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# Silicon vertex detector with timing for the Upgrade II of LHCb

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ABSTRACT

LHCb has recently submitted a physics case for an Upgrade II detector to begin operation in 2031. The upcoming upgrade is designed to run at instantaneous luminosities of $1.5 \times 10^{34}\,\mathrm{cm}^{-2}\,\mathrm{s}^{-1}$, to accumulate a data sample with a corresponding integrated luminosity of over $300\,\mathrm{fb}^{-1}$. The LHCb physics programme relies on an efficient and precise vertex detector (VELO). Compared to Upgrade I, the data output rates, radiation levels and occupancies will be about ten times higher. To cope with the pile-up increase, new techniques to assign $b$-quark–hadrons to their primary vertex, and to perform the real-time pattern recognition are needed. To solve these problems, a new 4D hybrid pixel detector with enhanced rate and timing capabilities in the ASIC and sensor will be developed. This report will discuss the most promising technologies to be used in the future upgrade for the HL-LHC, with emphasis on the timing precision as a tool for vertexing in the next generation detectors. An initial simulation effort has been made to investigate what would be the required temporal resolution sufficient to mitigate pile-up and identify secondary vertices, which points to at least 20 ps per track. The most recent results from beam tests motivated by time measurements will be presented together with the R&D scenarios for the future upgrade. Improvements in the mechanical design of the Upgrade II VELO will also be needed to allow for periodic module replacement. The design will be further optimised to minimise the material before the first measured point on a track and to achieve a fully integrated module design with thinned sensors and ASICs combined with a lightweight cooling solution.

## 1. Introduction

The proposed future upgrade of the LHCb experiment, Upgrade II, aims to maximise the heavy flavour physics capabilities running at the High Luminosity-LHC. It aims to precisely measure effects from physics beyond the Standard Model in the sensitive heavy-flavour decays [1].

This will be achieved by increasing the maximum instantaneous luminosity for Run 5, reaching $1.5 \times 10^{34}\,\mathrm{cm}^2/\mathrm{s}$ at its peak. To cope with this increased instantaneous luminosity, an improved vertex detector is required.

The current vertex locator, the VELO Upgrade I [2], is a silicon tracker surrounding the interaction region, with an operational position situated at 5.1 mm from the beam, making it the closest to the interaction point in the LHC detectors (see Fig. 1).

The VELO's unique capabilities enhance the precision of measurements in heavy-flavour physics that can be performed at LHCb, which typically rely on the precise reconstruction of the secondary vertex and charged-particle kinematics to distinguish signal from background. This is done by correlating secondary vertices with the corresponding primary ones, thanks to the resolution of vertex reconstruction. This precision also allows diverse opportunities for studies beyond flavour physics.

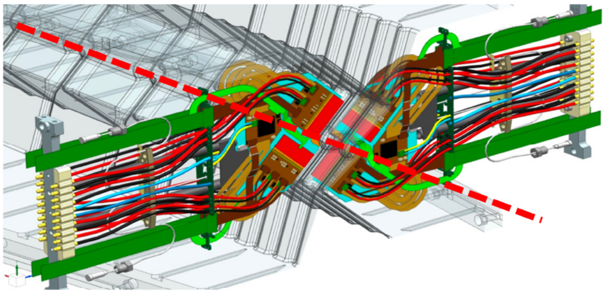

**Fig. 1.** Partial representation of VELO modules and beam trajectory.

## 2. Upgrade II design requirements

One of the main considerations for the VELO Upgrade II detector [3, 4] is the increase in pileup and luminosity, which results in an increase in fluence and the readout rates. The guiding principle is to maintain or improve the excellent performance of the VELO Upgrade I in terms of track and vertex resolutions, efficiency, and signal purity.

The upgraded detector not only needs to show no degradation in reconstruction performance, despite the increased pile-up, but should

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also ensure that future high-precision measurements are not limited by systematic uncertainties. With this, several challenges need to be overcome, starting with high occupancy, the need for radiation hardness and lower material budged, higher data rates, etc.

A large R&D programme must be deployed to deal with these challenges. In this paper, a few areas are reviewed:

- The need for timing performance, with the solutions under study right now
- The different sensor layout scenarios
- The sensor and ASIC technologies are under study to match the required performance
- The requirement for a further reduction in the material budget

## 3. Timing performance

A higher pileup implies that the primary vertex (PV) separation is reduced from 4.2 mm at Upgrade I to a value of around 1.5 mm at Upgrade II. Proton bunches overlap at approximately 180 ps, implying a significant time overlap over inelastic collisions that would affect vertex reconstruction with the current VELO time resolution of 1 ns as shown in Fig. 2. Therefore, the VELO in the current state would not be capable of differentiating primary and secondary vertices.

