Status of the LHCb VERtex LOcator[★]

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Abstract

LHCb is a single arm spectrometer at the LHC. It is dedicated to the study of CP violation in the B-hadron system. The VERtex LOcator (VELO) is a silicon microstrip detector providing accurate measurements of event primary and secondary vertices, impact parameters, and tracks. The second level trigger decision of LHCb is mainly based on information from a full readout of the VELO. This document gives a general introduction to LHCb as a context for a more extensive description of the VELO.

The VELO design emphasises the need for precise reconstruction of tracks down to momenta of a few GeV. The VELO operates inside the LHC beam-pipe, and the sensors, the hybrids, and the foil separating the primary and secondary vacuua must be built with the minimum possible material. The R- ϕ strip layout is optimised for efficient trigger operation and precise measurements at the smallest radii. The performance must be maintained in the harsh radiation environment close to the LHC beams. These issues have led to a choice of n-on-n, double metal technology for the VELO. This document describes the current status of the VELO design, incorporating changes which have been made in the context of the recent overall optimisation of the LHCb detector (“LHCb light”) [1], and summarises the underlying R&D for the technology choice. Issues concerning the electronics, the mechanical integration into LHCb and the LHC machine are discussed in detail elsewhere [3].

Key words: Vertex detector, silicon sensors, irradiation, trigger

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1 Introduction

The LHCb detector is designed to detect and reconstruct events where B mesons are produced in 14TeV pp collisions at the Large Hadron Collider (LHC). In these events, b and $\bar{b}$ hadrons and their decay products are typically found in the same very forward cone. The experiment is set up as a single arm spectrometer with an angular coverage between 10 and 300 mrad to maximise the acceptance for B meson decay products while benefiting from the Lorentz boost of b hadrons. Within the Standard Model, the only source of CP violation is the phase appearing in the quark mixing matrix. The LHCb experiment aims to exploit the very high statistics of $b\bar{b}$ production at the LHC to measure and over-constrain the parameters of this matrix, and explore possible contributions of New Physics to the CP violation observed. The experiment is dedicated for B-physics measurements via the specialised trigger, excellent proper time resolution, and the particle identification possibilities provided by the RICH systems. In this paper we describe the VERtEX LOcator (VELO), which is particularly associated with the triggering and vertexing.

The LHCb experiment has recently undergone an overall optimisation [1] aiming to minimise the amount of material in the detector in the light of the detailed engineering designs which are now reaching maturity, and aiming also to increase the robustness and efficiency of the trigger. The description and plots in this paper relate to the re-optimised VELO within this new structure. After describing the current VELO layout there are three main sections:

- Triggering and material

Events with b hadrons constitute only 0.5% of the total inelastic cross section of pp collisions at the LHC. At the nominal specific luminosity of $2 \times 10^{32} \text{cm}^{-2} \text{s}^{-1}$ $b\bar{b}$ events will be produced at a rate of 10^5 per second. The fraction of these interesting to the offline analysis is of order 10^{-2} . The trigger system is described in detail elsewhere in these proceedings [4]. In the second level of the trigger (L1) the rate is reduced from 1 MHz to less than 40 kHz. A complete readout of the VELO is used to identify large impact parameter tracks associated with candidate B-vertices, and this information is combined with an extrapolation through a small magnetic field to the Trigger Tracker detector to reject low momentum background. A low amount of material is critical to the efficient operation of the trigger. In section 3 we summarise the latest results on the VELO material studies.

- Triggering and strip layout

The $R\phi$ strip layout is intrinsic to the operation of the trigger. Within the R sensors the strips are distributed for optimal impact parameter resolution and even occupancy, resulting in a design where the minimum pitch is at the innermost part of the sensor. In the VELO-TDR [3] design the strips at radii below 24.1 mm were divided into four sectors in phi and above 24.1 mm

were divided into two sectors. In the optimised LHCb design, the VELO has assumed an increased importance in the role of track reconstruction. It was realised that the number of clone and ghost tracks, as well as the execution time, could be improved by redistributing the strips into four sectors at all radii [2]. The impact parameter resolution performance with the new design is discussed in section 4.

- **Radiation damage and VELO performance**

In order to maintain low material the VELO uses double metal readout. An extensive R&D prototyping programme has been carried out to show that the precision and efficiency needed can be maintained under irradiation. The main results from this programme are summarised in section 5.

2 VELO layout

The VELO is placed as close to the beam line as possible, in a secondary vacuum separated from the primary LHC vacuum by a 250 μm thick Aluminium foil. Deep corrugations are formed around the beam axis so as to minimise the amount of material traversed by particles before the first measured point in the silicon, while still being viable within the mechanical constraints. In addition, corrugations in the outermost part of the foil allow an overlap between the two halves of the VELO. The VELO is composed of 21 stations measuring R and ϕ in the range $8\text{mm} < R < 43\text{mm}$, between $-170\text{mm} < z < 740\text{mm}$ relative to the nominal interaction point. This number has been reduced from the original 25 stations, but simulation studies show that while the number of hits per event has been reduced, the number of tracks with three or four hits remains unchanged, and the impact parameter resolution and acceptance of the VELO is maintained [1]. The two halves are separated during injection and ramping of the LHC to allow the 30mm aperture required. The current layout is illustrated in figure 1.

