the much higher event rate (five proton-proton interactions per beam crossing) a flexible fully software trigger will be employed and coupled with re-optimized network capable of handling multi terabytes data stream. The upgraded trigger will process every event (the visible rate at the LHCb is estimated to reach 30 MHz) using information from every sub-detector to enhance its decision and maximize signal efficiencies – especially for the hadronic channels.

3. Tracking system

The upgraded tracking system will comprise the Vertex Locator (VELO), Upstream Tracker (UT) and Scintillating Fibre tracker (SciFi). All these new systems feature larger granularity that ultimately allows to more complex pattern recognition requirements in a high pile-up environment to be fulfilled and cope with a much higher integrated radiation dose. They are expected to perform sufficiently well after accumulating approximately $50\ \mathrm{fb}^{-1}$ of data. Extra attention needs

[3] Given that the machine performance will be similar to the one during Run 1 and Run 2

to be given to the VELO that will operate in harsh radiation environment. The closest, innermost active part of its pixel sensors, will operate at merely 5 mm from the proton beams where the particle fluence can reach almost $1.0 \cdot 10^{16}$ 1 MeV n_{eq}. At the upgrade, the hardware trigger will be replaced be replaced by a novel trigger-less system with output rates of up to 40 MHz. All tracker system components must be equipped with readout electronics that comply with this new trigger scheme. There are many challenges related with the design of such front-end chips that need to be able to perform initial raw data pre-processing and digitization on detector.

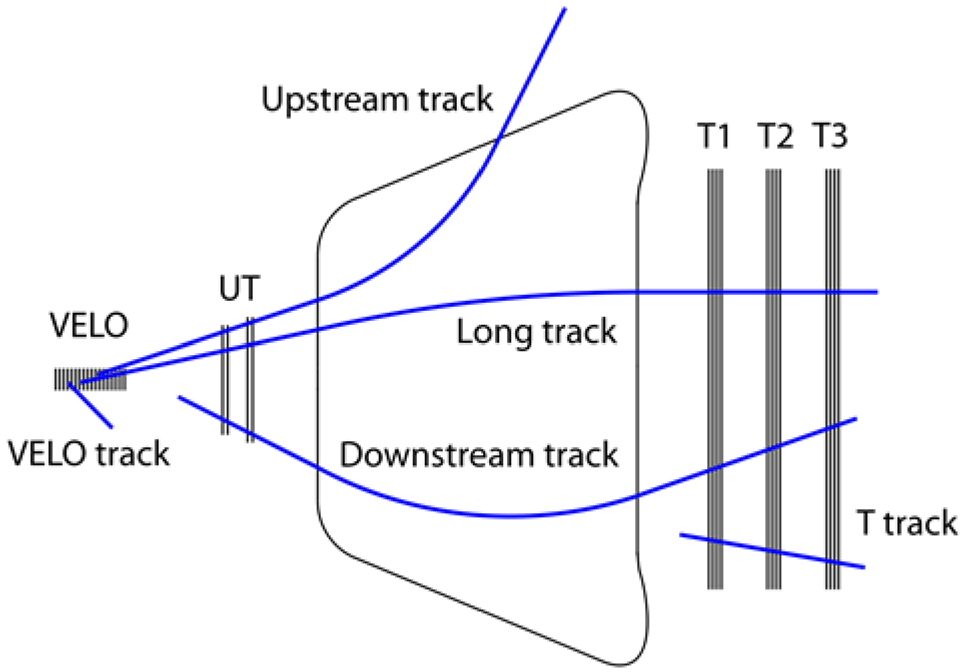

Figure 2. Schematic view of the tracking system of the upgraded LHCb detector. The relative position of the respective sub-systems is also visible with VELO and UT providing measurements before the magnet.

3.1 Vertex Locator

The principal task of the current VELO is to enable LHCb to trigger on and reconstruct displaced vertices, as well as playing a significant role in the tracking. It must cover the full momentum and angular range of the LHCb detector. Its role in the trigger system is crucial since it can provide impact parameter measurement that can be used to significantly reduce the minimum bias event rate. The information from the VELO is critical to identify characteristic displaced vertices of heavy flavoured particles, thus, in fact enabling the core physics programme of LHCb. The current VELO consists of 84 single-sided radial (R) and azimuthal-angle (ϕ) measuring silicon micro-strip sensors operated in a secondary vacuum inside the LHC beam pipe. One R- and one ϕ-type sensor are paired and mount on each side of a VELO module that is cooled by evaporative CO_2 circulating in stainless steel pipes embedded within aluminum pads which are mounted to the base of the module. The detector is divided into two moveable halves, allowing it to retract during LHC injection, with modules arranged perpendicularly to the beam (see Figure

3). The modules are separated from the primary vacuum with an $300\ \mu m$ thin aluminum foil (RF-foil).

