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The LHCb VELO detector: Design, operation and first results

Efrén Rodríguez Rodríguez, on behalf of the LHCb collaboration

Galician Institute of High Energy Physics (IGFAE) - Universidade de Santiago de Compostela, Spain

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ABSTRACT

The LHCb experiment has been upgraded during the second long shutdown of the Large Hadron Collider at CERN, and a new set of refurbished detectors are currently operating at the LHC. The Vertex Locator (VELO) detector surrounds the proton beams interaction region, it is responsible of the reconstruction of the proton–proton collision (primary vertices) as well as the decay vertices of long-lived particles (secondary vertices). The VELO consists of 52 modules using hybrid silicon pixel detector technology. Compared to the previous detector, the new VELO encompass an enhanced track reconstruction speed and precision, even at the expected much higher occupancy conditions, thanks to its pixel geometry and the reduced distance to the LHC beams, with the first sensitive pixel being at just 5.1 mm from the beam line.

The sensors consist of 200 μm thick n-on-p planar silicon sensors, read out via front-end ASICs. The detector contains 41 million 55 μm × 55 μm pixels, read out by a custom developed front-end ASIC (VeloPix), cooled by evaporative CO_2 circulating in 500 μm thick silicon microchannel substrates. The VELO operates in an extreme environment, which poses significant challenges to its operation. During the lifetime of the detector, the sensors are foreseen to accumulate an integrated fluence of up to 8×10^{15} 1 $\mathrm{MeVn_{eq}cm^{-2}}$, roughly equivalent to a dose of 400 MRad. Moreover, due to the geometry of the detector, the sensors will face a highly non-uniform irradiation, with fluences in the hottest regions expected to vary by a factor 400 within the same sensor. The highest occupancy ASICs foresee a maximum pixel hit rate of 900 Mhit/s and an output data rate exceeding 15 Gbit/s. The design, operation and early results evaluating the radiation damage and detector performance throughout the first year of operation will be presented in this paper.

1. Introduction

The Large Hadron Collider beauty (LHCb) experiment [1] (Fig. 1), installed at the Large Hadron Collider (LHC) at CERN, focuses on probing the frontiers of our understanding of fundamental particles and forces by studying the physics of heavy quarks, particularly the b (beauty) and c (charm) quarks. A critical component of this experiment is the Vertex Locator (VELO), a highly sophisticated silicon pixel detector designed for precise tracking and vertex reconstruction. The VELO plays an essential role in identifying secondary vertices, crucial for studying b- and c-physics, which delve into the behavior of heavy quarks.

The new VELO brings significant improvements to handle the 10-fold increased luminosity of 2×10^{33} $\mathrm{cm^{-2}sec^{-1}}$ and to collect up to 50 $\mathrm{fb^{-1}}$ data by the end of Run-4 (in 2029), featuring a faster readout system that operates with a purely software trigger at 40 MHz. These enhancements are pivotal for improving impact parameter and spatial resolutions, thereby increasing the LHCb's capability to analyze particle interactions with unprecedented precision. This paper will provide a thorough examination of the VELO detector, including its design, operation, and recent enhancements, especially following Long Shutdown 2 (LS2). It will cover the operational challenges, technological advancements, and innovative design choices in detail. Additionally, the text will outline the obstacles and achievements encountered during the commissioning phase, alongside the preliminary outcomes from the initial year of operation.

2. Operational enhancements of the LHCb VELO detector

2.1. Enhanced readout system

As already mentioned, the upgraded LHCb operates with a purely software trigger, reading out the whole detector at the bunch crossing rate of 40 MHz. This approach allows the experiment to fully exploit the increased luminosity: removing the hardware trigger eliminates the 1 MHz limitation and makes the information of the full event already available at the first stage of the trigger. However, running the detector at 40 MHz required substantial changes to most of the LHCb subdetectors, and a complete replacement of the VELO. In particular,

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E-mail addresses: efren.rodriguez.rodriguez@cern.ch, efren.rodriguez.rodriguez@usc.es.

