The LHCb Vertex Locator — performance and radiation damage

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ABSTRACT: LHCb is a dedicated flavour physics experiment at the Large Hadron Collider at CERN. The Vertex Locator (VELO) is an important part of a LHCb tracking system, enabling precision measurement of beauty and charm mesons’ flight distance. The VELO consist of a set of silicon micro-strip detectors, arranged in two retractable halves, operating only 7 mm from the interaction region. In these proceedings the VELO performance during the Run 1 is summarised and radiation damage studies are presented.

KEYWORDS: Si microstrip and pad detectors; Radiation calculations; Data analysis; Particle tracking detectors (Solid-state detectors)
1 Introduction

LHCb (figure 1) is a dedicated experiment for the study of flavour physics at the LHC at CERN [1]. In particular the experiment is designed to study CP violation and rare beauty and charm particles decays and searches for New Physics evidences. The $b\bar{b}$ pairs production in proton-proton collisions is correlated in the forward region so the LHCb is a single-arm forward spectrometer covering the pseudorapidity range $2 < \eta < 5$. The LHCb physics programme is highly complementary to the direct searches preformed at ATLAS and CMS.

The interaction point is surrounded by the Vertex Locator sub-detector, which role is to precisely determine the position of both the primary and secondary vertices from the decays of beauty and charm particles (their flight distance is around 1 cm).

Tracking in LHCb is provided by one station before the magnet (Tracker Turicensis — 4 layers of of silicon strip modules) and 3 stations behind the magnet — silicon Inner Tracker and gaseous straw tubes of Outer Tracker.

1.1 Vertex Locator

The LHCb Vertex Locator (VELO) is a silicon-strip detector positioned around the interaction region. The innermost region of the active silicon is only 8.2 mm from the LHC beam. For this reason the VELO consists of two movable halves which can be retracted up to 30 mm during injection and before the beams declare stable. Each half contains 42 modules which are in a secondary vacuum and separated from the primary vacuum by a 300 $\mu$m thick aluminium foil.
Figure 1. The LHCb forward spectrometer at the LHC.

Figure 2. The diagram of sensors positions along z direction (left-hand side). Schematic representation of the R-type and Φ-type sensor (right-hand side).

Figure 3. The schematic view of n⁺-on-n sensor with second metal layer layout.

A VELO module consists of two 300 µm thick semi-circular sensors with 2048 strips situated on both sides of the module (figure 2), that provide measurements of the radial coordinate (R-type sensor) and the azimuthal angle (Φ-type sensor). Sensor pitch varies between 40 and 101 µm. Signals collected on strips are routed using a double metal layer that carries them to front-end electronics. Of the 84 sensors, 82 are oxygenated n⁺-on-n (n-type implant in an n-type bulk with a back p-type implant, see figure 3), the remaining two are n⁺-on-p. Four pile-up veto modules, which contain only R-type sensor, are located upstream of the interaction region.

Sensors are operated at −8°C with an evaporative CO₂ cooling system. For a dedicated scans or test the system is able to cool the sensors down to −30°C.
2 VELO performance

The ability to reconstruct vertices is crucial for the LHCb physics program. The R and \( \phi \) coordinates provided by VELO are used to reconstruct production (primary) and decay (secondary) vertices of beauty and charm particles that enables accurate measurements of their lifetimes. Detached vertices play a vital role in the High Level Trigger since they are an indication of \( b \) or \( c \) flavoured hadrons. The global performance of VELO during the Run I is given in the following section.

2.1 Signal and noise

To maintain a high level of trigger efficiency requires a good signal to noise ratio in the VELO.

The signal is obtained by measuring the charge distribution of clusters on tracks and fitting a Landau convoluted with a Gaussian. The noise on the chip depends on the input capacitance which is proportional to the length of the strip. The noise increases in the R-type sensors as a function of the radius. The distribution of a signal of one the \( \Phi \)-type sensor and noise in the R-type sensor are shown in figure 4.

The most probable value of the Landau (about 38 ADC counts\(^1\)) and the noise level below 2 ADC counts are used to calculate the signal to noise (S/N) ratio, which is shown in figure 5, both for R and \( \Phi \) type sensors.

