The Silicon Inner Tracker for LHCb

Olaf Steinkamp

Physik-Institut der Universität Zürich
Winterthurerstrasse 190, CH-8057 Zürich, Switzerland

On behalf of the LHCb Inner Tracker Group\textsuperscript{1,2}

Abstract

A silicon strip detector is being developed for the Inner Tracker of the LHCb experiment. The Inner Tracker consists of 9 planar tracking stations and covers a total sensitive area of about 14 m\textsuperscript{2}. Experimental boundary conditions suggest detectors with a read-out pitch of about 240 μm and a strip length of 22 cm, and front-end electronics with a fast shaping time of the order of 25 ns. Material budget is a crucial issue since mechanical supports and front-end electronics are located inside the acceptance of the experiment. Studies on the sensor geometry, front-end electronics and detector mechanics are presented.

\textit{Key words:} silicon detector, LHCb, tracking detector

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1 Introduction

LHCb [1] is a dedicated B-physics experiment under development to operate at the LHC at CERN. The main goal of the experiment is a precise determination of many different CP violating amplitudes and the measurement of rare decays of B mesons. It will use a moderate luminosity of $2 - 5 \times 10^{32} \text{cm}^{-2}\text{s}^{-1}$ and will be fully operational at the startup of the collider. Since the production of $b$ quarks at LHC is strongly peaked towards small polar angles with respect

\textit{Email address:} olafs@physik.unizh.ch (Olaf Steinkamp).
\textit{URL:} http://www.physik.unizh.ch/people/olafs (Olaf Steinkamp).
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to the beam axis, the LHCb detector is layed out as a single-arm forward spectrometer, with an acceptance coverage of up to 300 mrad in the bending plane of the dipole magnet. In the design of the experiment, special attention has been given to the precise reconstruction of primary and secondary vertices, to efficient particle identification over a wide momentum range, from 1 GeV/c to 100 GeV/c, and to efficient triggers for B meson decays. Different components of the experiment are described elsewhere in these proceedings.

The efficient and precise reconstruction of the tracks of charged particles and their momenta is one of the most challenging tasks in LHCb. A magnet spectrometer consisting of a 4 Tm dipole magnet and nine planar tracking stations has been designed for this purpose. Each of these stations has four detection layers with vertical and near-vertical detection cells, the detection cells being rotated by a small stereo angle, clockwise and counter-clockwise, in two of the four layers. This layout provides precise coordinate information in the horizontal plane, which is the bending plane of the magnet, and sufficient spatial information for pattern recognition in the vertical plane. The largest tracking station covers a sensitive area of about 4.5 × 6.5 m². In Monte-Carlo studies, an average momentum resolution of 0.39% is obtained, which is dominated by multiple scattering for momenta up to 100 GeV/c.

Each tracking station employs two different detector technologies. Charged particle densities can be as high as 10⁶ cm⁻² s⁻¹ in the innermost region near to the beam pipe, but fall off rapidly with increasing distance from the beam axis. The largest part of the sensitive surface of each tracking station will be covered by a straw drift tube detector. However, close to the beam pipe particle densities are prohibitively high for the use of this detector technology. This part of the tracking station will be covered by a silicon strip detector, the Inner Tracker.

The charged particle flux in the LHCb spectrometer is dominated by electrons and positrons from gamma conversions in the material of beam pipe and detector, and by pions from the primary vertex. The expected charged particle rates thus translate to a moderate 1-MeV neutron equivalent fluence of 5 × 10¹³ cm⁻² after 10 years of operation in the hottest region of the detector, although the integrated radiation dose can be as high as 20 Mrad after 10 years.

2 Detector Layout

The size and shape of the area covered by the Inner Tracker was determined from the requirement of acceptably low occupancies, which should not exceed 15% in the straw tracker, while keeping the area covered by the expensive sili-
con technology as small as possible. Optimization studies lead to the layout [2] illustrated in figure 1, in which the Inner Tracker covers a cross-shaped area around the beam pipe.

Fig. 1. Layout of an Inner Tracker station. Dimensions are in cm.

Each Inner Tracker station consists of four detector boxes, above, below and to both sides of the beam pipe. Each of these boxes contains four detection layers (strips vertical, +/-5° stereo angle, vertical) and each detection layer consists of seven or eight staggered ladders of silicon sensors. The ladders are either 11 or 22 cm long, assembled from one or two silicon sensors, and are read out at one end. The four detection layers are enclosed in a common, light tight and thermally and electrically insulating housing. The complete Inner Tracker, consisting of nine stations, employs 36 detector boxes and about 1500 silicon sensors and covers a sensitive area of about 14 m².

An important design aim in the development of the Inner Tracker was to devise a modular and uniform system. In the current layout, each detector box can be operated as a standalone unit, and the full Inner Tracker can be produced using only one type of silicon sensor, two types of ladders, and three types of detector boxes.

3 Silicon Sensors

The momentum resolution of the LHCb tracking system being dominated by multiple scattering, a moderate spatial resolution of about 80 μm is sufficient for the Inner Tracker. This suggests the use of sensors with a large read-out pitch of typically 240 μm. Simulation studies show that at this pitch occupancies are below a few percent everywhere. Sensors should be as thin as possible in order to minimize the multiple scattering of particles in the detector material. On the other hand, the LHC bunch-crossing frequency of 40 MHz
requires the use of fast front-end electronics, with a shaping time of the order of 25 ns, in order to avoid overlapping events from consecutive bunch crossings. The combined requirements of fast read-out electronics, thin sensors and long read-out strips, limit the attainable signal-to-noise performance of the detector. The sensor strip geometry has to be carefully chosen in order to optimize this performance.

First prototype sensors [3] were designed and produced in single-sided p+n technology from 300 μm thick 4” wafers by the company SPA Detector, Kiev. The sensors had 64 read-out strips of 66.6 mm length, and the strip pitch was \( p = 240 \mu m \). Implant widths \( w \) corresponding to \( w/p = 0.2, 0.25 \) and 0.3, respectively, were implemented on three different groups of strips. The read-out strips were AC coupled and biased through polysilicon resistors. The sensors showed a typical depletion voltage of about 50–70 V and a total strip capacitance of 1.3–1.6 pF/cm. The strip capacitance increased, as expected, with increasing implant width. Unfortunately, all delivered sensors exhibited rather low break-down voltages of typically 100–130 V.

Several silicon ladders were assembled from these sensors and tested both in laboratory setups and in test beams at CERN. Ladders used either one or three silicon sensors, the latter resulting in a total read-out strip length of 20 cm. A first test beam [4], using 9 GeV/c charged pions at the T7 facility, was performed using the HELIX read-out chip [5]. The fastest shaping time of the HELIX of about 70 ns (FWHM) is too slow for LHCb, but its noise performance is quite similar to that expected for the final LHCb read-out chip (see section 4). A beam telescope assembled from HERA-B vertex-detector counters [6] allowed a precise reconstruction of the track impact point in the test ladder and a determination of the collected charge, the signal-to-noise performance and the particle detection efficiency, as function of the track position in between the read-out strips.

The spatial resolution of the test ladders was measured to be of the order of 50 μm. However, the tests also demonstrated a significant charge loss in the inter-strip region that, for the 20 cm long ladder at fastest shaping time, resulted in a sizeable efficiency loss. As illustrated in figures 2 and 3, the efficiency loss was more pronounced for smaller values of \( w/p \) and decreased with increasing bias voltage. We interpret this as the result of a localized region of low electric field in between the strips. Charge carriers generated in this region drift very slowly and are either trapped or arrive too late at the read-out strip. An effort to simulate this effect is ongoing. If this interpretation is correct, it should be possible to suppress the charge loss by significantly overbiasing the silicon sensor. