PROCEEDINGS OF SCIENCE

Upgrade of the LHCb VELO detector

Mark Williams[*†]
CERN
E-mail: mark.williams@cern.ch

The LHCb experiment is a single-arm forward spectrometer optimised for performing heavy-flavour physics analyses, using proton-proton collisions provided by the LHC machine. A major upgrade of the LHCb experiment will take place prior to the start of Run 3 operations in 2021. The upgraded Vertex Locator (VELO) is an essential component of this upgrade. Its main role is to enable high precision track and vertex reconstruction, with data-driven readout to the software trigger at 40 MHz, in the higher-luminosity environment of Run 3. To achieve this goal, significant improvements are planned with respect to the current detector, including a switch from microstrips to pixels, upgraded electronics, and a new cooling system. I will briefly motivate the need for an upgrade, describe the main aspects of the VELO upgrade design, and compare the expected performance from simulation with the current detector performance.

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[*]Speaker.
[†]On behalf of the LHCb VELO Upgrade group.

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1. Introduction

The LHCb experiment was designed to probe heavy quark interactions with world-leading precision, including searches for rare decays and new states, CP violation analyses, and measurements of lifetimes, masses, and production and decay properties of bottom and charm hadrons. During Run 1 of LHC operations (2010-2012) it accumulated 3 fb^{-1} of proton-proton collision data, giving the world's largest sample of bottom and charm hadron data. This has enabled the development of a fruitful and exciting physics program, with over 250 papers already published [1], and more than 20 analysis talks at this conference. LHC Run 2 (2015-2018) has recently started, and should provide a further 5 fb^{-1} of integrated luminosity for analysis.

The LHCb detector is a single-arm forward spectrometer, covering the pseudorapidity region $2 < \eta < 5$ [2]. Closest to the interaction point is the Vertex Locator (VELO), a silicon microstrip detector providing high precision track and vertex reconstruction. Downstream of the VELO are additional tracking stations either on side of a 4 Tm dipole magnet. Particle identification is provided by two RICH detectors, followed by electromagnetic and hadronic calorimeters, and a multilayer muon system.

During 2019–2020 the LHCb detector will undergo a major upgrade, with the principal objective of increasing the collected yields of signal samples to be analysed in Run 3 and beyond (2021–), which will lead to order-of-magnitude increases in the precision of key parameters. The current LHCb detector is optimised for running at instantaneous luminosities significantly below those that can be reached by the accelerator, so the delivered luminosity is limited by offsetting the colliding beams. In 2011 (2012) running, this luminosity was set to around $2\ (4) \cdot 10^{32}\ \text{cm}^{-2}\text{s}^{-1}$. For Run 3, the luminosity will be increased fivefold to $20 \cdot 10^{32}\ \text{cm}^{-2}\text{s}^{-1}$. This will lead directly to increased sample sizes for those channels which can be most-easily identified by the current hardware triggers, such as decays containing one or more muons. However, for hadronic final states the trigger rates would quickly saturate with the current detector. To overcome this limit, the upgraded LHCb detector will remove the hardware trigger altogether, and utilise a software trigger to provide full offline-quality reconstruction in real time. This requires that all detector components used in the trigger must have full readout at 40 MHz, including the VELO, which provides vital trigger information for these hadronic decays.

Compared to the current detector, the upgraded VELO [3] will have a significantly higher output rate. It will be exposed to higher luminosities, which motivates the change from silicon microstrips to pixel technology. It will approach the interaction point more closely (5.1 mm compared to 8.2 mm at the nearest point), and will require significant radiation tolerance to operate for the anticipated lifetime of the detector ($\sim$50 fb^{-1}). The cooling system will be upgraded to use two-phase CO_2 in etched microchannels. In addition, there will be major upgrades to the mechanical and electronic systems and the RF foil which separates the VELO modules from the primary beam vacuum.

