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The LHCb vertex detector

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Abstract

LHCb is a next generation experiment for the study of CP violation in B-meson decays. Efficient triggering is a key issue in this 14 TeV proton collision experiment with a bunch crossing frequency of 40 MHz. The vertex detector delivers full analog event information at a rate of 1 MHz to the level-1 trigger for identification of tracks with a high impact parameter. The silicon micro-strip sensors of the vertex detector are installed in a secondary vacuum close to the beams. They must be retracted during beam injection. The signals of the strips are read out with radiation hard analog chips called 'Beetles'. The performance of the Beetle1.1 was measured in a test beam. System tests are planned for 2004.

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1. Introduction

The LHCb experiment is designed to study CP violation and other rare phenomena in B-meson decays with high precision [1]. At LHC, a 14 TeV proton collision machine with a bunch crossing frequency of 40 MHz, the B and $\overline{\mathrm{B}}$-hadrons will predominantly be pair produced by gluon fusion and boosted along the beam axis in the same forward (or backward) cone. LHCb is therefore designed as a single-arm spectrometer with a forward angular coverage from approximately 15 to 300 mrad [2]. The LHCb design luminosity of $2 \times 10^{32}\,\mathrm{cm}^{-2}\,\mathrm{s}^{-1}$ results in an expected rate of 10^{12} $\mathrm{B\overline{B}}$ pairs per year. This large amount of B-mesons allows for profound understanding of quark flavor physics in the framework of the Standard Model and may reveal a sign of the physics beyond.

At LHC about 1 in 160 events contains a B-meson. Given their lifetime and boost, they travel a few millimeters before they decay into other particles. The vertex detector provides full analog event information at a rate of 1 MHz to the level-1 trigger, which identifies these B-events by the high impact parameter of the decay products and reduces the event rate to 40 kHz. In Section 2, the design considerations of the vertex detector will be explained in more detail. The design of the

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silicon sensors for the vertex detector will be presented in Section 3. In Section 4, the performance of the Beetle read-out chip is discussed.

2. Design of the vertex detector

The vertex detector will allow to reconstruct the decay length of a B-meson with a resolution of about 22 μm in the transverse and 144 μm in the longitudinal direction $(D_s\pi)$. In combination with a momentum resolution of 0.4% of LHCb, this means we can resolve B_s-oscillations with 5σ sensitivity up to a mass difference of $68\,\mathrm{ps}^{-1}$ within 1 year of data taking. The Standard Model prediction of this mass difference is 20–25 ps^{-1}, but new physics may drastically affect this value.

The silicon strip sensors used for track reconstruction are arranged as schematically shown in Fig. 1 [3]. Forward tracks are almost perpendicular to the detector plane and can be reconstructed accurately. The active area of the silicon sensors starts at just 8 mm from the beams. During injection, the minimum required aperture is 30 mm, so the sensors need to be retracted. Each station, therefore, consists of two sets of sensors covering slightly more than 180° to obtain full ϕ-coverage and to accommodate for alignment. The complete vertex detector can be repositioned with $2XY$ tables to center around the beams before the two detector halves are moved into their measurement positions. In total, there are 21 stations for the vertex detector. Outside the acceptance in the backward direction two extra stations are mounted, that constitute the pile-up detector. This device is used in the level-0 trigger to identify events with too many primary vertices. A thin aluminum foil shields the silicon sensors against RF radiation from the beams. It also acts as a wakefield guide and avoids pollution of the beam vacuum due to outgassing of cables and electronics. The complex shape of this foil is shown in Fig. 2. It accommodates for overlap between the detectors and reduces the average radiation length that the particles traverse.

The foil has a thickness of only 250 μm and is produced using super plastic hot gas formation, a technique that allows for extreme deformations in thin foils. It can withstand a pressure difference up to 15 mbar without plastic deformation, which implies that the pressure on both sides needs to be monitored and controlled at all times. The simplest and most stable mode of operation is by maintaining a secondary vacuum in the volume that contains the silicon sensors. A cross-section of one of the detector housings is shown in Fig. 3. The bellow needed for retraction of the sensors, the sensors and the foil are indicated. The procedures for bake out of the primary vacuum and installation of the silicon sensors involve transient states with controlled simultaneous evacuation and venting of both vacua [4].

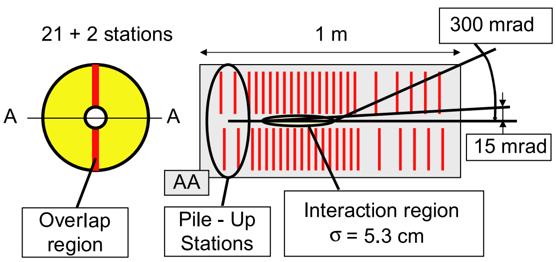

Fig. 1. Sensor arrangement in vertex detector.

