LHCb vertex locator, overview and recent progress

Lars Eklund*

CERN, CH-1211 Genève 23, Switzerland

Available online 9 October 2006
on behalf of the LHCb VELO Group

Abstract

The LHCb experiment is dedicated to the study of b-hadron physics. The vertex locator (VELO) is the sub-detector that reconstructs primary and secondary vertices, which are of importance for the processes under study. The VELO detector is described and results from a beam test with close to final components are presented. The paper also reports on the reconstruction of interaction vertices in the silicon detectors and a method to correct for cross talk in the serial analogue link is described.

© 2006 Elsevier B.V. All rights reserved.

PACS: 29.40.Gx

Keywords: Vertex detector; Silicon micro-strip; Digital filter

1. Introduction

The Large Hadron Collider (LHC) is a 14 TeV proton-proton collider scheduled to be commissioned in 2007 at CERN, Geneva. The LHCb experiment [1] is built to make precision measurements of b-flavoured hadron physics. LHCb will constrain the elements of the CKM matrix [2] and study rare b-decays to probe for physics beyond the Standard Model. LHCb will operate at a luminosity of $2 \times 10^{32} \text{ cm}^{-2} \text{ s}^{-1}$ which will generate in the order of 10^{12} $b\bar{b}$ pairs per year, with the full spectrum of b-hadrons.

The vast majority of the $b\bar{b}$ -pairs will be produced at low polar angles, with both constituents emitted in the same direction. LHCb exploits this fact and is built as a single spectrometer arm with an angular coverage of 15–300 mrad. The vertex locator (VELO) [3] is the detector situated closest to the interaction region with the purpose of reconstructing primary and secondary vertices. The VELO plays an integral role both in the on-line event selection and in the off-line reconstruction. A part of VELO, the Pile-Up VETO, participates in the first level trigger to reject events with multiple interactions. Further-

more, the VELO is included in high level trigger where displaced vertices and transverse momentum information are used in the selection. The proper lifetime of the b-mesons are measured from the primary and secondary vertices reconstructed by the VELO.

2. The vertex locator

VELO consists of 42 silicon micro-strip modules placed orthogonally to the beam around and downstream the interaction region. Each detector module has two half-circular silicon sensors, one measuring the radial distance R from the beam axis and the other measuring the azimuthal angle Φ . The R -sensors have 2048 circular strips with a linearly increasing pitch from 40 μm at $R = 8.2 \text{ mm}$ to 102 μm at $R = 42 \text{ mm}$, each strip covering 45° in Φ . The Φ -sensors have 2048 radial strips with a small stereo angle. There are 683 inner strips covering low radii and 1365 outer strips covering large radii. The pitch on the Φ -sensors varies from 36 to 97 μm . The sensors are 300 μm thick with n-on-n technology and have a second metal layer to route out the signals to the Beetle [4] front-end chip. The VELO will operate in a harsh non-uniform radiation environment where the expected fluence is $1.3 \times 10^{14} \text{ n}_{\text{eq}}/\text{cm}^2/\text{year}$ at $R = 8 \text{ mm}$.

*Tel.: +41 22 767 2309; fax: +41 22 767 9425.

E-mail address: lars.eklund@cern.ch.

The VELO detector module is made of a carbon fibre and TPG¹ sandwich with one electronics hybrid laminated on each side. Each side has one silicon sensor and 16 Beetle front-end chips and the nominal power consumption is 20 W per module. The detector modules are cooled by a CO₂ circuit via cooling cookies mounted on the carbon fibre surface. The first sensitive element is a mere 8.2 mm from the beam axis to minimise the extrapolation distance. As a consequence of the proximity to the beam axis, the detector modules are retracted 30 mm when LHC is injecting the beam. To minimise the material before the first measured track point, LHCb has no conventional beam pipe. The detector modules are operated in a secondary vacuum separated from the beam vacuum by a 250 μ m thick aluminium foil.