2.2 Primary vertex resolution

The primary vertex (PV) resolution is evaluated by splitting the tracks in an event into two randomly chosen, equal sets. Each set is then used to fit the PV and the separation between two vertices is used to determine the resolution. The \( x \) and \( y \) resolutions for events with one PV as a function of the number of tracks used in the fitting procedure are presented in figure 6. With 25 tracks per vertex

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\(^1\)ADC count corresponds to about 450 electrons.
the PV resolutions are: $\sigma_x = 13.5 \mu m$, $\sigma_y = 12.5 \mu m$ and $\sigma_z = 90 \mu m$. For 2- and 3-PV events the resolutions are slightly worse.

2.3 Impact parameter resolution

The High Level Trigger uses the VELO data from the R-type sensors to determine the primary vertex position and to find tracks with large impact parameters (the shortest distance of approach to the primary vertex) relative to this vertex. Geometric resolution of impact parameters is vital in separation of short- and long-life particles. The error on the impact parameter arises from the intrinsic resolution of the detector and multiple Coulomb scattering, which in turn depends on the thickness of the material and the transverse momentum of the particle. To obtain a good IP measurement it is important to keep the first measurement of a track close to the primary vertex. Figure 6 (right) shows the resolution of IP in $x$-direction as a function of the inverse of transverse momentum for 2012 data and simulation.
2.4 Single hit resolution

The individual hit resolution of the sensors has been determined in a test beam by measuring the residuals of a radial coordinate of a cluster and tracks. Single hit resolution is the width of the unbiased residuals distribution. This quantity is a strong function of the sensor pitch and projected angle (i.e. the angle perpendicular to the strip direction), as shown in figure 7. Without charge sharing between adjacent strips the resolution of a single hit is expected to be close to $\text{pitch} / \sqrt{12}$. In case of the VELO with analogue readout one can use multiple strip clusters to improve the resolution. The best measured precision is close to 4 $\mu\text{m}$ for the small pitch and optimum angle, which is the best vertex detector resolution at the LHC.

3 Radiation damage

The first active strip in the VELO is only 8.2 mm from the beam, while the outer strips are about 40 mm away. So the VELO sensors are subjected to high radiation doses — maximum fluence is $50 \times 10^{12}$ 1 MeV $n_{eq}$/cm$^2$ per 1 fb$^{-1}$ (see figure 8). The dose is also highly non-uniform with a strong dependence on both radius and $z$ position of the station.

The radiation is responsible for a macroscopic change in the bulk of material what changes the electrical properties of silicon. The main observed effects are:

- increase in leakage current, caused by creation of generation and recombination centres,
- change of the effective doping concentration with significant influence on operating voltage needed for total depletion,
- loss of charge collection efficiency due to charge carrier trapping.
A few methods for damage monitoring have been proposed, among them are:

- Current-Temperature scans (I/T)
- Charge Collection Efficiency scan (CCE)

The summary of radiation effects on silicon during first year of VELO operation is published in [2]. In these proceeding new results are presented, most of them correspond to the full Run I data taking period, that has been finished at the beginning of 2013.

3.1 Leakage current

The reverse bias leakage current in silicon sensors varies linearly with fluence, when full depletion voltage is reached. Increase of sensor current is a direct indication of radiation damage in silicon. The total leakage current for a particular sensor is a combination of bulk and surface current. The surface currents component decrease with fluence while the bulk contribution is dominant after severe irradiation and shows linear dependence with fluence [3]. This tendency is shown in figure 8, where the raw measured currents (at operating voltage of 150 V) are shown. The plot also shows the recorded temperature and small drops in current during winter shutdowns.

The bulk component of the currents varies exponentially with temperature. Measurements of the reverse current as a function of temperature (I/T scan) allow to identify the bulk contribution and to extract the effective band gap, $E_g$. The I/T scans taken after the Run I has been finished, for all the sensors, are presented on figure 9. Points are fitted with an exponential function and the obtained value (based on dataset of 2.7 pb$^{-1}$ [4]) is $E_g = 1.16 \pm 0.06$ eV, which is consistent with the world accepted value [5].