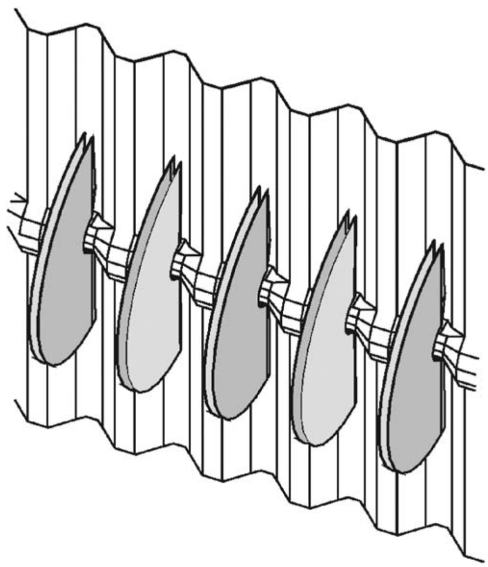

Fig. 2. Sensors with foil.

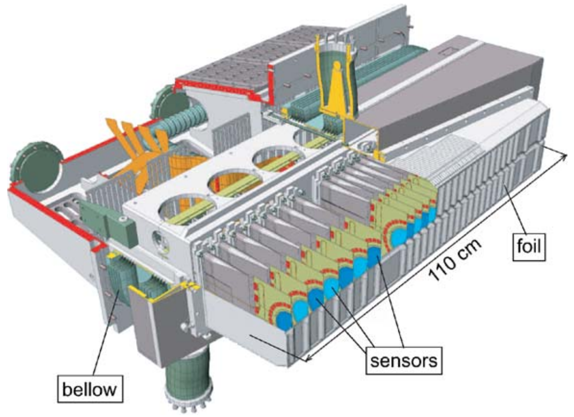

Fig. 3. Cross-section of the silicon strip detector housing.

3. Silicon sensors

The silicon micro-strip sensors contain 2048 strips and are 220 μm thick. The signals are routed via a double-metal layer to the read-out system. Each station has two sets of sensors with *R*-strips and ϕ-strips mounted back to back. As a result, the highest *XY*-resolution is achieved for tracks closest to the interaction region. The inner radius of the active area of the sensor is 8.0 mm and the outer radius is 42.2 mm. The pitch varies from 40 μm (32.5 μm) in the inner region to 101.6 μm (96.6 μm) for the $R(\phi)$-sensor. The ϕ-strips have a dog-leg shape due to the stereo angles of -20° in the inner region and $+10^\circ$ in the outer region. The stations are alternately installed with the *R*- and ϕ-strips upstream, which helps to resolve ambiguities when *R* and ϕ information of different tracks is combined. A typical event in LHCb has about 70 tracks. The *RZ*-coordinates of hits in a 45° segment are projected to efficiently identify tracks with high impact parameter in the level-1 trigger.

The silicon sensors have to operate in a harsh radiation environment due to the proximity to the LHC beams. The expected maximum flux is 2×10^{14} charged hadrons and 1×10^{13} neutrons per square centimeter per year and varies slightly from station to station. As the sensor material, n-on-n oxygenated silicon was selected. Hit identification can stay close to 100% efficient for n-on-n detectors even when the depletion depth is reduced to 60% of the total detector thickness. The r^{-2} dependence of the radiation intensity in this region poses an additional challenge, because the detector has to withstand the high bias voltages needed for the irradiated parts of the sensor in a region that is not yet type inverted. The temperature of the sensors should be kept below $-5\,^\circ C$ to avoid thermal runaway. The cooling of the sensors is provided by a closed-loop CO_2 evaporation cooling system. This system is mounted outside the acceptance as much as possible and high conductivity carbon is used as a support for sensors and chips to conduct the heat with a minimal amount of material.

4. Read-out chip

The Beetle [5] is a 128 channel read-out chip with an analog pipeline that implements the RD-20 front-end architecture [6]. The chip design is based on 0.25 μm CMOS integrated circuit technology. The chip was designed to withstand high radiation doses and tests up to 300 kGy (corresponding to about 15 years of LHCb operation) showed no deteriorating effects. A prototype hybrid equipped with 16 Beetle1.1 chips was extensively tested at the 120 GeV pion beam facility at CERN. A 300 μm thick PR02-R p-on-n silicon sensor was used as detector [7].

The clock frequency of the chip is 40 MHz, equal to the bunch crossing frequency of LHC. The sampling phase is tuned to the peak of the pulses generated by the traversing particles. In the beam-test, the system was extended with two scintillators to generate the trigger and an *XY* tracking station. The beam was continuous in the spill. Hence, in this setup the phase between the clock pulse and the trigger was not fixed and the time difference between the two was measured with a TDC. A single trigger issued the read-out of eight consecutive time samples of 25 ns, spanning a total period of 200 ns.