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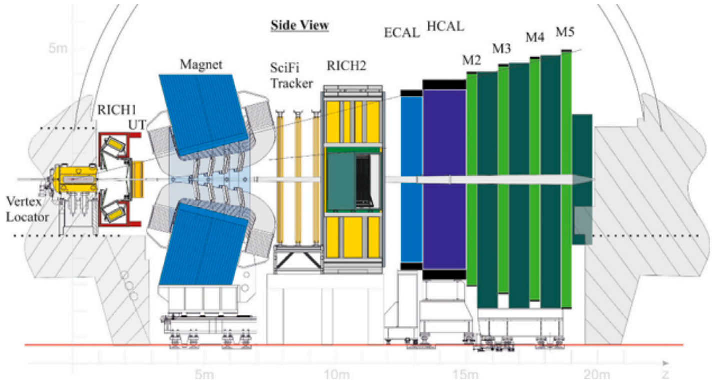

Fig. 1. Side view of the LHCb detector.

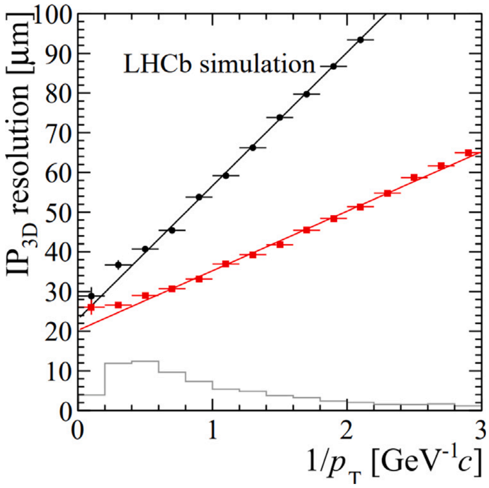

Fig. 2. Comparison of the simulated impact parameter resolutions between the upgraded VELO (in red) and the original VELO (in black), both sets are calculated for $\nu = 7.6$, $\sqrt{s} = 14$ TeV. The light gray histogram shows the relative population of b-hadron daughter tracks in each $1/p_T$ bin.

the increased data rates expected in the detector required a full redesign of the readout system, which will be described in the following sections.

To withstand these demanding conditions, the new VELO was equipped with radiation-hard pixel sensors. Due to the unusual placement of the LHCb vertex modules, perpendicular to the LHC beams, sensors were designed to handle highly nonuniform fluences about 8×10^{15} $1\mathrm{MeVn_{eq}cm^{-2}}$. Additionally, the sensors in the upgraded VELO were designed to be kept at temperatures below −20 °C, further safeguarding them against effects of the radiation damage.

The choice of a pixel-based detector significantly reduced ghost tracks and expedited reconstruction algorithms, enhancing hit resolution and vertex reconstruction, thus refining VELO overall accuracy. Notably, Fig. 2 shows a comparison of the simulated impact parameter resolutions between the upgraded and original VELO; the former exhibits superior resolution across all the range of transverse momentum ($1/p_T$).

3. Challenges and solutions in the LHCb VELO detector

The VELO operates under extreme conditions close to the LHC beamline, at just 5.1 mm from the beam. This proximity subjects it to intense radiation, necessitating the use of radiation-hardened components. The high data readout rates from proton–proton collisions pose significant challenges in data processing and thermal management. Furthermore, the VELO operates in a secondary vacuum, a requirement set by LHC to prevent contamination to the main LHC vacuum in the event of a leak. This introduces the need for an aluminum foil barrier, which constitutes a significant portion of the detector's material budget and is the primary contributor to the interaction point (IP) resolution. The material's radiation length ($X \approx 0.5$) is also a critical factor in the detector's design and performance.

