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The LHCb silicon tracker

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Abstract

LHCb is a dedicated B-physics and CP-violation experiment for the Large Hadron Collider at CERN. Efficient track reconstruction and excellent trigger performances are essential in order to exploit fully its physics potential. Silicon strip detectors providing fast signal generation, high resolution and fine granularity are used for this purpose in the large area Trigger Tracker station in front of the spectrometer magnet and the LHCb Inner Tracker covering the area close to the beam pipe behind the magnet. Long read-out strips of up to 38 cm are used together with fast signal shaping adapted to the 25 ns LHC bunch crossing. The design of these tracking stations, the silicon sensor strip geometries and the latest test results are presented here.

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1. Introduction

LHCb [1] is designed as a dedicated B-physics experiment at the LHC, the pp-collider currently under construction at CERN. CP-violation and

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other precision measurements with B-mesons play an increasingly important role in the tests of the Standard Model and searches for physics beyond.

The LHCb detector is a single arm forward spectrometer, taking advantage of the angular distribution of the produced $b\bar{b}$ pairs, which peaks strongly along the beam direction. The detector has a 300 mrad polar angle coverage in the bending plane of the magnet and 250 mrad perpendicular to it. The silicon-microstrip vertex detector, the Trigger Tracker (TT)-station before the magnet and the tracking stations T1–T3 behind the magnet are used to reconstruct charged particle trajectories. The detector is completed by two RICH detectors for particle identification, electro-magnetic and hadronic calorimeters and muon detectors at the far end of the spectrometer.

The T1–T3 stations are split into the Inner Tracker [2], consisting of silicon strip detectors in the region of high particle densities near the beam-pipe, surrounded by the Outer Tracker built from straw-tubes. The Inner Tracker together with the TT-station [3,4] are referred to as the LHCb Silicon Tracker. The entire solid angle of the TT-station is covered by silicon strip detectors in order to give optimal performance of the second trigger level, where the TT-station is used to add transverse-momentum information to large-impact parameter tracks.

Simulation studies have shown that the momentum resolution in LHCb is dominated by multiple scattering over a wide range of momenta. This results in a spatial resolution requirement which is met by silicon micro-strip detectors with a read-out pitch of the order of 200 μm. Large read-out pitch and long read-out strips, adapted to the expected hit occupancies, are used throughout the Silicon Tracker in order to reduce the number of read-out channels and hence the costs. The Silicon Tracker covers a total area of 12.2 m^2 with 270k read-out channels.

2. Inner tracker design

Each Inner Tracker station [2] consists of four individual detector boxes which are arranged around the beam pipe as shown in Fig. 1. The side boxes contain Si-ladders that are 22 cm long and are built out of two sensors. The detector boxes above and below the beam-pipe employ single-sensor ladders. The geometry is well adapted to the distribution of the charged particle density in the experiment which is highest within the horizontal bending plane of the magnet. Each detector box houses 28 Si-ladders in four detection layers, with the two inner layers placed with a $\pm 5^{\circ}$ stereo angle. The boxes provide electrical and thermal insulation.

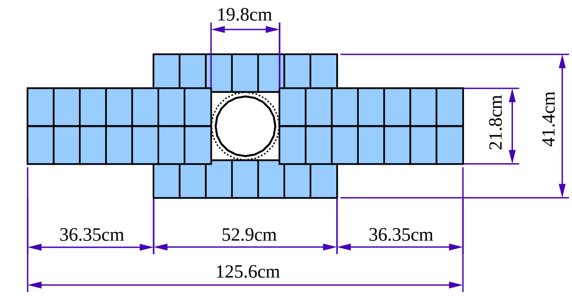

Fig. 1. The layout of one Inner Tracker station consisting of four individual detector boxes.

The single-sided, AC coupled p^+n silicon strip sensors are 7.8 cm wide and 11 cm long. The sensor thickness is chosen to be 320 μm for the short ladders and 410 μm for the two sensor ladders in order to ensure sufficient signal in the presence of the increased noise due to increased load capacitance. The read-out pitch is 198 μm and each ladder is read out via 3 Beetle [5] read-out chips. The Beetle is a 128-channel, custom-made analog read-out chip using commercial 0.25 μm CMOS technology with a radiation hard design. It operates at 40 MHz and saves events into a pipeline with a maximum latency of 160 clock cycles. The shaping time can be varied via an internal programmable register (V_{fs}) which changes the feedback resistance. The analog data of triggered events are sent via a copper cable about 5 m long to service boxes located just outside the acceptance of the experiment, where the signals are amplified and digitised before they are multiplexed onto a 100 m digital optical link.