Since the vertex detector plays a central role for the trigger system, as explained above, the modernized detector must at least maintain or improve its physics performance while delivering readout at 40 MHz in the high luminosity condition of the upgrade. This can only be achieved by a complete replacement of the silicon sensors and front-end electronics. Sufficient granularity, needed for efficient tracking, and radiation hardness can be achieved with a device based on based on silicon hybrid pixel sensors[4].

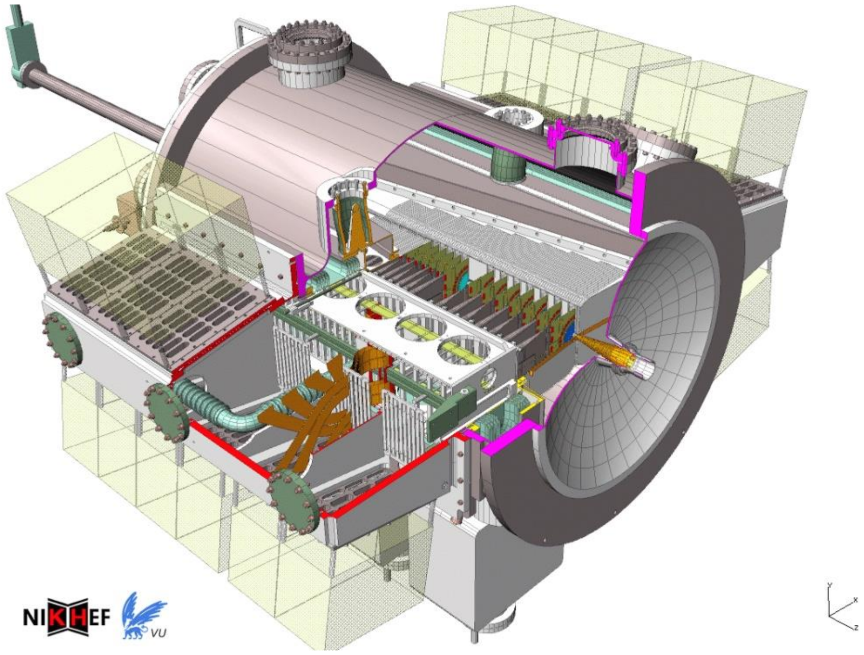

Figure 3. Layout overview of the current VELO, illustrating the vacuum tank, module positioning and RF foil.

The module cooling design must also be significantly changed in order to protect the innermost part of the silicon from thermal runaway effects after significant irradiation, and to cope with the high-speed VeloPix ASIC (Application-Specific Integrated Circuit) power dissipation. For this reason, the VELO group decided to use a novel approach with the cooling integrated within the module itself (in contrast to the currently installed detector). The cooling is provided by evaporative CO_2 circulating within miniature channels in a substrate which forms the backbone of the module[5]. The upgraded detector reuses large parts of the current mechanical infrastructure, in particular the vacuum tank, and elements of the very successful mixed phase CO_2 cooling system. The layout of the module with etched cooling microchannels is shown in Figure 4.

[4] The sensors will feature 55 µm square pixels.

[5] The described scenario is also called Plan A. Since it is technologically challenging also an alternative scenario, called Plan B, was proposed which assumes using ceramic substrats instead of silicon ones.

3.2 Upstream Tracker

The foreseen location of the UT detector will be in between RICH1 and the LHCb spectrometer magnet that is currently occupied by the TT (Tracker Turicensis) detector, which comprises four detection layers based on silicon 500 μm thick micro-strip sensors. The first and the last detection layer have vertical readout strips, whereas the sensors in the second and third detection layers are rotated by a stereo angle of $+5^o$ and -5^o, respectively. The TT has performed very well during LHC Run 1 and played a crucial role in long-lived neutral particles reconstruction (such as K_s^0 mesons) that decay outside of the acceptance of the vertex detector. Furthermore, momentum resolution of tracks reconstructed by the VELO and downstream tracker can be increased by approximately 20% by adding to them information from the TT.