3.1. The RF-box: Design and function

The RF-box, crafted from a specialized aluminum alloy (AlMg4.5Mn0.7 EN-AW5083), plays a multifaceted role in the VELO. It houses the detector modules while separating the primary and secondary vacua, crucial for protecting against RF pickup from the LHC beams and is required to sustain differential pressures up to 10 mbar. Its design incorporates regions with minimal thickness of ∼ 150 μm to optimize the material budget, essential for maintaining the VELO's high-resolution capabilities.

4. Improvements in electronics and cooling

The VELO's operational enhancements are not limited to its detection capabilities. Significant advancements were also made in its electronics and cooling systems:

4.1. Front-end electronic

The VELO's new front-end electronics is engineered to handle increased data rates and improve track reconstruction accuracy. The retractable 5 Gb/s transmission lines, depicted in Fig. 3, are designed to be flexible and move in tandem with the module. This feature allows for seamless integration and adaptability within the VELO system, enabling efficient data transmission. The lines utilize radiation hard tested aerospace-grade dielectric technology, similar to that employed in NASA's spacecraft. This innovation ensures efficient data handling with minimal losses and outgassing, vital for both the detector's and the LHC's functionality. Furthermore, a unique high-rate data transmission protocol (GWT, 5 Gb/s) was developed, diverging from the standard LHCb protocols, specifically tailored to reduce power dissipation and enhance system efficiency and reliability.

4.2. Cooling

The upgraded cooling system of the VELO [2] addresses the thermal management challenges arising from higher operational speeds and radiation levels. It utilizes a two-phase evaporative CO_2 cooling mechanism with silicon micro-channel substrates, which is pivotal for maintaining operational stability and integrity. This system is capable of dissipating up to 40 W per module, keeping the VELO modules at −30 °C, thereby ensuring their longevity and performance. The silicon

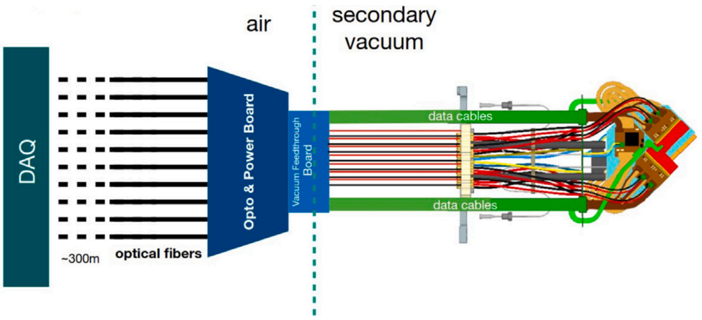

Fig. 3. Schematics of a module with the DAQ system.

micro-channel substrates, of ∼500 μm thickness, used in the cooling system not only provide efficient heat dissipation directly to the ASICs but also serve as the mechanical support for the readout chips and sensors. This dual functionality ensures matched thermal expansion coefficients, minimizing the risk of distortion and maintaining the integrity of the electronic components.

5. Electronics and modules of the LHCb VELO detector

The electronics within the LHCb VELO are integral to its operational success, engineered to adeptly manage the detector's substantial data throughput and stringent operational requirements [3]. The VELO is composed by 52 modules (Fig. 4), with the new pixel detector at the core of these enhancements, specifically designed to reduce ghost tracks, thereby enabling quicker and more accurate track reconstruction algorithms that markedly elevate the VELO's operational efficiency. Furthermore, substantial improvements to the front-end electronics have been implemented to optimize data flow management, ensuring seamless data processing and analysis.

5.1. VELO modules: Design and materials

To enhance its resilience against the high radiation levels anticipated in its operating environment, the VELO incorporates hybrid pixel sensors crafted using the advanced 130 nm TSMC technology. This design choice ensures the sensors' durability up to an impressive 400 Mrads. Central to the VELO's functionality is the VeloPix ASIC [4], meticulously designed for binary data-driven readouts, emphasizing the detector's efficiency and reliability in data processing. The VeloPix ASIC, with a thickness of only 200 μm, consists of a 256 × 256 pixel matrix, with $55 \times 55\ \mu m^2$ pixels. Three ASICs are bump-bonded to a silicon sensor, 200 μm thick, 12 ASICs in total per module. The choice of the sensor thickness allows to balance the need for minimizing the material budget and maximizing the signal to noise ratio, while at the same time preventing structural issues such as warping.