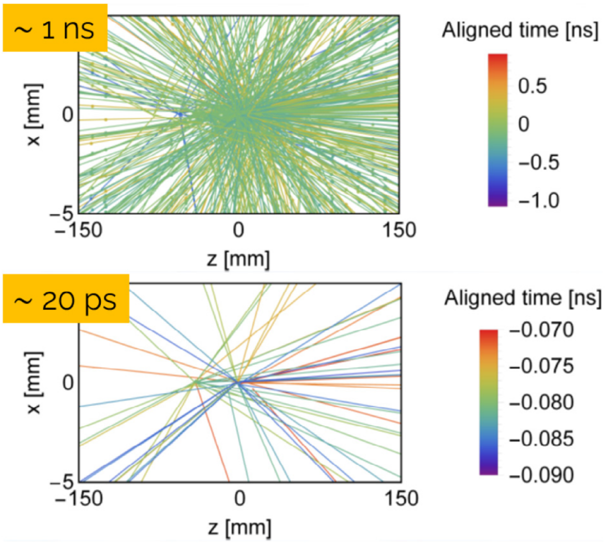

**Fig. 2.** Illustration of the track density generated by 42 collisions from a single bunch crossing. On the top, the whole bunch crossing time period is considered (≈ 1 ns). Only a few collisions and corresponding tracks would remain if a time cut of 20 ps was applied, as shown by the plot at the bottom.

Increasing the global VELO time resolution to 20 ps, only a few collisions and corresponding tracks remain, allowing us to distinguish primary and secondary vertices. Thus, detailed studies have been performed to demonstrate that a good temporal resolution is necessary to reach the specifications. This can be obtained through track timestamping.

Trajectories of charged particles from different primary vertices can intersect by chance, and an increased pile-up regime leads to more random track combinations, producing combinatorial background. The time information of the tracks propagated to the vertex can be used to recover the signal purity without suffering a significant decrease in PV efficiency, as seen in Fig. 3. A comparison is made between 3D tracking in Upgrade I conditions and 3D and 4D tracking in Upgrade II conditions.

A large efficiency loss is observed in the 3D-only approach due to the inability to resolve the primary vertices. The expected Upgrade I performance is nearly recovered by adding timing to the vertexing algorithm. The small remaining degradation might be mitigated by tuning the parameters and making other improvements to the reconstruction algorithm.

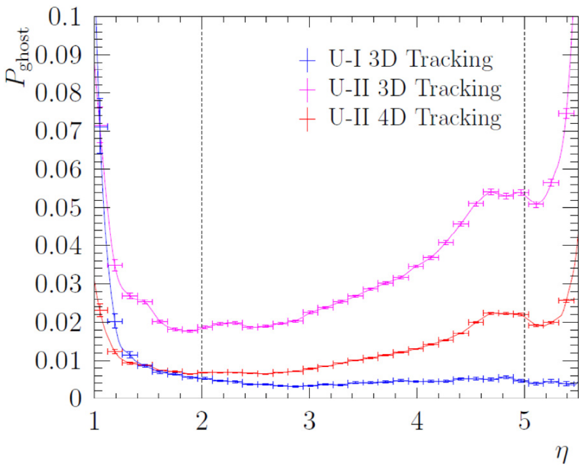

**Fig. 3.** Ghost rate for long tracks as a function of the track $\eta$, for Upgrade I conditions and Upgrade II conditions with both 3D and 4D tracking algorithms.

Track timestamping can be achieved in two ways; one approach is to add dedicated timing planes at the end caps of the VELO. They have the advantage of being further away from the luminous region, which relaxes the requirements on the radiation hardness and their pitch. At least three segmented timing layers would be required to provide independent timestamps, each with at least 25 ps resolution. This option implies a much higher detector area, adding restraints on material budget and a higher production price. The second option, to overcome these disadvantages, consists of moving to full 4D-tracking sensors in VELO, which means precise timing at every hit. The target resolution of 20 ps can be achieved by the combination of multiple measurements per track of 50 ps resolution per hit. A comparison of both choices efficiency is shown in Fig. 4.

The time information per hit also helps to reduce the number of combinations that need to be considered for the tracking, potentially improving the reconstruction. This also has implications for the reduction of ghost track rates. The 4D tracking shows higher efficiency in primary vertex temporal reconstruction, with spatial resolution being similar following the parameters studied in Section 5.

## 4. Sensor layout scenarios

The innermost radius of the VELO is a key driving parameter due to high irradiation values from the high luminosity. The main constraint is to, at least, keep the same detector performance values, throughout the expected irradiation.