Despite its excellent performance, the current TT detector must be replaced for the LHCb upgrade. The front-end chip Beetle is not compatible with 40 MHz full-detector readout. The granularity of the TT silicon sensors is not sufficient and would lead to unacceptably high occupancies when running in the upgrade conditions. Finally, silicon sensors were not designed to be sufficiently radiation hard to handle the expected radiation damage, close to the beam pipe.

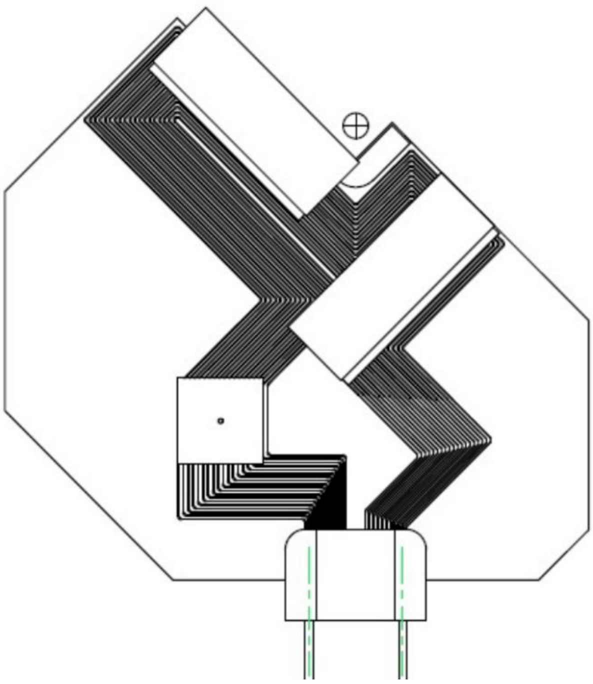

Figure 4. Schematic view of the upgraded VELO module with etched cooling channels (Plan A). This innovative solution is developed to protect the inner parts of the silicon sensors from the thermal runaway after a large radiation dose and to handle power dissipated by high-speed VeloPix ASICs.

The construction of the UT detector is very similar to the current TT tracker (see Figure 5). It has four detector layers, exactly like the TT, but featuring silicon micro-strip sensors with smaller thickness, finer segmentation and larger acceptance[6] thanks to the shape of the sensors (see Figure 6). Sensor design allows them to survive with acceptable performance at the expected upgrade fluence. The geometry configuration and material budget are optimised for best performance based on simulation studies. Thanks to a novel front-end chip, SALT (Silicon ASIC for LHCb Tracking), with an advanced digital processing block the signals recorded on sensors are processed on detector rather than being taken out via long cables. Both silicon sensors and electronics will be cooled by a system using a well-established technology with evaporative CO_2.