The signals from the silicon strips are amplified, filtered and stored in a 160 cells long analogue pipeline in the Beetle chip. Each chip is clocked at 40 MHz and handles 128 input channels. The events selected by the first level trigger are read out on four serial analogue ports per front-end chip. The data is transmitted via kapton cables and a vacuum feed-through to pre-compensating amplifiers that drive the signals through a 60 m twisted pair link to the counting house. The amplifiers and the signal repeaters for control and monitoring signals are situated immediately outside the VELO vacuum tank and hence exposed to the estimated radiation level of 73 krad throughout the lifetime of the experiment. They are based on commercial components that are qualified for radiation environment by procedures standardised in the HEP community. The signals are sampled by the TELL1 [5] DAQ board. The TELL1 performs pedestal subtraction, digital filtering, common mode noise subtraction, channel re-ordering and clustering. The processed data is transmitted via a Gigabit Ethernet network to a Linux farm for further event selection and storage.

3. Velo performance

Three prototype detector modules were tested in a beam test at the CERN SPS in November 2004, with a 120 GeV/c pion beam. The arrival time of the particles from the asynchronous beam was determined with a TDC. The time-structure of the LHC beam is emulated by cuts applied on the TDC time in the analysis. The detector modules were made of close to final components and read out via a prototype of the analogue link. Tracks were reconstructed with the aid of a beam telescope and the tracks were projected onto the devices under test.

The key performance parameters of the system were measured and a few special studies of particular features were made. For instance, Fig. 2 shows the resolution versus strip pitch for a 300 μ m thick *R*-measuring sensor. Fig. 1 shows three plots to probe the operational window for the signal to noise (*S/N*) threshold in the clustering algorithm.

Fig. 1. Cluster efficiency, noise occupancy and spill-over fraction versus *S/N* inclusion cut in the clustering algorithm. Measured for a 300 μ m Φ -sensor in the beam test November 2004.

The requirements are to achieve a cluster efficiency larger than 99%, a noise occupancy lower than 5×10^{-4} and a spill-over rate of less than 25%. Efficiency is defined as the probability to find a cluster at the point where the reconstructed track intersects with the detector plane. Noise occupancy is defined as the probability to find a cluster in absence of a track. And finally, spill-over is defined as the probability to reconstruct a cluster in the following bunch crossing at the intersection point of a track.

¹Thermalised pyrolytic graphite.

Clusters are reconstructed by first searching for seed strips that have S/N higher than a certain threshold. Adjacent strips are then added to the cluster if they pass a second lower cut. The S/N has to be sufficiently large so that a threshold can be found where both the requirements of the cluster efficiency and noise occupancy are met. As seen in Fig. 1 these criteria are easily met for a non-irradiated sensor. The spill-over requirement puts a stronger constraint to the S/N cut but, it is still possible to achieve together with the efficiency demand. The Beetle is a highly configurable chip and the characteristics of the front-end can be tuned. Hence the operational window can be further widened by decreasing the integration time. At a price of a slightly lower S/N the front-end pulse falls off faster and gives a lower spill-over rate.

4. Systems issues

VELO has reached the end of the R&D phase and the detector components are in production or are about to go into production. The next phase will be assembly and commissioning where VELO will be integrated into a working detector system. This section describes two system issues that have been addressed.

4.1. Interactions in the silicon planes

The assembly of the detector front-end and associated control and read-out electronics will lead to a full system test. Each detector half consists of a high precision base-plate where the detector modules are mounted, the cooling circuits, kapton interconnects and a detector hood with vacuum feed-throughs. This unit together with its control and readout electronics will be verified before installation in the LHCb experiment. The ambition is to operate one detector half in a beam test in the summer of 2006, reconstruct tracks and vertices, and align the detector. The detector half will be mounted in a stand-alone vacuum tank with the beam traversing the silicon sensors where a fraction of the particles will interact and form vertices. The modules will be cooled by a prototype CO_2 cooling circuit.

The LHCb reconstruction software profit from the R - Φ geometry of VELO and assumes that the tracks originate close to the beam axis and are almost linear in R - z . This is not the case for tracks from interactions in the silicon sensors and a special pattern recognition software has been developed in the LHCb framework. The tracks can be fed to the VELO alignment framework, based on Millepede [6], for a verification of the full reconstruction and alignment chain.

