First test-beam results with a prototype of the LHCb vertex detector

Frederic Teubert

*CERN, EP division, CH-1211 Geneva, 23 Switzerland
frederic.teubert@cern.ch*

on behalf of the LHCb-VELO Collaboration

Abstract

The current design of the LHCb vertex detector (VELO: VERtex LOcator) is described. The use of the VELO detector in the second level trigger and the radiation environment at the LHC influence the choice adopted. A first prototype of the detector has been tested on test-beams at CERN, and first preliminary results are presented in this contribution.

Key words: LHCb; vertex detector; test-beam

1 Introduction

The large $b\bar{b}$ cross section ($\sim 500\mu\text{b}$) in proton-proton collisions at $\sqrt{s} \sim 14$ TeV makes the LHC collider an ideal laboratory for the study of the b-quark. At a luminosity of $2 \times 10^{32}\text{cm}^{-2}\text{s}^{-1}$ there will be around 10^{12} $b\bar{b}$ pairs produced per year. The average energy of the B-mesons is about 80 GeV and therefore, the mean flight time of the B-mesons is close to 7 mm. This should allow to easily identify secondary vertices using current vertex detector technologies. Moreover, LHCb is designed to operate always with an average luminosity of $2 \times 10^{32}\text{cm}^{-2}\text{s}^{-1}$. In this way, events are dominated by single proton-proton interactions and the occupancy remains low.

The angular distribution of the produced $b\bar{b}$ pairs is peaked at very low angles. LHCb is a single-arm spectrometer designed to cover the angular range between 15 mrad and 300 mrad, ($4.9 > \eta > 1.9$), and to fully exploit the b-physics potential of the LHC collider. The angular acceptance is limited by

radiation damage considerations for its lower value, and by the total cost of the experiment for its higher value.

Figure 1 shows a schematic representation of the LHCb detector. Two Cherenkov detectors designed to complement each other in the momentum range covered (between 1 and 150 GeV) allow an excellent π/K separation ($> 3\sigma$ over the full momentum range). The tracking system gives a good invariant mass resolution, (for instance, $\sigma(M_{B \rightarrow \pi\pi}) \sim 15$ MeV).

Probably one of the most critical elements of LHCb is the trigger system and the need to trigger on displaced vertices at the low level trigger influences the design of the vertex detector. This is the reason why in section 2 a short description of the LHCb trigger is given. The design of the vertex detector is given in section 3. In section 4 the results obtained with a prototype of the detector in the test-beam are shown. The last section is devoted to summarise the main results shown in this letter, and to give an outline of the future R&D activities of the LHCb vertex group.

2 The LHCb trigger system

The LHCb trigger system is designed to have four levels. The first level trigger (Level-0) is implemented in hardware and has to run at 40 MHz input rate with a fixed latency of 4 μ s. It is designed to reduce the input rate to 1 MHz by triggering on high Pt electrons in the electromagnetic calorimeter, high Pt hadrons in the hadronic calorimeter or high Pt muons in the muon chambers. It is foreseen to have also a trigger veto against multiple interactions in a single LHC crossing, using two special stations of the vertex detector [1], which are not discussed in this contribution.

The second level trigger (Level-1) has to run at 1 MHz input rate with a variable latency of several hundreds of μ s. The input rate is reduced to 40 KHz by triggering on displaced secondary vertices using the LHCb vertex detector.

The next two trigger levels have access to the information from several sub-detectors reading the event buffer. The Level-2 trigger reduces the input rate to 5 KHz by combining the information of the tracking system with the vertex detector at a variable latency of about 10 ms, while the Level-3 makes a more complete event reconstruction in about 200 ms and finally reduces the input rate to 200 Hz to be written on tape.

Fig. 1. The current layout of the LHCb detector seen from above.

Fig. 2. The distribution of the VELO detector along the beamline direction.

3 VELO baseline design

Silicon detectors with a small strip-pitch (from $40\text{ }\mu\text{m}$ to $105\text{ }\mu\text{m}$) and low multiple scattering ($150\text{ }\mu\text{m}$ thin detectors) have been chosen for the LHCb vertex detector (VELO: VERtex LOcator). Seventeen stations perpendicular to the beam, distributed along the z -axis as it is shown in figure 2, are mounted in Roman pots to allow to retract 3 cm each half station during LHC injection. In normal running conditions, the detectors are placed at 1 cm from the beam line. Each station has an R-detector (with circular strips) and a ϕ -detector (with radial strips), and successive ϕ -detectors have a $\pm 5^\circ$ stereo angle to allow the two projections to be combined. The total detector length is about one meter, and the separation between stations varies between 4 and 12 cm.

3.1 Mechanical support and RF shield

The design of the vacuum tank and support structures of the VELO detector needs to satisfy several requirements. It must have low mass in the acceptance region and provide for alignment and retractability of the detectors. The detectors and front-end electronics are located in a secondary vacuum, therefore the mechanical support has to maintain high-vacuum compatibility while providing feed-through of 22000 signal wires (50 twisted-pairs per hybrid) to the outside. A first design of this structure can be seen in figure 3.

The detectors are cooled by heat conduction via the aluminium support frame, which is maintained at a low temperature (5°C). A $100\text{ }\mu\text{m}$ aluminium foil separates the primary from the secondary vacuum and also provides partial

Fig. 3. First technical design of the vacuum tank and mechanical support.

RF-shielding of the detectors. In the baseline design of the RF shield described in reference [2] each detector is encapsulated by the Al foil, so that each particle going through the detector has to go through $200\text{ }\mu\text{m}$ of aluminium. Such a design is likely to exhibit strong coherence RF-coupling, and it is necessary a wake field suppressor. New possibilities for the RF shield are being considered to minimise this effects, like having a waving surface (TOBLERONE shape) between the detectors and the beam line.

The construction of the complete assembly is made in two halves which can be moved apart vertically, see figure 3. The two halves have a longitudinally offset of 2 cm, and a small overlap region to facilitate the alignment. It is expected that they will be positioned to an accuracy of $5\text{ }\mu\text{m}$.

3.2 Detector design

The design of the VELO detector is constrained by the requirements of the second level trigger (L1). Moreover it has to be radiation hard and has to provide a good vertex resolution. In order to achieve a fast secondary vertex reconstruction ($\sim 500\text{ }\mu\text{s}$), the $R\phi$ geometry has been chosen. In reference [1] one can find more details on how the L1 algorithm takes profit of this geometry.

The $R\phi$ geometry also helps in having a better resistance to radiation com-

LHC-B

60° silicon vertex detector elements

Fig. 4. The strip layout for the R and ϕ measuring detectors.

pared with other geometries (for instance the XY geometry), because the number of strips at small radius are minimised. The baseline detector design for VELO is a single-sided n in n micro-strip detector as they have been proven to be more radiation hard. The size of the strips is variable and goes from 40 μm up to 80 μm for the R-detectors, and from 40 μm up to 105 μm for the ϕ -detectors, as shown in figure 4. The detectors will be operated at low temperature (5°C) under the hypothesis that the detectors at smaller radius are replaced every year.

The baseline design is to have 150 μm thin detectors. Thinner detectors allow to work with lower depletion voltage and therefore increases the resistance to radiation. Moreover, thinner detectors reduce multiple scattering effects improving the detector performance.

Insufficient space is available (without introducing significant dead areas) to route out all the strips in a single metal plane. A double-metal technology as applied by DELPHI [3] has been chosen.

3.3 Readout scheme

The front-end electronics has to store the pre-amplified detector signals in an analogue buffer at an input rate of 40 MHz, waiting for the L0 decision (1 MHz). They need to integrate the signal shape in 25 ns. They are mounted at approximately 7 cm from the beam axis, hence the radiation tolerance of the chips must exceed several hundred krad per year. The SCT128A chip has a fast bipolar analogue front-end and CMOS analogue pipeline and is fabricated in a DMILL technology, see reference [4] for more details. Some modifications are

needed to fully match the LHCb requirements, but it is considered to be one of the baseline solutions for VELO and also for the RICH detectors at LHCb. In parallel, substantial effort is being made to design a new chip (BEETLE) based on the deep sub-micron technology and using the experience with the HELIX chips, see again reference [4] for more details.