2. Overview of VELO upgrade design

As with the current VELO, the upgraded detector will be composed of two halves, which can be moved apart during beam injection and then returned to their nominal operating positions, 5.1 mm from the beam, during stable collisions. Each half consists of a bank of 26 modules, oriented perpendicular to the beam axis (z), as shown in Fig. 1. The positions of modules from the left and right halves are offset in z to provide full coverage of active detector elements when the VELO is closed, with the z positions optimised to give the best tracking performance based on simulation studies. The entire VELO system is contained within the beam enclosure to minimise the amount of material traversed by particles prior to their first measurement point. To protect the primary LHC vacuum, each VELO half is fully enclosed by an aluminium RF box to form a secondary vacuum. Close to the beam this box is replaced by a thin corrugated RF foil.

Figure 2 shows a front-on view of one left-right pair of modules. On each module, four silicon pixel sensors are mounted, with two each on the front and back to provide overlapping acceptance. Each sensor (43 mm $\times$ 15 mm) is bump-bonded to three VeloPix ASICs, with elongated pixels in the gaps between the ASICs to ensure no loss in coverage. The ASICs are mounted on a cooling substrate, etched with internal CO_2 microchannels, on which are also mounted the hybrid boards which provide input power, communication, and readout connectivity.

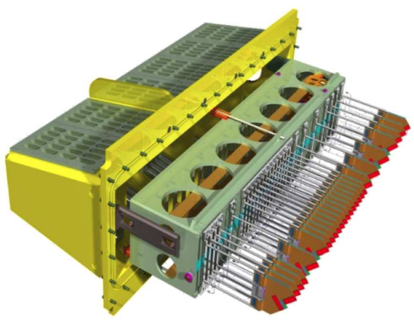

Figure 1: Drawing of one half of the upgraded VELO detector, with the enclosing RF box/foil removed, showing the 26 modules aligned along the beam direction.

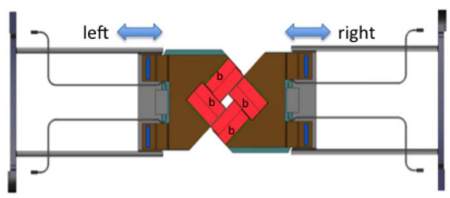

Figure 2: Front-view of a left-right pair of modules, with a projective view of the active silicon region (in red). In reality, half of the silicon sensors are placed on the back side of the module, to minimise gaps in acceptance.

3. ASICs and sensors

The VELO upgrade will use a custom readout chip, VeloPix, designed to provide the required readout performance and radiation hardness. The chip uses 130 nm technology, and comprises a 256 $\times$ 256 pixel matrix. It can operate with very high data rates (800 Mhits/s), with data-driven readout. To accommodate the high data rate, the chip will only provide binary hit information for each pixel. The chip design will be submitted for production by the end of 2015.

A similar ASIC, Timepix3 [4], has been used for existing studies of VELO upgrade components. Compared to VeloPix, Timepix3 provides lower (but still high) data rates of 80 Mhits/s, but includes a full analogue readout of both time-over-threshold (corresponding to the charge collected by the pixel) and time-of-arrival. The latter feature gives excellent time resolution, with 1.5 ns bin granularity. The properties of this ASIC make it ideally suited for use in testing and characterising sensor performance, as summarised in Sec. 6.

The silicon pixel sensors of the VELO upgrade match the 55 μm pixel size of the ASIC, and must fulfill the following requirements. They must be thin, to minimise the material within the detector acceptance; the baseline thickness in the design specifications is 200 μm. They must be radiation hard, capable of tolerating a fluence of 8×10^{15} 1 MeV n_{eq} cm^{-2}, with highly non-uniform exposure. After full irradiation, sensors are required to tolerate a bias voltage of 1000 V, with a hit efficiency exceeding 99%.

With these goals in mind, a sensor evaluation program is currently underway, with a variety of prototypes from two different vendors (Hamamatsu, Micron) under investigation. These include sensors with different guard ring sizes (250–600 μm) which protect sensor edges from breakdown at high voltage; different implant widths (35–39 μm), which can affect charge collection efficiency, and different doping substrates (n-on-p (baseline) or n-on-n). To characterise the sensor behaviour, they are bonded to Timepix3 ASICs and wire-bonded to a custom hybrid board, with devices tested both before and after realistic irradiation programs. Performance has been evaluated using electrical testing, radioactive source data, and test beam data, as described in Sec. 6.