Changes in the reverse current can be related to the delivered luminosity. The simulated data were combined with LHCb online luminosity measurement, the predicted currents, for a different $z$-positions of a sensors, are presented in figure 9. The measured currents are in agreements with expectations.
3.2 Depletion voltage studies

The depletion voltage, defined as the reverse bias voltage required to fully deplete the sensor, has been monitored as a function of the delivered luminosity. The depletion voltage is proportional to the effective space charge which changes with irradiation. It is expected that the depletion voltage of n⁺-on-n sensors decrease with fluence until the n-type bulk inverts into p-type. Following manufacture, the depletion voltage of each VELO sensor was measured using the variation of the capacitance as a function of voltage. After VELO installation an alternative method has been proposed, described in detail in [2]. The amount of charge collected by silicon increases with the applied bias voltage until the sensor is fully depleted. Then a further increase of voltage causes only small rise of collected charge what is related with the short shaping time of charge collection. So a bias voltage scan is performed on sensor to obtain the Effective Depletion Voltage (EDV). The change in EDV for all VELO sensors with fluence is presented in figure 10.
As expected the EDV for n⁺-on-n sensors is found to decrease, reaching the minimum of about 18 V and then increase almost linearly with fluence, independent on the initial depletion voltage. The data are in agreement with the Hamburg model [6] with small deviations in the regions of type inversion (EDV should drop to zero volts) due to the limitations of EDV method.

As the fluence delivered to the sensors varies significantly with radius, each sensor is divided into five radial regions. As expected, the EDV for n⁺-on-n sensors decreases with the fastest rate in inner sections exposed to higher fluences (see figure 10 right-hand side). After 2.7 fb⁻¹ of delivered luminosity, almost all VELO sensors have type-inverted at least in inner regions.

3.3 Cluster finding efficiency (CFE)

Efficient track reconstruction based on cluster finding in VELO sensors is vital for the physics program of LHCb. The method described in previous subsection is used also to measure the Cluster Finding Efficiency (CFE). A cluster is defined as a one or several adjacent strips with charge above a certain threshold. Before irradiation the mean CFE of VELO sensors was greater than 98% but after irradiation (starting at about 0.43 fb⁻¹), in R-type sensor it dropped significantly, as shown in figure 11. The inefficiency is particularly prevalent at large sensor radius and higher bias voltage.

An explanation of this phenomenon considers the presence of second metal layer routing lines which in R-type sensors are perpendicular to the strip implants. The source of CFE loss is attributed to charge induction on the second metal layer. The radiation damage influence the electric field of the sensor which result in a induced signal on the second metal layer routing lines. The charge loss is higher in regions distant from the strip and close to the routing line and doesn’t occur in Φ-type sensors (routing lines are parallel to the strips and routed on top of the outer strips there). The drop of CFE is measured when the distance between the hit positions to the nearest strip is smaller than to the routing line. These results are shown in figure 11 (right-hand side) which shows the relation between the drop of CCF and the distance from a routing line and a strip.

Figure 11. The CFE for one R-type sensor as a function of radius and delivered luminosity (right-hand side). CFE as a function of routing line and strip distance for an R-type sensor after 3.4 pb⁻¹ of delivered luminosity (right-hand side).
4 Conclusion

The LHCb VErtex LOcator (VELO) detector has operated very well since the start of LHC operation. The detector performance is already close to design parameters, with exceptionally good hit resolution that is close to 4 $\mu$m for the optimal pitch and track projected angle.

Effects of radiation damage have been observed and monitored in the VELO silicon sensors. An increase of leakage current is within the predicted values. Study of effective depletion voltage showed that most of the n$^+$-on-n type sensors are type inverted. The change in effective depletion voltage is in agreement with expectations from Hamburg model. The observed drop in Cluster Finding Efficiency is explained by the radiation inducted change in electric field configuration what may cause loses of the collected charge to adjacent routing lines. The Current VELO performance is superb and this detector will continue taking data until 2018.

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