To comply with these requirements, 2 limit scenarios are being considered. Scenario A $(S_A)$, which is closest to the beam, would keep the innermost radius at 5.1 mm and the same sensor layout as Upgrade I. With these conditions, the ASIC needs to deal with a factor ∼ 7.5 times higher hit rate than the VELO Upgrade-I ASIC, adding the timing information for each hit. With such a close distance to the interaction point, the new radiation dose implies that regular detector replacements may be needed. Scenario B, $(S_B)$, would be the furthest away from the beam. It would have the radius relaxed to 12.5 mm, matching the cluster occupancies of Upgrade I. The increase in the distance to the collision point requires significantly better hit resolution in order to maintain Upgrade I spatial resolution. This implies that the pixel size must be reduced to less than 42 μm. The material budget must be carefully controlled in this scenario, requiring lighter RF foil, but also improvements in sensor, ASIC, and substrate materials, and would require major mechanical redesign.

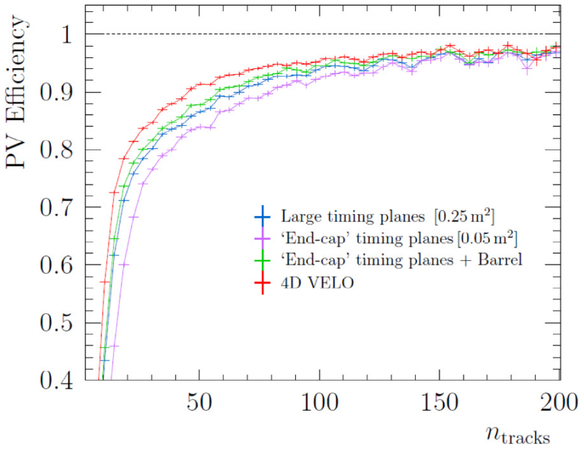

**Fig. 4.** PV reconstruction efficiency as a function of track count, depicted for the various timing plane options and compared to the 4D VELO option.

## 5. Sensor and ASIC requirements

Sensor R&D is closely related to ASIC development; their limitations will govern scenario choices and will be an important input to the decision on inner radius. Table 1 is a list of the ASIC requirements for both scenarios. We are going to review some of the most significant ones in this challenging upgrade:

- The possibility of reducing the pixel pitch and upscaling the matrix size in order to maintain spatial resolution in Upgrade I for scenario B.
- The possible mechanical redesign to adapt for replacements during technical stops due to exposure to doses beyond the limit of what many radiation hard sensors can withstand in scenario A.
- The need for fast discharge time per pixel to keep the pileup of hits under <1% due to a high hit rate in scenario A, with an estimated hit rate of 3.8 Ghits/s per ASIC.

**Table 1**
List of ASIC requirements for scenarios $S_A$ and $S_B$.

| Requirement | Scenario $S_A$ | Scenario $S_B$ |
|---|---|---|
| Pixel pitch [μm] | ≤55 | ≤42 |
| Matrix size | 256 × 256 | 335 × 335 |
| Time resolution RMS [ps] | ≤30 | ≤30 |
| Loss of hits [%] | ≤1 | ≤1 |
| TID lifetime [MGy] | >24 | >3 |
| ToT resolution/range [bits] | 6 | 8 |
| Max latency, BXID range [bits] | 9 | 9 |
| Power budget $[\mathrm{W/cm^2}]$ | 1.5 | 1.5 |
| Power per pixel [μH] | 23 | 14 |
| Threshold level [e$^-$] | ≤500 | ≤500 |
| Pixel rate hottest pixel [kHz] | >350 | >40 |
| Max discharge time [ns] | <29 | <250 |
| Bandwidth per ASIC of 2 cm$^2$ [Gb/s] | >250 | >94 |

For this upgrade, three main possibilities are being considered for the sensors: Hybrid planar, 3D sensor, and Low Gain Avalanche Detector (LGAD).

The planar sensors offer achievable time resolution with low thicknesses. This also helps to obtaining a more uniform weighting field. But, in this kind of sensor, the signal is proportional to the thickness and high fluence resistance implies a low collected charge. These factors lead to signal processing becoming a challenge. Therefore, there are no clear timing goals achievable while maintaining a signal-to-noise ratio.

The 3D sensors have proven good radiation resistance. Because of this, they are good candidates for the High Luminosity LHC tracking detector upgrades. The geometry of 3D sensors has a characteristic small column to column distance. This is beneficial in terms of timing performance due to short charge travel distances. In these sensors, the signal is proportional to the thickness, they have high pixel capacitance and can achieve time resolutions of 20 ps. A possible drawback lies in the inefficient volumes at the columns, with challenging high geometrical efficiency at small pitch.