The ASICs are wirebonded to the front-end hybrids, from which signals are sent to the OPB boards, through flexible transmission lines. The OPBs convert the electrical signals to optical signals and will send them to the DAQ system based on Field-Programmable Gate Arrays (FPGAs) technology.

The VELO sensors, with a combined area of $0.12\ m^2$ and comprising 41 million pixels, are designed to withstand extreme radiation levels and very high hit rates. Utilizing advanced technology known for its radiation hardness, these sensors ensure reliable performance under very harsh conditions with a gradient up to a factor ×400 within the same sensor due to the proximity of to the interaction point. This factor is known and inherent to the detector's design; its effects were accounted for during the design and development of the modules and will be monitored throughout the detector's operational life.

6. Data acquisition and readout system of the LHCb VELO detector

6.1. Advanced readout links and FPGA integration

The Data Acquisition System (DAQ) of the LHCb VELO is a critical component of its operational infrastructure, designed to handle the enormous data flow generated by the detector. At the heart of this system are the advanced readout links, capable of operating at 5 Gb/s per module, which form the backbone of the VELO's data transfer capabilities. A novel ultra-low power transmission protocol, different from the standard used in all other LHCb detectors, was developed to reduce the heat produced in the VeloPix readout chip and flexible micro-strip transmission lines based on aerospace technology, radiation hard and outgassing resistant materials, were used to carry data though the secondary vacuum.

Another key element of the DAQ is the integration of FPGAs [5], playing a pivotal role in the VELO's data processing, offering a flexible and powerful solution for real-time data analysis. The integration of clustering algorithms directly into the FPGAs is a significant enhancement, allowing for a more efficient and streamlined data processing workflow.

6.2. Reduction in power consumption

One of the notable achievements of the VELO's DAQ system is the significant reduction in power consumption, especially in comparison to previous systems. By integrating the data processing algorithms into the FPGA, the VELO team has successfully minimized the power requirements of the DAQ system without compromising on efficiency or data throughput. The total nominal power budget per module is conservatively 30 W, giving a total of 1.56 kW for the 52 modules of the whole VELO. This reduction is not only beneficial for the operational costs and environmental impact of the detector but also crucial for maintaining the stability and longevity of the electronic components, which can be sensitive to heat and power fluctuations.

7. Installation and commissioning of the LHCb VELO detector

The installation and commissioning of the VELO detector entail critical procedures for its integration within the LHC environment. These processes include the strategic placement of modules within the RF box, ensuring the system's alignment and operational readiness. The commissioning phase is characterized by extensive testing to verify the functionality of electronic, cooling, and vacuum systems, alongside the data acquisition framework. This phase is crucial for calibrating the detector to perform optimally under the LHC unique conditions.

The VELO detector control systems ensure the integrity of the sensors and the smooth integration with LHC operations. Mastery over these systems is vital due to the detector complex functionality and the operational intricacies of the LHC. The control systems' precision is reflective of the detailed nature of the commissioning tasks. The

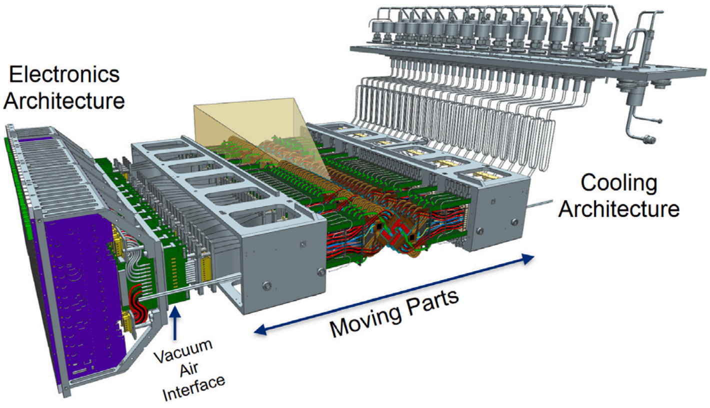

Fig. 4. 3D model of the VELO modules and electronics and cooling architecture.