Interactions in the silicon sensors can also be used for alignment of the VELO when it is installed in LHCb. The layout of the VELO with two retractable detector halves and interactions in a confined central region divides the VELO into four loosely coupled parts from an alignment point of view. Only small fraction of the tracks from the collision region traverse more than one

quadrant of the detector. However, beam-halo particles will interact in the silicon sensors and when reconstructed they provide an additional set of constraints for the alignment.

4.2. Digital filtering

As described in Section 2 the detector is read out via a serial analogue link where the signals travel through several different media before digitisation. The integrity of the data is assured by impedance matching the parts of the data link and by a driver circuit compensating the attenuation. However, some residual signal distortion cannot be excluded. In addition the silicon sensor and front-end chip introduce cross talk between adjacent channels. Hence a digital filtering method was developed and tested during the beam test described in Section 3. Due to an incorrectly tuned analogue link, cross talk of up to 25% was observed and successfully corrected for.

The analogue link is regarded as a linear time-invariant system and the method consists of three steps. First the transfer function is determined, secondly the approximative inverse of it is calculated and finally the corrections are applied on the data. The transfer function is determined by measuring the impulse response, i.e. measuring the response of the system if a single channel contains a signal. This can be achieved either from using the

Fig. 2. Track residuals and resolution versus strip pitch, with or without correction for the cross talk via the FIR filter. Measured for a 300 μm R -sensor in the beam test November 2004, with an incident track angle of 7° .

calibration pulse injection circuit in the front-end chip or from beam data by selecting tracks passing sufficiently close to the centre of a strip implant to guarantee that no charge sharing occurred. Both methods were used and gave consistent results.

Since the digital filter is applied on-line by the pre-processing FPGA the inverse have to be approximated by a function that can easily be implemented in that technology. A Finite Impulse Response (FIR) filter was chosen which has the characteristics that it can be implemented as a finite sum of the input values without any feed-back loop. Furthermore the assumption that the cross talk did not extend more than two time samples, or 50 ns, in either direction was made. The filter coefficients were determined by the algorithm described in Ref. [7].

A fifth-order FIR filter applied to the beam test data fully suppressed the cross talk. Two sets of filter coefficients were used treating odd and even channels separately since the cross talk affects odd and even channels differently due to an asymmetry in the layout of the Beetle pipeline. The effects of the corrections on the residuals and resolution of an R -measuring sensor can be seen in Fig. 2. For small radii increasing channel number means increasing radius, whereas the strips are read out in the reversed order at larger radii. Since the cross talk is larger to higher than to lower DAQ channel numbers, this can be seen as a clear step in the track residuals before FIR corrections at around 50 μm pitch. The step is greatly reduced after corrections. Fig. 2 also shows an improvement in resolution since the digital filter remove the smearing introduced by the cross talk.

5. Summary

The LHCb VELO is a silicon micro-strip detector designed for primary and secondary vertex reconstruction. It consists of 42 detector modules with R - Φ geometry positioned orthogonally to the beam axis around and downstream of the interaction region. It has n-on-n double metal layer silicon sensors and an analogue front-end chip. Close to final prototypes were successfully tested in a beam test in November 2004 and VELO is now entering the production and integration phase. Systems issues have already been addressed, of which two were mentioned here. A study of using interactions in the silicon sensors for alignment was discussed and a method of using a digital FIR filter to correct for distortions in the analogue serial link was described.

References

- [1] LHCb Technical Design Report, Reoptimized Detector Design and Performance, CERN/LHCC, 2003-030 (2003).
- [2] M. Kobayashi, T. Maskawa, Prog. Theor. Phys. 49 (1973) 652.
- [3] LHCb VELO Technical Design Report, CERN/LHCC 2001-011 (2001).
- [4] N. van Bakel, et al., The Beetle Reference Manual, LHCb Note LHCb-2001-046.
- [5] G. Haefeli, et al., TELL1—Specification for a common read out board for LHCb, LHCb Note LHCb-2003-007.
- [6] V. Blobel, C. Kleinwort, A new method for the high-precision alignment of track detectors, arXiv:hep-ex/0208021.
- [7] M. Unser, M. Eden, Signal Process. 36 (1994) 163.