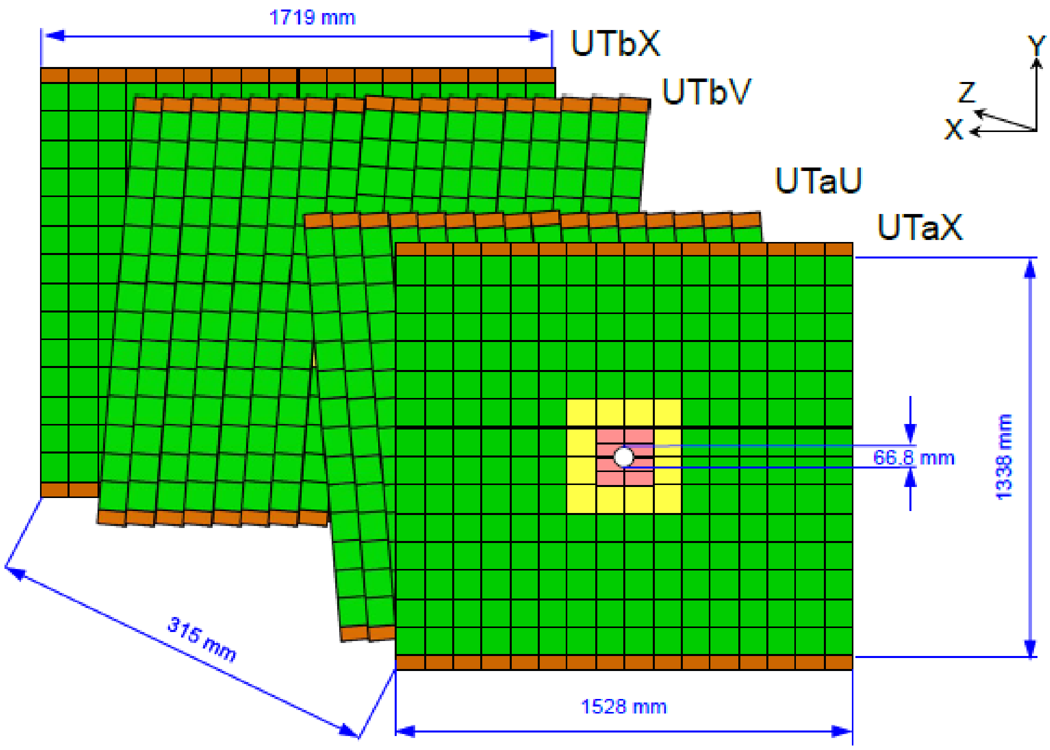

Figure 5. The UT detector geometry. The first and the last measuring planes have sensors with vertical strips (parallel to the y-axis), whereas the middle two are at $\pm 5^o$ (stereo angle).

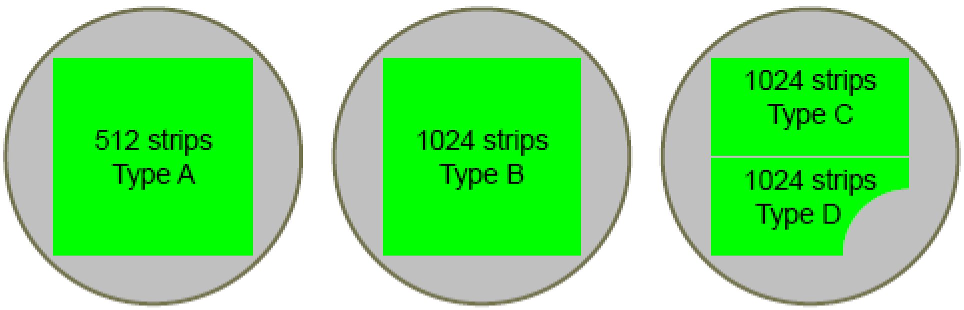

Figure 6. Sketch of the three mask designs for the UT upgrade showing their shape and specifying the number of readout channels.

[6] Based on experience from both Run 1 and Run 2 requirements regarding the clearance to the LHC beam-pipe have been relaxed, which will make it possible to significantly improve the forward acceptance of the detector. For this the innermost sensors will have circular cut outs.

3.3 Scintillating Fibre Tracker

Current LHCb detector has three downstream tracking stations T1 – T3. They were designed to provide standalone pattern recognition with a high efficiency together with high resolution in the bending plane of the LHCb magnetic field. The stations consist of two completely separate detectors: the Outer Tracker (OT) and the Inner Tracker (IT). The former is constructed using large straw gaseous detectors and covers around 99% of the 30 m^2 detector surface. The latter is a silicon micro-strip detector covering an area of 0.35 m^2 in the high track density region around the beam-pipe. Each station consists of four detection planes which provide measurements of the co-ordinates (x, u, v, x), with strips or straws orientated at (0^o, $+5^o$, -5^o, 0^o) with respect to the vertical axis. The design of the tracking stations has been optimised to provide the best possible performance at luminosities expected at the upgrade conditions. Extensive simulation studies showed that at the upgrade conditions the occupancy of the OT would be far too high to provide reliable and efficient tracking. Also, the readout electronics of both OT and IT detectors would not be suitable for new data acquisition scheme.