Analogue, rather than binary, readout has been chosen since it allows for a better monitoring and control of the radiation damage in the detector. Furthermore, it provides better precision of the reconstructed hits and better signal over noise ratio. Following the positive L0 answer, the data is digitalized using a nine bit ADC, and split into two paths:

- Data are preprocessed (pedestal subtraction, common noise correction and cluster search), and sent to the second level trigger system.
- In the second path the data are stored in a buffer, waiting from a decision of the second level trigger.

On receiving a positive answer from the trigger the data are transmitted over 60 m, by optical data link, to processing electronics.

4 Test beam performance

A prototype of the detectors described in section 3 were designed by the LHCb vertex group and fabricated by Hamamatsu Photonics. A total of 12 prototype detectors (6 R-sectors and 6 ϕ sectors of 61°) were tested in 1998 and 1999. The detectors follow closely the VELO design except that they are $300\text{ }\mu\text{m}$ thin detectors, and therefore the results obtained from the test-beam need to be normalised to what one should expect for a $150\text{ }\mu\text{m}$ thin detector.

In a first test-beam in April-May 1998, the detectors were equipped with (slow shaping) VA2 readout electronics allowing to study the alignment limitations, cluster resolution and the trigger algorithm performance. In a second test-beam in April-May 1999 one of the R-detectors was equipped with a not-yet modified version of the SCT128A chip to test the performance in terms of signal over noise ratio and shaping time. The results of this beam tests are reported in the following sub-sections.

4.1 Test beam setup

The detectors and the electronics were mounted into a telescope comprising of three partial disks each equipped with an R-measuring and a ϕ -measuring detectors. Mounted directly in front of the telescope were a series of thin copper

targets ($300\text{ }\mu\text{m}$) providing a source of secondary vertices that have been used to check the performance of the L1 trigger algorithm [1]. The arrangement of the targets was such that the superposition of several vertices would mimic an LHCb event.

4.2 Alignment and detector performance

The ability to align the detectors with a good precision is an important issue for the trigger performance. At the LHC it is foreseen to calculate the alignment constants online with the measured tracks. However, it is not possible to use this alignment constants (calculated in 3D in space) in the RZ plane. Therefore, the L1 trigger algorithm can only made a partial use of this alignment constants, see reference [1]. In order to have an efficient trigger performance the relative position of the detectors needs to be controlled with a precision better than $10\text{ }\mu\text{m}$.

The position of the detectors in the telescope was determined using a 3D survey machine with a precision of few μm , and has been compared with the alignment constants computed from the minimisation of the χ^2 of the measured tracks. The agreement between both sets of alignment constants is better than $50\text{ }\mu\text{m}$, but is still far from the required precision. More work is necessary to understand the source of such a precision, but it is clear that some kind of feed-back is necessary when the detectors are being installed. In the final procedure, we expect to be able to align the detectors with a precision better than the required $10\text{ }\mu\text{m}$.

The measurement of the cluster resolution obtained from the residuals of the hits in the second station, is about $6\text{ }\mu\text{m}$, in good agreement with the expectations from a pitch size of $40\text{ }\mu\text{m}$ and tracks at normal incidence.

Figure 5 shows the reconstruction of the z-coordinate of the primary vertex using in average three tracks per event. One can observe the different peaks corresponding to the different targets in front of the detectors. The resolution obtained in the target closest to the detectors (about 7.5 cm from the first detector) is about $450\text{ }\mu\text{m}$. This can be translated into a resolution of about $56\text{ }\mu\text{m}$ for an LHC-event, taking into account the expected number of tracks for and LHC-like event (~ 36 tracks), 2π angular coverage in the $R\phi$ plane and deconvoluting the effect of the extrapolation to the first measured point. This $56\text{ }\mu\text{m}$ resolution compares reasonable well with the expected $40\text{ }\mu\text{m}$ from MC simulations [2].

Fig. 5. Reconstruction of the z-coordinate of the primary vertex using the tracks measured in the detectors.

