Compiled from conference proceedings, IWORID 2005, Grenoble LHCb Note 2005-80

Performance studies of the silicon strip detectors of the LHCb Silicon Tracker

B. Adeva, [5] M. Agari, [1] C. Bauer, [1] A. Bay, [3] R.P. Bernhard, [4] R. Bernet, [4] J. Blouw, [1] B. Carron, [3] Y.Ermoline, [4] D. Esperante, [5] R. Frei, [3] J. Gassner, [4] W. Hofmann, [1] S. Jimenez-Otero, [3] K.T. Knöpfle, [1] S. Köstner, [4,*] F. Lehner, [4] S. Löchner, [1] C. Lois, [5] M. Needham, [4] V. Pugatch, [2] M. Schmelling, [1] O. Schneider, [3] B. Schwingenheuer, [1] O. Steinkamp, [4] U. Straumann, [4] M.T. Tran, [3] P. Vazquez, [5] A. Vollhardt, [4] D. Volyanskyy, [4] H. Voss, [4,*] A. Wenger [4]

Abstract

LHCb is one of the experiments at the Large Hadron Collider at CERN. It is dedicated to B-physics and CP-violation measurements. To fully exploit its physics potential, a good tracking performance with high efficiency in the high particle density environment close to the beam pipe is required. For this purpose, the LHCb Silicon Tracker uses strip detectors with large read-out pitch and long strips. We give a summary of the R&D program of the Silicon Tracker and of performance studies for the long term operation in the LHC radiation environment.

Key words: LHCb, silicon, tracker, detector
PACS: 07.77.Ka, 29.40.Wk,

1. Introduction

The LHCb detector (1) at the Large Hadron Collider is dedicated to study the physics in the decay of b-flavoured hadrons. It is designed as a single arm forward spectrometer adapted to the angular distribution of the $b\bar{b}$ pairs which are produced predominantly at low polar angles.

A silicon-strip vertex detector, the TT station (2) located in the fringe field in front of the 4 Tm dipole magnet and the tracking stations T1-T3 downstream the magnet are used to reconstruct charged particle trajectories. The tracking stations are split into a straw tube Outer Tracker

* corresponding authors, email: Helge.Voss@cern.ch, Stefan.Koestner@cern.ch
[1] Max Planck Institut für Kernphysik, Saupfercheckweg 1, 69117 Heidelberg, Germany
[2] Ukrainian Academy of Science, UA-252 143, Kiev 143, Ukraine
[3] LPHE, EPFL Lausanne, Bât. des Sciences Physiques, 1015 Dorigny, Switzerland
[4] Physik-Institut der Universität Zürich, Winterthurerstr. 190, 8057 Zürich, Switzerland
[5] Universidad de Santiago de Compostela, Campus Universitario Sur, 15706 Santiago de Compostela, Spain

and the silicon-strip Inner Tracker (3) in the high particle density region near the beam pipe. The TT station covers the full acceptance of the experiment with silicon-strip detectors and provides together with the vertex detector an estimate of the transverse momentum of charged particles at the Level-1-trigger.

2. Silicon Tracker Design

The Silicon Tracker project comprises the Inner Tracker and the TT station. Simulation studies have shown that the momentum resolution in LHCb is dominated by multiple scattering up to 80 GeV/c. This results in a spatial resolution requirement which is met by silicon-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.

Each Silicon Tracker station consists of four detection layers where the inner two layers are arranged with a $\pm 5^\circ$ stereo angle. The Inner Tracker stations consist of four individual detector boxes surrounding the beam pipe. 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 with 11 cm long strips. Each detector box houses 28 Si-ladders in total. The TT station is housed in a single large box surrounding the beam pipe. The box which provides electrical and thermal insulation is split in halves that can be retracted for installation and maintenance and for the bake-out of the beam pipe.

Single-sided AC coupled p^+n silicon-strip sensors are used for the TT station and the Inner Tracker. The Inner Tracker sensor thickness is 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 with a width-over-pitch ratio of 0.25.