3. TT-station design

The TT-station consists of four layers arranged in two half stations, TTa and TTb, separated by 30 cm along the beam axis and enclosed in a single box providing electrical and thermal shielding. The operation temperatures of the TT-station and the Inner Tracker are foreseen to be 5 °C in order to reduce the noise contribution due increased leakage current caused by irradiation. Fluences of up to $5.5 \times 10^{13}\,\text{cm}^{-2}$ 1 MeV neutron equivalent are expected at the centre of the TT-station after 10 years of operation.

The box can be split vertically in order to retract the two halves, allowing access to the beam-pipe for the bake-out procedure. As in the Inner Tracker, the first and the fourth layer have vertical read-out strips, while the inner two layers have a stereo angle of $\pm 5^\circ$.

For the sensors used for the TT-station, the most cost-efficient solution which fully matches our requirements, is to employ a sensor design from the outer barrel of the CMS silicon tracker [6]. The 500 μm thick sensors have a width of 9.6 cm and a length of 9.4 cm. The 512 read-out strips with a pitch of 183 μm are read out via 4 Beetle [5] read-out chips.

The sensors are arranged in read-out sectors of one and two sensors in the centre around the beam pipe as indicated in Fig. 2. Read-out sectors consisting of three sensors bonded together are used near the centre of the bending plane and four sensors, i.e. 38 cm long strips, in the outer area of the detector. The read-out hybrids are located at the outer edge of the detector, outside the acceptance. The inner sectors are connected to the read-out hybrids via 40 cm long Kapton interconnect cables. A cable of 58 cm length connects to the single sensor near the beampipe. This results in a load capacitance of up to 57 pF for the pre-amplifier.

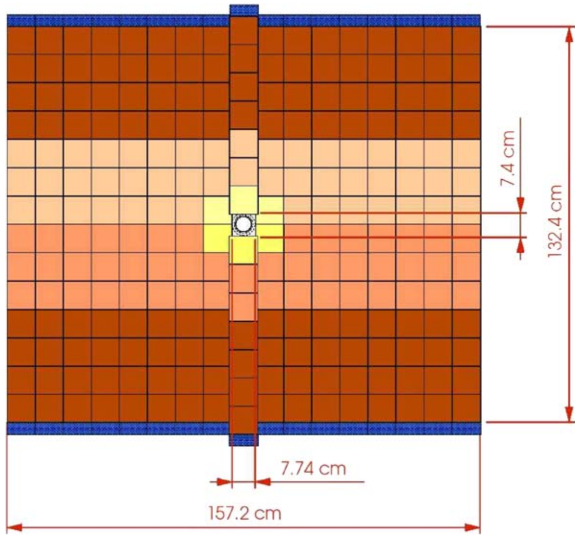

Fig. 2. The layout of one layer in the TT-station (TTb) is shown. The entire LHCb angular coverage is provided by silicon strip detectors. Short read-out sectors are used in the centre around the beam pipe, longer read-out sectors of up to four sensors elsewhere.

4. Test results

Several prototype modules were built with different sensor thickness, strip length and implant:pitch ratio in order to study the resulting noise behaviour w.r.t. the input load capacitance, the overall S/N ratio, the charge loss in the inter-strip region for the large pitch detectors and the shaping time. These results are used in order to extrapolate the performance to the actual detector layout.

Starting with the expected charge generated in the sensors, the equivalent noise charge for different strip capacitances is deduced from the observed S/N values. The results are shown in Fig. 3 together with the expectation from laboratory measurements, where load capacitances have been connected to the input of the Beetle chip on a test-bench. Good agreement is found for the dependence of the noise on the load capacitance, with a small offset indicating an additional constant noise source in the test-beam set-up. This dependence can be used to extrapolate the S/N expectation for modules with increased load capacitances due to Kapton interconnect cables or additional sensors.

The shaping time has been varied by means of the V_{fs} setting in order to study the remaining signal 25 ns after the maximum, i.e. in the

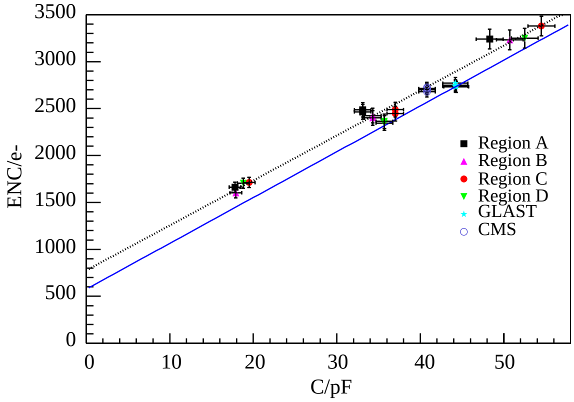

Fig. 3. The equivalent noise charge obtained with the Beetle read-out chip depending on its input load capacitance. Regions A–D correspond to different implant and pitch widths on LHCb Inner Tracker prototype sensors. Other measurements were taken with modules built from CMS [6] and GLAST [7]. The dashed blue (upper) line is the best fit to the test-beam data while the solid black (lower) line is the expectation from laboratory measurements.

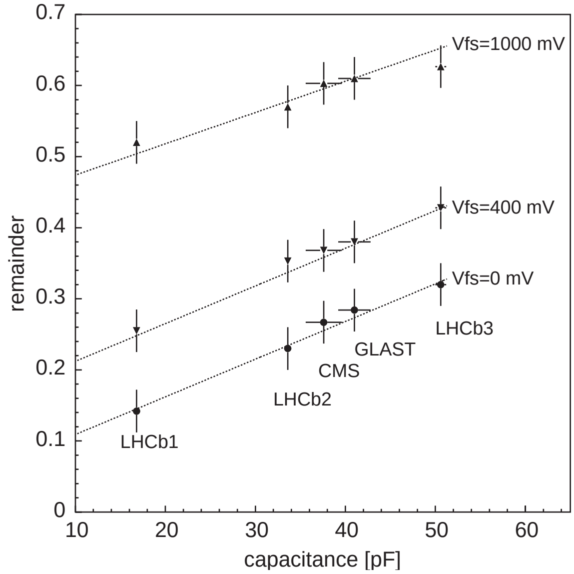

Fig. 4. Signal remainder fraction after 25 ns, i.e. one bunch crossing.

consecutive bunch crossing. The signal width increases with increasing load capacitance as seen in Fig. 4. It is shown that with V_{fs} settings below 400 mV, the signal remainders can be kept below 30% and 50% as required for the Inner Tracker and the TT-station, respectively. The maximum load capacitances for the Inner Tracker and for the TT-station are $\approx$ 35 pF and $\approx$ 57 pF, respectively.

Fig. 5 shows measurements of the S/N ratio for different positions of the incident particle relative to the read-out strips, for a module built out of three CMS-OB2 sensors. The decrease of the S/N ratio between the strips is due to a charge loss in this area already observed in previous measurements [2]. The final detector design requires the S/N ratio to be high enough between two read-out strips such that full hit detection efficiency can be obtained with less than 0.05% noise clusters per read-out strip and event.

In a recent test-beam period, a TT-module consisting of three CMS-OB2 sensor and a 40 cm Kapton interconnect cable has been tested. Preliminary results indicate the S/N behaviour is as expected, though the analysis is on-going.

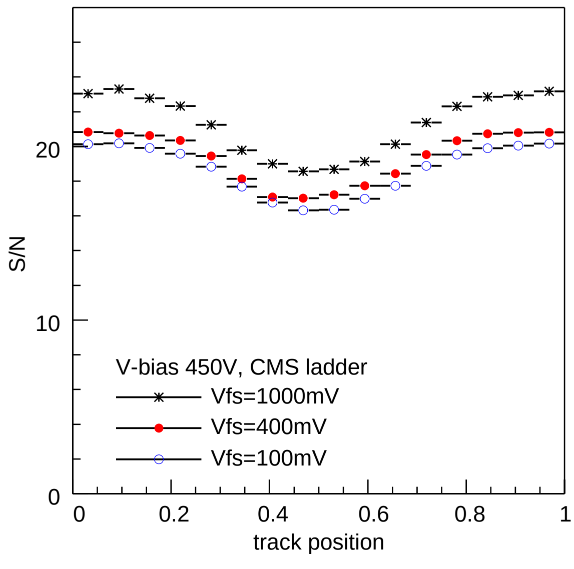

Fig. 5. The S/N for different shaping times, depending on the relative positions of the incident particle w.r.t. the read-out strips. Positions 0 and 1 correspond to the centre of the read-out strip.

5. Summary

The LHCb Silicon Tracker is designed using silicon strip detectors with up to 38 cm long read-out strips, a large pitch of ≈ 200 μm and fast read-out electronics adapted to the 40 MHz bunch crossing rate at the LHC. Test-beam measurements of the prototype modules have shown performance according to expectations and within the specification of the LHCb experiment.

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