VELO: the LHCb Vertex Detector *

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Abstract

The Vertex Locator (VELO) of the LHCb experiment is designed to measure precisely production and decay vertices of B–mesons. To allow the most accurate measurements the silicon microstrip detectors are placed within 7 mm of the LHC beams; the mechanics and integration with the LHC machine required for this are described. The close proximity to the beams leads to the operation of silicon microstrip sensors in a harsh and non–uniform radiation environment. Irradiated prototype $n$–on–$n$ and $p$–on–$n$ silicon microstrip detectors have been evaluated in a test–beam while being read out at 40 MHz. Measurements of the efficiency of these prototypes are presented. The particular dangers of $p$–on–$n$ detectors are outlined and the $n$–on–$n$ technology choice for LHCb is motivated. Finally, the use of the VELO in the 2nd–level of the LHCb trigger is discussed.

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

The LHCb experiment is dedicated to B–physics at the Large Hadron Collider. Its goal is to use the large B-hadron statistics available to make over–constraining measurements of CP–violation in the Standard Model, and hopefully observe inconsistencies indicative of new physics contributions. Precise vertex measurements are extremely important to LHCb for two reasons. Firstly,
the signature of a displaced vertex from the primary is characteristic of a B–decay, and is used in the 2nd level of the trigger to select events of interest. Secondly, excellent resolution of the B-decay time is required to minimise dilution of CP–violation and mixing measurements.

The LHCb experiment instruments the forward region of one hemisphere about the $pp$ interaction point. The pseudo-rapidity acceptance that must be covered by the Vertex Locator (VELO) is $4.9 \geq \eta \geq 1.5$. A series of 25 stations are arranged perpendicular to the beam direction over 1 m about the interaction point.

Two factors are important to allow precision vertex measurements: instrumentation as close to the vertices as possible, and minimal multiple scattering. These factors influence the mechanical and sensor designs of the VELO which are described in this paper. In particular, the choice of $n$–on–$n$ silicon for the sensors is motivated using test–beam measurements.

Due to the large backgrounds and high event rates at the LHC the VELO data are required at the 2nd–level of the trigger to isolate events with high–impact parameter relative to the primary vertex. The implementation and performance of trigger algorithms in the VELO is discussed in Section 6.

2 VELO mechanics and LHC integration

![Fig. 1. A schematic of the VELO design. The main components are labelled.](image)

Figure 1 is a schematic of the VELO design. The two main mechanical features of the VELO are the separation into two halves and the encapsulation of the silicon sensors in a secondary vacuum container. To allow measurements
as close as possible to the production vertices requires that the sensors op-
erate very close to the LHC beam lines. However, during the injection and
acceleration phases of the LHC a 3 cm radius aperture is required; during col-
lisions only a 5 mm aperture is needed. Therefore, each station is divided in
half; each half station consists of an $R$ and a $\phi$ measuring sensor. The sensors
and secondary vacuum box are retracted using a rectangular bellows during
LHC injection and acceleration. All moving parts are outside the secondary
vacuum.

The secondary vacuum box is designed to limit material before the first mea-
asurement. The silicon sensors are operated in a secondary vacuum, with only
a thin wall separating them from the primary (LHC) vacuum. An RF–foil sur-
rounds each half of the VELO; it is constructed of $250 \mu m$ aluminium within
the acceptance. Operation within the primary vacuum is precluded due to con-
tamination by VELO components via out-gassing, and RF–frequency pick–up
from the beams leading to large correlated noise in the sensors.

![Fig. 2. A schematic of a section of the RF–foil and the silicon sensors.](image)

The RF–foil has a complex corrugated structure as shown in Figure 2. The
outer corrugations allow the offset half stations to overlap, leading to full
azimuthal coverage and tracks in both halves for alignment. The inner corru-
gations reduce the radiation lengths ($X_0$), thus multiple scattering, before the
first measured point. Without corrugations a particle would traverse an aver-
age of $0.12 X_0$ before the first measurement; with corrugations this is reduced
to $0.032 X_0$.

More details of the mechanical design can be found in [1] and the references
therein.
3 Sensor design and radiation environment

Fig. 3. The layout of VELO (left) $\phi$–measuring and (right) $R$–measuring silicon sensors.

Fig. 4. The fluence as a function of radius for a sensor near the interaction point (7) and the most downstream sensor (25).

The silicon sensor design is illustrated in Figure 3. The $R - \phi$ geometry of the strip layout gives optimal standalone tracking performance for the vertex trigger. The charge collected on the implants is AC–coupled to aluminium readout strips. The $\phi$ sensor strips are segmented into inner and outer regions;
The signals from the inner region are routed to the readout chips, at the edge of the detector, via lines in a second metal layer. The pitch at the inner radius ($R = 0.8$ cm) is $37 \, \mu m$ and increases to $92 \, \mu m$ at the outer radius ($R = 4.2$ cm). The pitch on the $R$-measuring sensors also increases with radius from $40 \, \mu m$ to $92 \, \mu m$. All strips are read out using the routing lines in the second metal layer, which run to the outer edge of the detector crossing many strips.