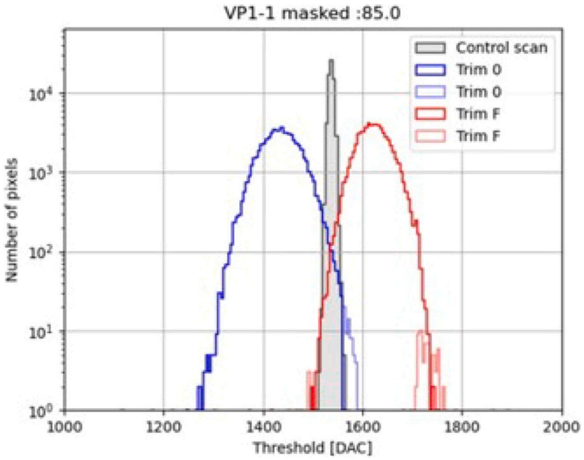

Fig. 5. Noise count distribution performed at minimum trim value (blue), maximum trim value (red) and final distribution after equalization (gray).

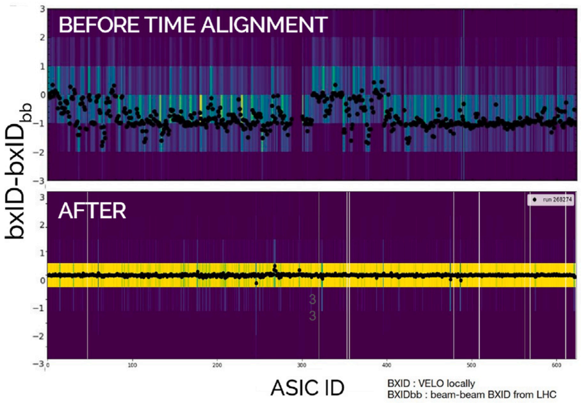

Fig. 6. Representation of the signal from a given BXID for all the ASICs in VELO, before and after alignment.

VELO detector integration within the LHC necessitates precise synchronization across the collider extensive 27 km circumference, managing millions of readout components and coordinating numerous synchronization clocks with minimal jitter. This is essential for the accurate and consistent collection and analysis of data.

7.1. Equalization process

In the VeloPix ASIC, pixel thresholds are set by a global baseline plus individual “trim” adjustments, a key aspect of the VELO detector equalization process [6]. This process calibrates each pixel to ensure consistent response to noise across the detector, involving threshold scans to identify optimal trim values. This fine-tuning, critical for detector performance, balances ASIC behavior and filters out noisy pixels (see Fig. 5).

7.2. Time alignment

Time alignment in the VELO detector commissioning is crucial for synchronizing ASICs to accurately process signals from particle hits [7]. Misalignments can occur due to signal amplitude variations, affecting the timing of data collection. The process uses an isolated Bunch Cross ID (BXID, unique identifier assigned to each particle bunch crossing event in LHC) to identify and adjust timing discrepancies, ensuring all components are synchronized. Further refinements involve Digital-to-Analog Converters (DAC) and signal threshold adjustments to align signals in time, enhancing the detector performance (see Fig. 6).

8. Early results and vertex reconstruction in the LHCb VELO detector

8.1. First results from the upgraded VELO

The early results from the upgraded LHCb VELO detector have been promising, showcasing the efficacy of the recent enhancements [8]. Following the commissioning phase, the detector has been able to demonstrate its improved capabilities in primary and secondary vertex reconstruction. Distinguishing which particle tracks come from a proton–proton interaction or from the decay of a long-lived particle created in one of them is of paramount importance for the LHCb experiment in order to study b- and c-quark physics. The ability to operate the VELO close to the beam with high precision and reliability is a testament to the success of the upgrade.