A suitable solution for the upgrades system that is sufficiently radiation hard was chosen after a careful consideration. The decision has been made to replace the upstream tracker by Scintillating Fibre Tracker (SciFi Tracker/SFT) which will cover the full acceptance after the magnet. The detector modules will have 2.5 m long plastic scintillating fibres with a diameter of 250 µm what provide the required granularity. The modules will contain six layers of scintillating fibres. The proposed solution asserts high hit efficiency, good spatial resolution (close to 100 µm) and low material budget within the LHCb acceptance. The fibres will be read out by Silicon Photomultipliers (SiPMs). Since the photomultipliers may suffer from radiation damage a mono-phase cooling system will be used to keep them at temperature -40^o. The active component of the SciFi (scintillating fibres) will be arranged into mats that, in turn, form 12 measuring layers of the detector. The single 250 µm fibres are arranged in multi-layer mats (see Figure 6) to produce a sufficient light yield at the photodetector.

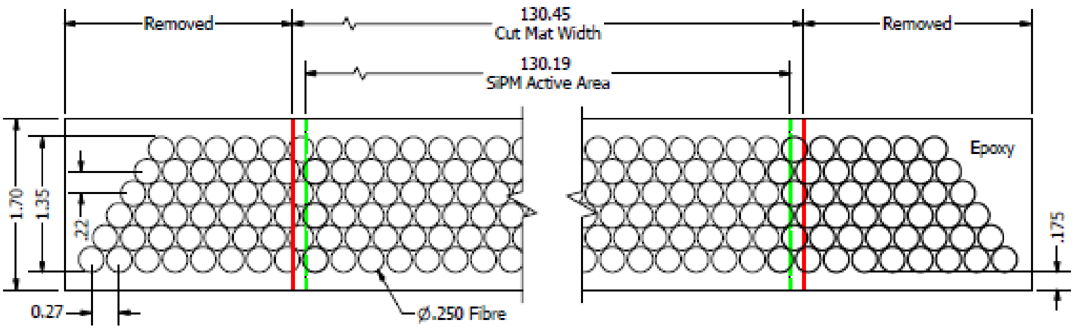

Figure 6. A schematic view of scintillating fibres arrangement in the mat.

4. Particle identification

Particle identification (PID) is an essential attribute of any flavour-physics experiment in general and has a major role in the LHCb operation in particular. Charged hadron (especially pion-kaon separation) identification is performed by two Ring Imaging Cherenkov (RICH) detectors over the momentum range 1.5 – 100 GeV/c. The calorimeter system enables photon and electron identification. Many interesting decay channels have muons in their final states and the excellent muon system of the LHCb spectrometer allows for an efficient identification of them. On top of this the calorimeter and muon systems are critical to the LHCb trigger as they give the input to the L0 decision, which is the earliest trigger level of the current experiment.

4.1 RICH system

The current RICH system consists of two detectors employing three different Cherenkov radiators. RICH 1 uses silica aerogel and C_4F_{10} gas, and is located upstream of the spectrometer dipole magnet and covers an angular acceptance of $25 - 300$ mrad. RICH 2, that is located downstream of the magnet, is responsible for the high momentum coverage with the angular acceptance $15 - 120$ mrad. It employs a CF_4 gas radiator.

The overall mechanical structure of both RICH detectors will remain unchanged in the upgrade, however RICH 1 will be significantly modified. Since, it was found that the current aerogel radiation will be of limited effectiveness in a high luminosity environment, it will be removed. Second major consequence of the upgrade is that the photon detectors must be completely replaced, since the current hybrid photon detectors (HPDs) have their readout electronics encapsulated within the tube. It is proposed to replace the HPDs with commercial multi-anode photomultipliers and external readout electronics that will conform to the specifications of the upgraded DAQ system. Particle Identification (PID) will be an important component of the software trigger, and RICH information will be used there. More information regarding the upgrade of RICH system can be found in [9].

4.2 Calorimeter system

The calorimeter system has performed exceptionally well throughout Run 1 and the presently ongoing Run 2 data taking. The upgraded experiment poses however new challenges such as the contribution to the software trigger decision and preforming the full readout at 40 MHz. Both measurements and extensive simulation campaigns showed that the calorimeter modules will survive higher radiation doses expected during the upgrade operation. Inner part of the electromagnetic calorimeter will need replacing, but this operation does not need to be performed until Long Shutdown 3 (LS3). In order to conform to the readout strategy, a complete redesign and rebuilding of the front-end and back-end electronics must be done. An additional consideration in this redesign comes from the decision to reduce the gains of the PMTs to ensure a longer lifetime at the upgrade conditions. This reduction in PMT gain must be compensated by a gain increase in the electronics. Furthermore, since the new flexible software trigger will not need a hardware component to achieve the necessary background suppression, the requirements for the entire calorimeter system will be less demanding. Thus, a decision has been made to simplify it and remove both SPD (Scintillating Pad Detector) and PS (Preshower) detectors (see also Figure 1).