The strips are subject to a non-uniform irradiation by charged particles, which depends on the radius and position relative to the interaction point as illustrated in Figure 4. The radiation varies by a factor of 30 from the inner to outer radius, with a peak value of $1.3 \times 10^{14} \, n_{eq}/cm^2/year$. Throughout this paper $n_{eq}$ refers to the equivalent damage caused by neutrons of 1 MeV kinetic energy; other particle irradiations are scaled to this unit [2].

4 Prototype sensors and test-beam set-up

Prototype sensors similar to the final design have been produced in both $p$–on–$n$ and $n$–on–$n$ technologies [1]. The $p$–on–$n$ prototypes\(^1\) are almost identical in strip layout to the final design illustrated in Figure 3, and the thickness of the detector was $200 \, \mu m$. The $n$–on–$n$ prototypes\(^2\) have a different azimuthal coverage of $72^\circ$. However, the strip pitch and layout is similar to the final design, and a second metal layer is used for the readout. The thickness of the $n$–on–$n$ prototype is $300 \, \mu m$.

$\phi$–measuring sensors of both types were irradiated non-uniformly in a 24 GeV beam of protons at the CERN PS [3]. The range of fluences were $(0 - 6.4) \times 10^{14} \, n_{eq}/cm^2$ and $(0 - 2.5) \times 10^{14} \, n_{eq}/cm^2$ for the $p$–on–$n$ and the $n$–on–$n$ prototypes respectively. The detectors were fully annealed (a few weeks at room temperature), subsequently they were stored and operated at $-10^\circ C$ to prevent any additional increases in the depletion voltage after irradiation.

The detectors were read out with SCTA128A chips [4] at 40 MHz. The irradiated detectors were placed in a beam-telescope of 4 stations of non-irradiated $R$ and $\phi$–measuring sensors of the $n$–on–$n$ type, read out with VA2 chips [5]. The telescope was operated in a beam of 120 GeV pions and muons at the CERN SPS. Tracks reconstructed in the telescope have an extrapolation error of $\sim 4 \, \mu m$ at the irradiated detectors.

\(^1\) Manufactured by MICRON Semiconductors.
\(^2\) Manufactured by Hamamatsu Photonics K.K.
Fig. 5. The efficiency of the $p$–on–$n$ prototype. The efficiency is proportional to the size of the boxes.

Fig. 6. The map of the irradiation fluence received over the surface of the detector. The dose is proportional to the size of the boxes.

5 Efficiency measurements of the prototypes

Clusters on the test detector were reconstructed with the requirement that their signal–to–noise was greater than 5 [6]. The efficiency of the prototypes was determined by extrapolating a track from the telescope and searching for a cluster within 300 $\mu$m of the intercept point. Events with only one track reconstructed in the telescope were considered.

The efficiency over the surface of the $p$–on–$n$ prototype, when operated at 300 V, is illustrated in Figure 5. There are two features of note. Firstly, the region of greatest inefficiency corresponds to that of highest fluence, which is shown in Figure 6. Secondly, the inner region is more efficient than the outer for a similar fluence.

After a dose equivalent to the maximum received in one year of LHCb op-
operation, the efficiency was 92% for the outer region of $p$–on–$n$ sensor. For optimal operation of the LHCb vertex trigger, 99% efficiency is required. Furthermore, the signal–to–noise cut cannot be decreased without degrading the performance due to fake clusters [7].

The effects can be explained by comparing the charge collection in a fully depleted and an underdepleted $p$–on–$n$ sensor, which is represented schematically in Figure 7. The parts of the detector which are more heavily irradiated require a higher voltage to be fully depleted. At a fixed voltage, certain parts will be fully depleted, while other parts will have a non-depleted layer of differing thickness. In the fully depleted case, the charge from a particle traversing the bulk will be focused on to the $p^+$–implants of the strip, giving a narrow cluster. If the detector is underdepleted, as in the lower schematic of Figure 7, there is an underdepleted layer next to the $p^+$ implants which acts as an insulator when AC–coupled fast electronics are used [8]. Charge from a traversing particle will only drift in the depleted region, and a mirror charge will be induced in the aluminium readout lines of several nearby strips, defocusing the cluster [9]. Furthermore, in the outer region of the $p$–on–$n$ prototype detectors charge may also be induced in the routing lines in the second metal layer. These problems are not expected to occur for an underdepleted $n$–on–$n$ sensor [9], where the underdepleted region is on the opposite side of the detector to
Fig. 8. Comparison of $p$–on–$n$ and $n$–on–$n$ prototypes’ efficiencies as function of the depleted depth of the detector.

the segmented $n^+$ implants.