3 Material budget of the VELO

The amount of material seen by particles traversing the VELO affects the track and impact parameter resolution. Although the centre of mass energy of the LHC is 14 TeV, tracks of interest for the off-line analysis in LHCb are from decays of B mesons and have energies of tens of GeV. Furthermore, inelastic interactions of particles with the detector lead to a reduced tracking efficiency for the LHCb detector as a whole. For this reason, the VELO detector has been re-optimised in order to minimise the average radiation and interaction lengths seen by particles traversing its volume, and to keep the av-

Fig. 1. Layout of the VELO in LHCb light with 21 stations. A zoom on the central region shows the innermost corrugations. The amount of material traversed before the first measured point in this design is 2.7% in the range $2.0 < \eta < 4.2$.

erage radiation length before the first sensitive hit to a minimum. The VELO material distribution has been investigated using the GEANT3 description of the VELO[5]. A distribution of virtual GEANT trajectories was generated uniformly in ϕ and η . These trajectories step through the volumes of the detector recording information on the material composition and distance traversed in each component. The information is then interpreted as an average interaction and radiation length. Similar studies were performed using both the new GEANT4 [6] geometry description and a 2D approximation. Both yield compatible results. Such studies have led to the baseline design of the VELO with 21 stations each consisting of two $220\ \mu\text{m}$ silicon planes. The hybrids also lie within a portion of the sensitive volume and hence their design has been optimised based on the findings of these scans. The results of a scan on the current baseline design and the break-up of individual contributions to the average X_0 are presented in figure 3. It can be seen that the main contribution is due to the $250\ \mu\text{m}$ thick aluminium RF shield. A detailed break-up of the relative contributions due to the hybrids are shown on figure 3.

4 Strip Layout

As discussed in the introduction, for reasons of trigger robustness it is desirable to rearrange the strips on the R sensor into four sectors in ϕ , at all radii. Three different options were considered in the new design:

Fig. 2. Right: average X_0 seen by particles traversing the VELO as a function of azimuth angle ϕ and pseudo-rapidity η . Left: Relative contributions to the average X_0 seen by particles traversing the VELO in the pseudo-rapidity range $2.0 < \eta < 4.2$. The total is 18.9% of an X_0 . 2.7% of an X_0 is seen before the first sensitive hit. The average Λ_0 is 4.5%.

Fig. 3. Contributions of the hybrids to the average X_0 (left) and Λ_0 (right) seen by particles traversing the VELO in the range $2.0 < \eta < 4.2$.

- 1. A gradual increase in pitch from $40 \mu\text{m}$ to $103 \mu\text{m}$
- 2. A constant $40 \mu\text{m}$ pitch to a radius of 13.1 mm, followed by $75.2 \mu\text{m}$ pitch at larger radii
- 3. A constant $40 \mu\text{m}$ pitch to a radius of 18.2 mm, followed by $92.8 \mu\text{m}$ pitch at larger radii

The new design is shown schematically in figure 4, together with a plot showing the impact parameter resolution as a function of transverse momentum for the different designs. The TDR design is nowhere more than 5% better than the modified designs. Hence the new design has been adopted, with option 1 being chosen, for the re-optimised VELO design.

Fig. 4. Cartoon of the new VELO strip layout. The plot shows the impact parameter resolution as a function of transverse momentum, for the VELO TDR design (black points) and the modified 45 degree sector designs 1,2 and 3 (red asterisks, green open circles, blue filled circles).

5 Performance under irradiation

Due to the proximity to the LHC beams, the VELO has to operate in a harsh radiation environment. The hadron fluence per year of the new VELO design is shown in figure 5. The VELO must combine double metal readout and 40 MHz operation while continuing to give full efficiency and a resolution of around $6 \mu\text{m}$ for $40 \mu\text{m}$ pitch. The highly non-uniform nature of the irradiation also poses a challenge, as the detector has to withstand the high bias voltages needed for the irradiated part in the region of the detector which is not yet inverted. Prototyping for the VELO has led to the choice of n-on-n technology [8,9,7]. Future areas of research within the VELO group include Czochralski silicon, for which test beam data from a high resistivity strip detector have been taken and are under analysis, p-bulk silicon[10], and thin detectors.

6 Conclusions

After several years of prototyping and R&D, the LHCb VELO design is completed and the detector is ready to go into the construction phase. In the context of the global optimisation of LHCb the material contribution of the VELO has been minimised, and the strip layout has been re-optimised for robust trigger operation. The LHCb experiment, and the VELO, should start to obtain physics results at nominal LHCb luminosity on day 1 of the LHC operation.

Fig. 5. Hadron fluence in equivalent 1 MeV neutrons per cm^2 per year for the silicon planes closest and furthest from the interaction point

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