One can reconstruct the transient response of the Beetle chip to charge depositions of minimum ionizing particles by plotting the pulse height as a function of the time difference measured by the TDC, as shown in Fig. 4. The characteristics of this response are mainly determined by the

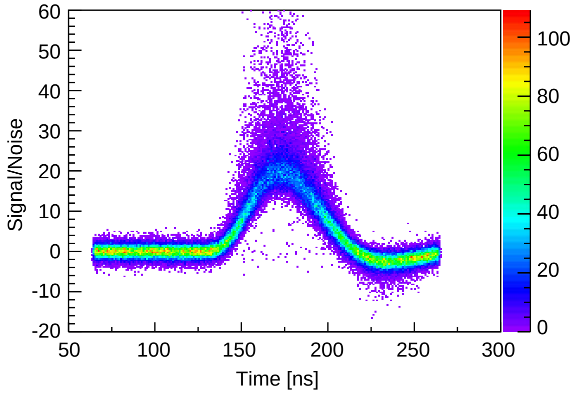

Fig. 4. Response of the Beetle1.1. The amplitude is plotted versus time. The highlights indicate the number of entries.

transfer function of the front-end circuit of the chip. The time-constants and gain of this circuit can be tuned.

The most interesting pulse shape characteristics for LHCb are: rise time, signal/noise ratio and spill-over. Rise time is defined as the time difference between the moments where the pulse height amounts to 10% and 90% of the maximum pulse height. Spill-over is the value of the pulse height 25 ns after the pulse reached its maximum height divided by the maximum pulse height. These two characteristics indicate whether the read-out is fast enough to process events that are only 25 ns apart. Signal/noise ratio is the most probable pulse height divided by the RMS of the baseline fluctuations. The pulse shape characteristics for the Beetle1.1 tuned for LHCb are: signal/noise ratio = 17.5 ± 1, risetime = 23.5 ± 1 ns, spill–over = $36.1 \pm 2\%$. The average capacitance of strips and routing lines connected to the chip is about 10 pF for this setup. Combined with a measurement of the ENC relation of the front-end circuit ($500e^- + 50e^-pF^{-1}$) and the scaling from 300 μm to a 220 μm thick detector, this results in a predicted range of signal/noise ratios of 11–16 for the various sensor areas in the LHCb vertex detector.

The Beetle1.3 is the latest version of the chip and contains various improvements. The pre-amplifier current limit of 350 μA is increased to the maximum design value of 2 mA by solving a design flaw in the DAC circuitry. The amplification of the output is increased by a factor of 16, since the output signal was too small compared to environmental noise. Another problem in the design, causing trapped charge in a capacitance of the read-out amplifier circuit to transfer −30% of the signal to the next read-out, is solved as well. The threshold circuit of the comparator, needed for the digital output, is increased from 3 to 5 bits per channel to cope with channel to channel offset variations and still provide sufficient resolution (better than 0.05 MIP). Furthermore, the 80 MHz cross-talk from the logical circuits to the analog output is reduced. A fully equipped hybrid with 16 Beetle1.3 chips will be tested in the SPS beam in the first half of 2004. This is probably the chip version that will be installed in the vertex detector.

5. Conclusions

The LHCb experiment is designed to study CP violation and other rare phenomena in B-meson decay with high precision. We will be able to resolve B_s-oscillations with 5σ sensitivity up to a mass difference of 68 ps^{-1}.

The radiation hard 220 μm thick n-on-n oxygenated micro strip sensors are installed in a secondary vacuum only 8 mm from the beams. During injection, the minimum required aperture is 30 mm, so the sensors will be retractable. The *RZ*-coordinates of hits in a 45° segment are projected to identify tracks with high impact parameter in the level-1 trigger at a rate of 1 MHz.

The sensors are read-out by analog chips called 'Beetles'. The pulse shape characteristics of the Beetle1.1 tuned for LHCb are: signal/noise ratio = 17.5 ± 1, risetime = 23.5 ± 1 ns and spill − over = $36.1 \pm 2\%$. Combined with the ENC relation of $500e^- + 50e^-\,pF^{-1}$ and the scaling from 300 μm to a 220 μm thick detector, this results in a predicted range of signal/noise ratios of 11–16 for the various sensor areas of the LHCb vertex detector. The Beetle1.3 is the latest version of this chip and contains various improvements. This version is expected to be installed in the vertex detector. System tests are planned for early 2004.

References

[1] S. Amatao, et al., LHCb Technical Proposal, CERN/LHCC 98-4, February 1998.
[2] R. Antunes Nobrega, et al., LHCb Reoptimized detector, CERN/LHCC 2003-030, September 2003.
[3] P.R. Barbosa Marinho, et al., LHCb VELO, CERN/LHCC 2001-011, May 2001.
[4] Van den Brand, et al., Vacuum 67 (2002) 363.
[5] N. van Bakel, et al., Beetle reference manual, LHCb 2001-046.
[6] R. Brenner, et al., Nucl. Instr. and Meth. A 339 (1994) 564.
[7] S. Klous, et al., Characteristics of 16 Beetle1.1 chips on a VELO hybrid, LHCb 2003-069.