For the TT station, the sensor design from the outer barrel of the CMS silicon tracker (4) could be used. This design features 500 μm thick sensors that have 512 strips on 9.6 cm wide sensors with a length of 9.4 cm. The strip pitch is 183 μm and the width-over-pitch ratio 0.25. The sensors are arranged in read-out sectors with a length of 1,2,3 and 4 sensors matching the different particle densities in the detector. All read-out hybrids are located at the edge of the detector outside of the acceptance. The inner read-out sectors are connected via up to 58 cm long Kapton interconnect cables. This design results in load capacitances of up to 57 pF for the pre-amplifier of the read-out chip.

All ladders are read out via Beetle read-out chips (5). The Beetle is a 128 channel custom made analog read-out chip using commercial 0.25 μm CMOS technology design. It is operating at 40 MHz. The shaping time can be varied via an internal programmable register (V_{fs}) which changes the feedback resistance. This is an important feature which allows to optimize signal shape versus noise performance for the various detector geometries with different capacitive loads.

3. Performance Studies

Several prototype modules with different sensor thicknesses, strip lengths and implant-width over pitch ratios were built and tested in a 120 GeV/c π^- beam at CERN. A full documentation on the test beam results and the geometries of the ladders under test can be found in (6) (7).

An important parameter to characterize silicon-strip detectors is the signal-to-noise ratio (S/N). The signal scales linearly with the detector thickness, while the internal serial noise of the Beetle front-end amplifier increases with the capacitive load and with shorter shaping times.

The equivalent noise charge as a function of strip capacitance was deduced from the observed S/N values. The results are shown in Fig. 1 together with the noise performance from laboratory measurements, where discrete load capacitances were directly connected to the input of the Beetle chip on a test-bench. Good agreement is found for the

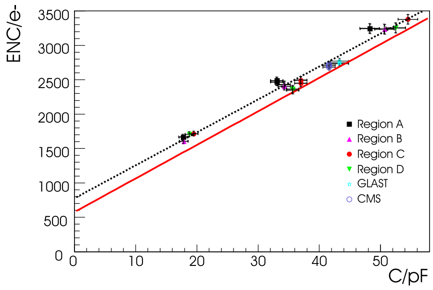

Fig. 1. Equivalent noise charge obtained with the Beetle read-out chip as a function of its input load capacitance. The measurement points correspond to the various detectors with different geometries. The dashed line is the best fit to the test-beam data while the solid line is the expectation from laboratory measurements.

dependence of the noise on the load capacitance, with a small offset indicating an additional constant noise source in the test-beam setup. The observed dependence can be used to estimate the expected S/N for modules with increased load capacitances due to Kapton interconnect cables or additional sensors. For a shaper setting of $\mathrm{V_{fs}}$ = 400 mV the parametrisation is fitted as ENC = $542 + 49.83 \times \mathrm{C}$, where C denotes the sum of backplane capacitance and inter-strip capacitance.

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. at the time of the next LHC bunch crossing. The signal width increases with increasing load capacitance. 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 capacitance is ≈35 pF for the Inner Tracker and ≈57 pF for the TT station.

The S/N ratio was measured as a function of the relative position of the incident particle w.r.t. the read-out strips and a charge loss in between the strips was observed (6). The dependence of this charge loss on the sensor geometry can be parameterised as a linear function $\mathrm{S_{between-strips}} = (1.06 - 0.66 \cdot (p-w)/d) * \mathrm{S_{on-strip}}$, where p is the strip pitch, w the implant width and d the thickness of the detector. The final detector design requires the S/N ratio to be high enough also in 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. The sensor parameters for the Silicon Tracker detectors were chosen such that these requirements are fulfilled.

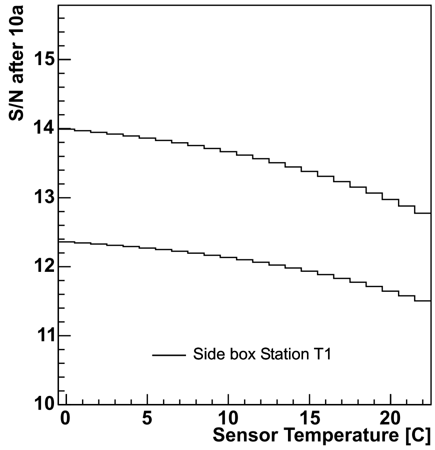

Fig. 2. S/N performance after 10 years of operation. With increasing sensor temperature the S/N value decreases due to the higher shot noise contribution. The lower line shows the scenario with an additional increase of the total strip capacitance due to surface effects.