4. Cooling

The upgraded VELO detector will dissipate up to 1.6 kW of power in total. At the same time, the sensors must be kept at a low and stable temperature of -20°C. This necessitates a cooling system that can reach the ASICs, which works in vacuum, and contains minimal material. The selected solution is a two-phase CO_2 evaporative cooling system, delivered to the required regions by etched microchannels within the cooling substrate.

In this design, liquid CO_2 is pumped via a manifold into a series of parallel channels in the substrate. On reaching the area to be cooled, the channels increase in cross-section (from 60×60 μm^2 to 120×200 μm^2) to promote boiling and maximise the cooling performance. The design is being tested and developed using a series of prototypes. The channel cross-section and layout have been optimised based on heat-load and pressure-flow tests. The prototypes fulfill all the required design specifications, both in terms of cooling performance and mechanical robustness.

5. RF Foil

The RF foil separates each VELO half from the beam, to isolate the primary beam vacuum from the secondary vacuum of the VELO, and shield the electronics from electromagnetic interference. It must fulfill a challenging set of requirements. First and foremost it must be air tight to preserve the vacuum separation. It must contain as little material as possible to minimise the impact parameter resolution, since the foil sits directly between the beam and the silicon sensors. The foil must be corrugated to accommodate the detector geometry, which also reduces the material traversed. At the same time, the electrical impedance of the foil must be small, to avoid creating troublesome wake-fields in the LHC machine. Finally, the foil must be mechanically rigid, thermally stable, and radiation hard.

The proposed design is a foil of 250 μm thick aluminium (AlMg4.5) milled from a solid block, as shown in Fig. 3. The corrugations are tuned to give the best possible physics performance, within the other constraints listed above. A program of engineering tests is currently underway, including production of half- and full-scale prototypes. The main technical challenge is preserving a consistent thickness with such a complex shape and thin walls. One option being tested is the use of

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chemicals to locally etch the foil in the region where the thickness most affects tracking performance. These studies are being performed in tandem with physics simulations, which demonstrate the importance of the RF foil design and thickness. An example is shown in Sec. 6.

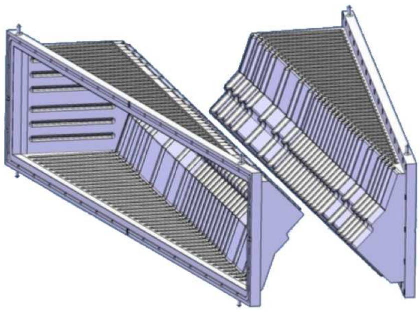

Figure 3: Engineering drawing of the corrugated aluminium RF foil, separating the VELO from the primary beam vacuum. Each corrugation houses a single module, minimising the beam-sensor distance and intermediate material.

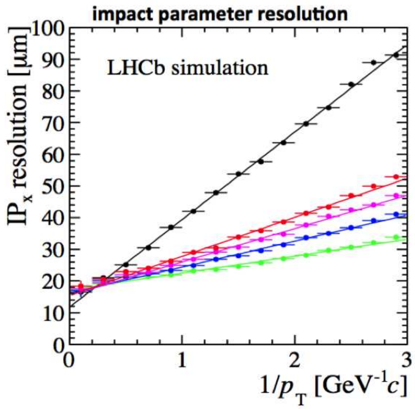

Figure 4: Track impact parameter resolution for the LHCb VELO detector. The four data series show, from top to bottom, the performance for the current VELO (black), and the upgrade with an RF foil of thickness 300 μm (red), 200 μm (magenta), 100 μm (blue) and 0 μm (green).