The readout of the $\phi$ sensor is such that the adjacent channels are an outer strip and an inner strip plus routing line in the second metal layer. The charge on the strips and the adjacent readout channels about the track intercept were measured. In the inner region the maximum for any irradiation is $\sim 5\%$; this is the cross talk in the readout chain. In the outer region the fraction increases to over 20% for a fluence of $2.5 \times 10^{14} \text{n}_{\text{eq}}/\text{cm}^2$. This additional charge on adjacent channels in the outer region is that induced on the second metal layer. This charge is lost to the cluster reconstruction, which explains the decreased efficiency in the outer region.

Identical efficiency measurements were performed on the irradiated $n$–on–$n$ detector. The results are given in Figure 8, along with those for the $p$–on–$n$ detector. The results are shown as a function of the fraction of the detector bulk’s thickness that is depleted, $f_{\text{dep}}$. This can be calculated given the measured depletion voltage, $V_{\text{dep}}$, for a certain irradiation [6], and the applied voltage at which the data were taken, $V$, using the relation: $f_{\text{dep}} = \sqrt{V/V_{\text{dep}}}$. The $p$–on–$n$ prototype efficiency drops as soon as there is an undepleted region in the detector; at 90% depletion the efficiency has dropped to 85%. For the $n$–on–$n$ prototype the efficiency remains at 99% until less than 60% of the detector is depleted.

When LHCb is operational the non–uniform irradiation of the sensors means
that at certain voltage the inner part of the detector may be underdepleted. Ideally the voltage will be raised to fully deplete the inner region, resulting in an overdepletion in the outer region. However, this may lead to problems of breakdown, or to effects such as micro-discharge noise \cite{10}, which could occur in the heavily overdepleted areas. As described in this paper, the charge spread in an underdepleted \( p\text{--on--}n \) detector leads to a lower efficiency, particularly in the presence of a second metal layer, as well as a decrease in the resolution. Therefore, the \( n\text{--on--}n \) technology was chosen for the LHCb VELO sensors.

6 The 2nd--level vertex trigger

In \( pp \) collisions at the LHC the \( b\bar{b} \) cross--section is approximately 160 times smaller than the hadronic cross--section. In addition the bunch crossing rate is 40 MHz. Therefore, to select events containing the \( B \)--decays of most interest a multi--level pipelined trigger scheme has been adopted. The 1st--level of the trigger is hardware based and identifies high transverse momentum (\( p_t \)) hadrons, leptons and photons. Also, events with more than one primary interaction are vetoed as these events are more difficult to reconstruct and occupy a disproportionate fraction of the available bandwidth. The output rate of the 1st--level is 1 MHz.

Fig. 9. The minimum bias retention rates as a function of trigger efficiency for three different algorithms for the decay \( B^0 \rightarrow \pi^+\pi^- \). The algorithms are described in the text.

The 2nd--level of the trigger uses the VELO to reconstruct tracks. The \( R\)--
sensors allow the reconstruction of tracks in the $R$–$z$ projection to find the primary vertex. Triplets of hits in successive stations are used to reconstruct the tracks. The low occupancy of 1% or less over the sensors leads to a high efficiency of 98% to reconstruct tracks. The primary vertex resolution is 70 $\mu$m in the $z$–direction. The azimuthal segmentation of the $R$–sensors gives a precision of 20 $\mu$m on the primary vertex in the orthogonal $x$–$y$ plane. The probability that a track came from the primary vertex is then calculated; those with low probability, thus large impact parameter, are reconstructed in 3D using the $\phi$–sensors as well.

The final solution has yet to be decided for the 2nd–level trigger algorithm. The retention of minimum bias events as a function of efficiency to select $B^0 \rightarrow \pi^+\pi^-$, for the algorithms under consideration, are given in Figure 9. The desired 2nd–level output rate is 40 kHz, which corresponds to a 4% retention of minimum bias events. The ‘L1 algorithm’ forms 2–track detached vertices on which to form a trigger decision [11]. The ‘L1 with L0 inf.’ links high impact parameter tracks with high–$p_t$ hadrons and leptons found in the calorimeters and muon– system in the 1st–level of the trigger [12]. The ‘L1 with $p_t$ inf.’ includes a $p_t$ measurement for the high impact parameter tracks [13]. The performance of around 85% efficiency for the algorithm including a measurement of $p_t$ is excellent. However, such a measurement of $p_t$ requires the introduction of a magnetic field between the VELO and the first tracking station; the technical feasibility of this is under study [14]. A decision will be taken at the end of 2002.

7 Conclusions

The LHCb VELO mechanical design allows precise vertex measurements to be made close to the interaction point and with minimal multiple scattering. Test–beam measurements have shown that $n$–on–$n$ silicon sensors, with the LHCb design, will give efficient and precise measurements while operating in the harsh radiation environment close to LHC beams. The particular dangers of operating an underdepleted $p$–on–$n$ detector with a double–metal layer have been studied. The standalone tracking and vertex measurements of the VELO are essential for the efficient operation of the 2nd–level of the LHCb trigger.

References


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