8.2. Importance of vertex reconstruction

Vertex reconstruction is a critical aspect of the LHCb experiment. It involves determining the points in space where particles collide or decay, providing crucial information about the particles involved in these processes. The upgraded VELO, with its enhanced equalization and time alignment, has significantly improved the experiment’s ability to reconstruct vertices accurately. These advancements are key to achieving the LHCb’s objective of studying particle interactions with high spatial resolution.

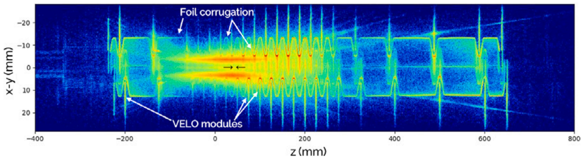

Fig. 7. VELO tomography by vertex reconstruction from material interactions.

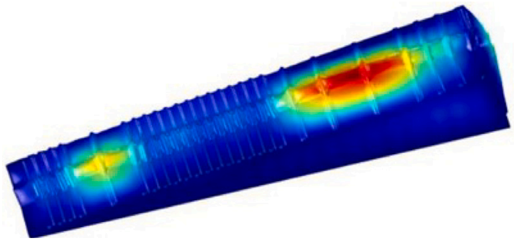

Fig. 8. Simulation of the plastic deformation sustained by the foil.

8.3. VELO tomography

One of the novel aspects of the upgraded VELO's capabilities is its use in VELO tomography. This technique involves the reconstruction of material interaction vertices, allowing for a detailed visualization of the interactions occurring within the detector. The ability to precisely reconstruct the position of the RF foil and of each module is an additional tool to crosscheck the accurate spatial alignment of the detector (see Fig. 7).

8.4. Data from 2023 and implications

The data obtained from the VELO in 2023, combined with the other LHCb detectors, has provided invaluable insights. This data is crucial not only for understanding the fundamental processes occurring in particle physics but also for testing the limits of the Standard Model and eventually finding New Physics. The successful operation and results from the VELO are critical in this regard, contributing significantly to the overall research goals of the LHCb experiment.

9. Challenges overcome: The RF-foil incident in the LHCb VELO detector

9.1. The RF-foil incident of 2023

In January 2023, due to a loss of control in the LHC vacuum safety system, a differential pressure of 200 mbar built up between the LHC and VELO volumes, significantly beyond the RF foil specifications of 10 mbar.

The RF-foil incident in the VELO led to significant deformation, assessed via tomography [9], confirming that the sensor modules were unharmed and the VELO could stay operational in an “open” position. The incident forced the VELO to operate further from the interaction point, at 24.5 mm instead of the optimal 5.1 mm, affecting its impact parameter resolution. Despite this, the VELO's design resilience allowed it to continue functioning, showcasing the importance of robust systems in high-energy physics experiments under challenging conditions (see Fig. 8).

9.2. Replacement and future plans

Following the incident, plans were made for the replacement of the RF box in December 2023, during the winter stop of the LHC. This replacement was not only necessary for restoring the VELO to its full operational capacity but also for ensuring the long-term sustainability and performance of the detector. The quick response and efficient handling of this incident demonstrated the team's commitment to maintaining the highest standards of operation for the VELO.

10. Future prospects and upgrades for the LHCb VELO detector

As the LHCb experiment advances in particle physics, the Vertex Locator (VELO) is set for pivotal upgrades in 2024, focusing on enhancing capabilities and sustainability amidst growing demands. A key upgrade is the RF foil replacement to uphold performance and reliability, alongside comprehensive detector optimizations in calibration and software.

Reflecting on recent achievements and challenges, including the RF-box incident, the VELO's journey underscores its resilience and the team's dedication to innovation. These ongoing upgrades, aimed at precision in b- and c-physics, highlight the VELO's enduring role in the LHCb's mission and the broader quest to decode fundamental universal forces. The detector's future, shaped by collective expertise, promises continued contributions to particle physics.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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