6. Physics performance and test beam results

A realistic model of the upgraded VELO detector has been implemented using the GEANT4 toolkit [5], and used alongside PYTHIA8 to simulate proton-proton collisions at 14 TeV, under the anticipated Run 3 conditions. The most important metrics to assess the detector performance are the impact parameter (IP) resolution, primary and secondary vertex resolution, and hit and track finding efficiencies. Figure 4 shows an example study of the IP resolution versus $1/p_T$ in one of the directions transverse to the beam. In this case, the current VELO is compared to four upgrade scenarios, each with a different RF foil thickness. This shows the importance of efforts to minimise the foil thickness, and also the improved performance of the upgraded detector with respect to the current design. The track reconstruction efficiency is also significantly increased in the upgraded VELO, as shown in Fig. 5, and is more stable over the full coverage of the detector. The upgrade surpasses the current VELO performance in all such key metrics, even with the higher track multiplicities.

As part of the research and design process, a dedicated Timepix3 'telescope' has been constructed for use in test beam facilities. This consists of eight detection planes, each comprising a single Timepix3 ASIC bonded to a silicon sensor, with a central moveable stage on which a device-under-test (DUT) can be mounted. Using dedicated readout and reconstruction tools, this telescope provides precise measurements of particle trajectories and timing as they pass through the DUT. The DUT performance can then be directly evaluated (e.g. the efficiency and purity of identifying a particle hit). A comprehensive sensor and ASIC evaluation program is underway using these data.

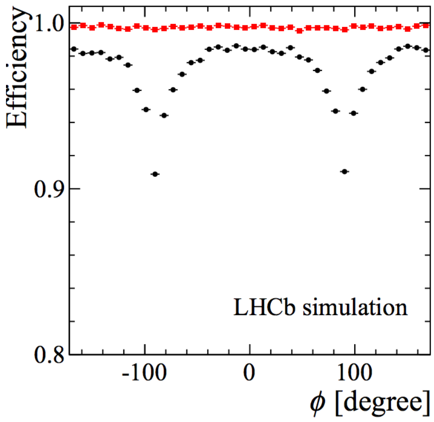

Figure 5: Track reconstruction efficiency for the current (black circles) and upgraded (red squares) VELO, for a sample of simulated $B^0 \to K^{*0}\mu^+\mu^-$ events.

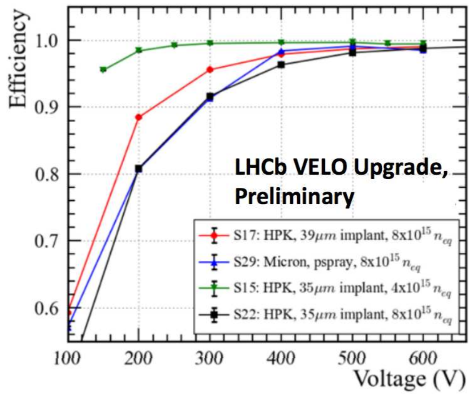

Figure 6: Hit efficiency versus bias voltage, for a selection of irradiated prototype sensors, using test beam data.

An example plot is shown in Fig. 6, which shows the single hit efficiency as a function of bias voltage. This clearly indicates that the required performance is achieved for all the tested sensors, with $>$ 99% efficiency above 600 V. A separate analysis of the total charge collected versus bias voltage confirms this result.

7. Summary

The LHCb upgrade will boost signal yields of many important channels by a factor of 20 or more, driven both by increased instantaneous luminosity and improved trigger efficiencies for hadronic final states. The VELO upgrade is a crucial component of this scheme, allowing full calibration, alignment, and track reconstruction to be performed in the software trigger (at 40 MHz), to ensure that the best possible trigger decisions are made. The new VELO will benefit from state-of-the-art silicon pixel technology, an advanced CO_2 cooling system, a refined RF foil, and upgraded mechanical and electrical systems. Once installed, the upgraded VELO detector will provide significant improvements in tracking efficiency and decay time resolution, giving the LHCb experiment the required sensitivity to probe the standard model with unprecedented precision.

References

[1] LHCb Publications `http://cern.ch/go/PZz7`

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