4.3 Fast readout chip (SCT128A) performance

One of the R-measuring detectors has been equipped with four SCT128A chips in April 1999. Before the installation at the test beam, the noise level was measured in the laboratory to be approximately 700 electrons per channel. In the test beam the noise level has been measured to be about 750 electrons in good agreement with the measurements at the laboratory. The average signal over noise ratio (S/N) has been measured to be about 20:1. If we assume a linear dependence between the S/N and the thickness of the detector one can extrapolate this measurement to a S/N about 10:1 for a 150 μm thin detector, which is a little bit low taking into account the expected degradation due to the radiation environment at LHC. The requirement for the VELO detector is an initial S/N ratio of 15:1 for a 150 μm thin detector [2]. Moreover, it is not clear that we can simply assume a linear dependence for such a thin detector, where the amplification of the electronics will play a very relevant role.

The rising time has been determined to be of the order of 25 ns by measuring the pulse-height versus the gate time. About 30 % of the maximum pulse height remains after 50 ns (i.e., after 25 ns from the peak value). This over spill is the maximum value acceptable to not to deteriorate the trigger performance at the LHC as evaluated from MC simulations.

5 Outlook and future plans

5.1 Outlook

A first prototype of the VELO detector has been tested in several test-beams at CERN. It shows reasonable performance, with cluster resolution of about $6\text{ }\mu\text{m}$ for a $40\text{ }\mu\text{m}$ pitch detector. Studies on the alignment procedure show that it is feasible to control the relative alignment of the detectors with a precision better than $50\text{ }\mu\text{m}$, but more work is needed to achieve the final goal of $10\text{ }\mu\text{m}$.

LHCb like events have been mimicked by arranging Cu-targets in front of the Si detectors. The resolution on the longitudinal component of the primary vertex obtained from the test beam data, corresponds to $\sigma_{PV} \sim 56\text{ }\mu\text{m}$, which compares reasonable well with the expectations ($40\text{ }\mu\text{m}$).

The first tests performed with fast electronics readout, (SCT128A chips), show reasonable performance. A signal over noise ratio of 20:1 is measured with the prototypes, which can be interpreted, assuming a linear extrapolation, as a signal over noise ratio of 10:1 for a $150\text{ }\mu\text{m}$ thin detectors and it is at the limit of what we would like to have in LHCb. We expect to improve this performance with a better design for the hybrids. The over spill remnant is measured to be about 30 % of the signal after 50 ns of integration time, which is also at the limit to not to deteriorate the LHCb trigger performance.

5.2 Future plans

The vertex group in LHCb foresees the following milestones:

- Some of this prototypes have been irradiated to about $3 \times 10^{14}\text{p/cm}^2$ with 20 MeV protons. They will be tested at CERN in a dedicated test-beam in August'99.
- Detectors with p in n technology have been ordered (which allows to have smaller pitch size). They will be tested at CERN in a test-beam, and the LHCb vertex group plans to come to a conclusion about the best technology by the end of 1999.
- The optimization of the detector geometry continues. Present studies are focused on having only two modules of 182° with 45.5° sectors. This design will simplify the alignment procedure. We are considering also the possibility to reduce the inner radius to 0.8 cm (compared with 1 cm).
- We plan to test the front-end electronics (modified SCT128A and BEETLE) plus the off-detector electronics in a dedicated test-beam by summer of 2000,

and come to a conclusion by the end of 2000.

- By spring of 2001 the VELO design will be finalised and documented in a Technical Design Report.
- Construction will have commenced in 2003 and comprehensive testing of the full assembly is anticipated in 2004 prior to the detector insertion.
- LHCb aims to be ready for the start of the LHC running, which is planned for 2005.

Acknowledgements

I'm very grateful for the assistance of my colleagues in the LHCb-VELO group in the preparation of this report.

References

- [1] N. Zaitsev, *Contribution to these proceedings*.
- [2] LHCb collaboration, *LHCb Technical Proposal*, **CERN/LHCC 98-4** (1998)
- [3] V. Chabaud *et al*, *Nucl. Instrum. and Methods*, **A368** (314) (1996).
- [4] M. Feuerstack-Raible, *Contribution to these proceedings*.