The LGADs have excellent timing performance by using a thin high field layer. Having the gain structure placed in the sensor itself implies a good gain for small thickness, achieving time resolutions in a range from 20 to 40 ps. One main drawback is that they suffer gain degradation at high fluences due to acceptor removal, and the non-uniform irradiation in the VELO adds difficulty in tuning the sensor gain.

In terms of the ASIC technologies, two main options are being studied for the replacement of the VeloPix ASIC for Upgrade I, which was developed in collaboration with the Medipix group. The first one would be the next generation of this ASIC, the VeloPix-II, implemented in 28 nm technology with 55 μm pixels. The TIMESPOT demonstrator chips (Timespot0 and Timespot1), implemented in 28 nm CMOS technology with a 55 μm pitch and optimised for 3D-trench sensors, are the second option under consideration. Both options are suitable for the experiment and technologies may be complaint with the specifications described before.

## 6. Mechanics

In this section we discuss three main topics, the RF-Foil, the cooling system, and the vacuum tank.

The RF-Foil is used to obtain a continuous beam mirror current to avoid wakefield excitation, shielding the detector electronics from RF pickup of the beams and separating the high purity primary LHC vacuum from the secondary detector vacuum. It must be conductive and able to withstand a pressure difference of 10 mbar. The corrugated shape aids in pressure tolerance while also reducing the amount of material before the first measured point. The use of the secondary vacuum helps to lower the constraints on material outgassing thanks to the vacuum chamber separation.

Several options are being considered for a redesign of the tank. A thinner foil, or even the complete removal of the foil, could significantly reduce the multiple scattering term of the impact parameter resolution.

Cooling is an important factor in the design since the modules must be kept cold to prevent thermal runaway, caused by leakage current after the sensors are irradiated. The cooling in the VELO Upgrade I is done by $CO_2$ via Silicon microchannel plates like in Fig. 5, but Upgrade II modules will dissipate more power and thus require lower temperatures. For this, other coolants, such as Krypton, are being considered.

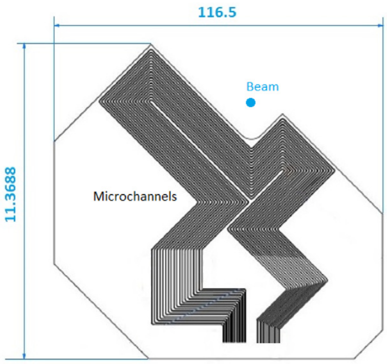

**Fig. 5.** Representation of the $CO_2$ microchannels for cooling of the VELO Upgrade I modules.

There are other factors to consider, such as large-scale production for replacement, with careful consideration of fluidic connectors. Other alternative technologies are also being considered, such as 3D-printed titanium.

The current VELO vacuum tank has been reused from the initial VELO design. However, it is unlikely to be suitable for the Upgrade II. Then a possible mechanical redesign of the vacuum tank would need to implement several changes as in Fig. 6.

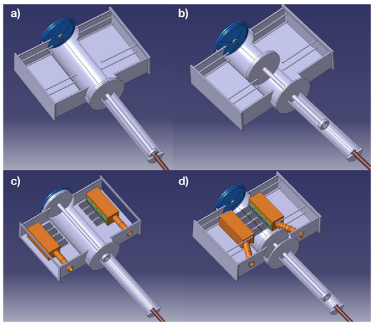

**Fig. 6.** Possible mechanical redesign of vacuum tank in the case of an "invisible" foil option.

Scenario A, implies the need for a possible swap of detector modules during technical stops due to high irradiation. Multiple designs for various RF foil approaches, including complete foil removal or different types and positions, would have to be considered, implying the need for improved vacuum and bakeout resistance. Finally, all the new designs must have space to host the local cooling distribution and for the VELO modules movement to approach the beam line.

## 7. Summary

Studies for the second LHCb upgrade are underway, with the detector planned to be installed for Run 5 in 2033.

Many challenges have to be faced before. For this reason, all the studies mentioned here are underway:

- Studies on two layout scenarios are being conducted. Keeping impact parameter resolution levels, with the possible solution of replacing modules during technical stops.
- Precise timing will be essential, with at least 20 ps global resolution needed. 4D tracking performance is better than separated timing planes, with a lower overall cost.
- R&D is underway for sensors and electronics: Fast timing sensors show promising results, satisfying spatial and temporal resolution
- Material budget is an important challenge; therefore several RF-Foil scenarios are being considered.
- A new vacuum tank and cooling system must be designed and tested to meet Upgrade II needs.

## 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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