4.3 Muon system

The efficient reconstruction and identification of muons is vital for the entire physics programme of the LHCb experiment since a number of rare decay channels such $B_{(s)} \rightarrow \mu^+\mu^-$ has muons in the final state. The muon system can be used to significantly enrich the heavy flavour content of selected data samples by requiring the muon candidate to have large transverse momentum. The present muon detector comprises five tracking stations M1 – M5. The first one

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is in front of the calorimeters and is important for the p_T measurement at the trigger level. The remaining stations are placed behind the hadronic calorimeter (see Figure 1) and are interleaved with iron walls that act as muon filters. The stations employ Multi-Wire Proportional Chambers (MWPCs), except for the innermost part of station M1 where Gas Electron Multiplier (GEM) detectors are used. The main requirement for the muon system at the upgrade is to provide as high reconstruction and identification efficiency for muons as possible and keep the misidentification of pions and other particles as low as possible.

Simulation studies and operational experience with the present system showed that it meets all the upgrade requirements performance-wise. In addition, the front-end electronics of the current system already reads full data at the required speed. However, the off-detector electronics, that provide hits, needs to be completely redesigned to conform with the new 40 MHz DAQ scheme. Also, the new software trigger puts less stress on the muon system and allows for its simplification. For this reason, a decision has been already made to remove the station M1. With respect to the larger particle fluence at the high pile-up upgrade conditions, additional shielding around the beam pipe, close to the hadronic calorimeter, will be installed to protect the innermost part of the station M2.

5. Summary

The LHCb experiment is making fundamental contributions for understanding the symmetry breaking between matter and anti-matter, providing a number of first and world's best measurements. Despite its superb performance in Run 1 and Run 2, in order to be even more effective from Run 3 onwards, a without major upgrade of the current detector is needed. To this end, an upgrade strategy has been defined and accepted by all participating countries. The upgrade project is well underway and it recently shifted from the research and design phase into the production phase. Arguably, the most delicate part of the upgrade project is to provide custom made front-end electronics. This was especially challenging since the front-end components are required to perform raw data processing and initial hit reconstruction on detector. The most innovative and complex chips are VeloPix and SALT (for the VELO pixel sensors and UT micro-strips respectively). First versions of both chips have been already produced and tested and the results are very promising.

The end of the Run 2 data taking and the beginning of installation of the upgraded detector is planned for 2019. The Run 3 data taking is supposed to start in 2021. LHCb collaboration is on its way to deliver the new system that will be able to operate at much higher luminosity than the present detector and will provide us with more exciting physics results, including potential New Physics beyond the Standard Model.

Acknowledgements

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References

[1] LHCb collaboration, *LHCb detector performance*, *Int. J. Mod. Phys. A* 30 (2015).

[2] https://home.cern/topics/large-hadron-collider (2017).

[3] LHCb collaboration, *Measurement of the* $B_s^0 \rightarrow \mu^+\mu^-$ *Branching Fraction and Effective Lifetime and Search for* $B \rightarrow \mu^+\mu^-$ *Decays*, *Phys. Rev. Lett*. 118, 191801 (2017).

[4] LHCb collaboration, *Observation of J/ψp Resonances Consistent with Pentaquark States in Λ0b→J/ψK−p Decays*, *Phys. Rev. Lett*. 115, 072001 (2015).

[5] LHCb collaboration, *Letter of Intent (LoI) for the LHCb Upgrade*, CERN-LHCC-2011-001 (2011).

[6] LHCb collaboration, *Framework TDR (FTDR) for the LHCb Upgrade*, CERN-LHCC-2012-007 (2012).

[7] LHCb collaboration, The Tracker TDR for the LHCb upgrade, CERN-LHCC-2014-001 (2014).

[8] LHCb collaboration, *The VELO TDR for the LHCb Upgrade*, CERN-LHCC-2013-021 (2013).

[9] LHCb collaboration, *The PID TDR for the LHCb Upgrade*, CERN-LHCC-2013-022 (2013).

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