4. Expected Performance after Ten Years of Operation

Simulations of the expected radiation dose for the Silicon Tracker can be found in (8). Close to the beam pipe it reaches up to approximately 10^{13} of 1 MeV neutron equivalent/cm^2 after 10 years of operation for the Inner Tracker and $5 \cdot 10^{13}$ 1 MeV neutron equivalent/cm^{2}for the TT station. The impact of this radiation damage on the performance of the Silicon Tracker is studied in (9) (10).

The leakage current due to radiation damage is proportional to the integrated flux and can be parameterised as $I_{leak} = \alpha \cdot \Phi \cdot V$ where: where $\alpha = 4 \cdot 10^{-17}\,\mathrm{Acm^{-1}}$ is the induced damage constant for 1 MeV neutrons (11) at 20 ° C, Φ is the particle flux in 1 MeV neutrons equivalent/cm^2 and V is the irradiated silicon volume. The leakage current depends exponentially on the silicon temperature:

$$\frac{I_{leak}(T_1)}{I_{leak}(T_2)} = \left(\frac{T_1}{T_2}\right)^2 \cdot exp\left(\frac{E_g(T_1 - T_2)}{2k_B T_1 T_2}\right), \qquad (1)$$

where $E_g = 1.2\,\text{eV}$ is the band-gap and $k_B = 8.6 \cdot 10^{-5}\,\text{eV/K}$ is the Boltzman constant. The increased leakage current leads to an enhancement of the noise due to shot noise. It has to be ensured that after ten years of operation the signal-to-noise performance of the sensors is sufficiently high to guarantee full hit reconstruction efficiency.

In Fig. 2 the estimated signal-to-noise performance after 10 years of operation is plotted as a function of the detector temperature for the innermost ladders of the Inner Tracker side boxes in the first station. Due to radiation damage on the surface, an enhancement of the strip capacitance could occur as observed in (12). A possible increase of the total strip capacitance by 15 % is taken into account for the lower line. Test beam measurements with sensors irradiated up to the equivalent of ten years of operation show that charge loss due to radiation damage can be neglected. The estimates show that even at room temperature a sufficient signal-to-noise ratio, higher than 11, can be expected for the hottest regions around the beam pipe. This holds as well for the inter-strip region with its additional 15 % charge loss. The situation becomes even better for the boxes on the top and bottom of the beam pipe. Differences between the various stations are not significant.

For a safe operation it has to be ensured that the required operation voltage does not exceed the specified 500 V. With increasing radiation damage the initial n-doping effectively decreases, until type inversion occurs and the sensors become effectively p-type. The required bias voltage decreases and increases again with the increasing p-doping concentration. The fluence-dependent depletion voltage of silicon sensors has been investigated and modeled in the so-called 'Hamburg model', which takes into account stable damage, short-term beneficial annealing as well as long-term reverse annealing (13).

The calculated change of the depletion voltage as a function of operation time at LHCb is shown in Fig. 3 for the 410 μm thick sensors in the side boxes, closest to the beam pipe. In this calculation, a safety factor of two on the expected radiation dose is taken into account. For a specified initial resistivity of 4-9 kΩcm, various operation scenarios were calculated to investigate the effects of operating temperatures and warm-up scenarios, which affect the beneficial and reverse annealing. For all scenarios the final full depletion voltage does not exceed 100 V after 10 years.

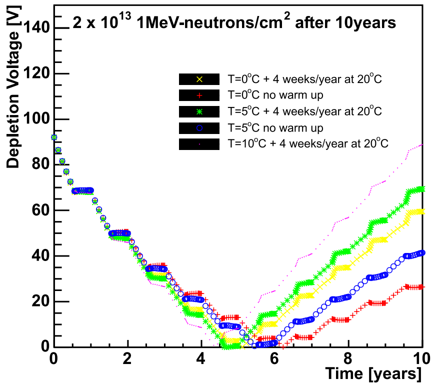

Fig. 3. Depletion voltage as a function of operation time for the Inner Tracker. For the 410 μm thick sensors of the side boxes the required depletion voltage is plotted as a function of operation time.

Cooling of the sensors helps to reduce the noise induced by leakage current, but it is primarily needed to ensure stable running conditions. As silicon has a negative temperature coefficient, the heat dissipated by the leakage current needs to be removed as otherwise the induced heating would in turn further increase the leakage current. This positive feedback is known as 'thermal runaway'.

For cooling of the sensors, the Inner Tracker relies on natural heat convection on the detector surfaces. The estimated heat convection transfer coefficient for natural convection averaged over the whole surface of the sensor is about $4 - 5\,\text{W/m}^2\text{K}$. The resulting cooling power is then given by multiplying this heat transfer coefficient by the detector surface and the temperature difference to the ambient.

The estimated heat dissipation and cooling power for the innermost sensors in the side boxes, where the dose is highest, is plotted in Fig. 4 as a function of the temperature of the detector surface. As long as the cooling power is higher than the dissipated heat, the detector operates under stable conditions. The figure shows that this is achieved already at sensor temperatures below 10°C at an ambient temperature of 5°C. If the integrated radiation dose is a factor two higher

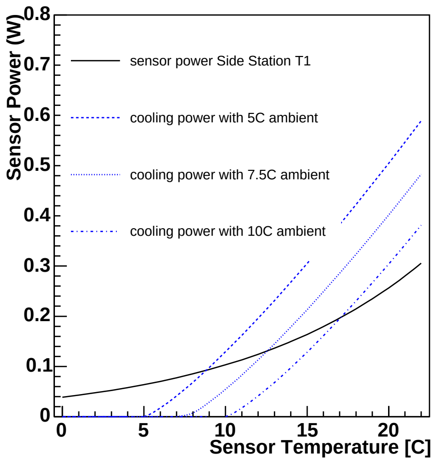

Fig. 4. Study of thermal runaway in the side boxes of the first Inner Tracker station. To remove the dissipated power, natural heat convection is assumed. The dashed lines represent the removed heat by natural convection for three different ambient temperatures as a function of the sensor temperature. A bias voltage of 300 V is assumed.

than expected, the situation becomes critical towards the end of the 10 years. As a safety measure the design foresees the possibility to exchange the ladders in the innermost region with those at the outer regions of the side boxes, where the flux is almost an order of magnitude smaller. Similar studies have been performed for the TT station over the full lifetime of the experiment, with a possible replacement of the innermost sensors (9).

5. Summary

The LHCb Silicon Tracker is designed using silicon strip detectors with up to 38 cm long read-out strips, a strip pitch of ≈200 μm and fast read-out electronics adapted to the 40 MHz bunch crossing rate at the LHC. The interpolation of results from test-beam measurements using various prototype modules were used to fix the final geometrical design parameters of the silicon sensors to match the requirements of the LHCb experiment. It has been shown that a stable and robust long-term operation in the expected radiation environment can be achieved over the lifetime of the experiment.

The production of the Inner Tracker and TT-modules has started and is expected to be completed by May 2006.

References

[1] LHCb Coll., CERN/LHCC 98-4.
[2] LHCb Coll., CERN/LHCC 2003-030.
[3] LHCb Coll., CERN/LHCC 2002-029.
[4] J.-L. Agram et al., CMS-Note 2003-015.
[5] U. Trunk et al., CERN/LHCC 2003-055.
[6] M. Agari et al., LHCb-Note 2003-082.
[7] M. Agari et al., LHCb-Note 2004-103.
[8] G. Corti and L. Shektman, LHCb-Note 2003-083.
[9] M. Siegler et al., LHCb-Note 2004-070.
[10] H. Voss and S. Köstner, LHCb-Note 2004-106.
[11] M. Moll et al., ROSE/CERN-RD48 Collaboration, NIM, A426, (1999), 87-93.
[12] S. Braibant et al., NIM, A485, (2002), 343.
[13] M. Moll, thesis, University Hamburg, 1999.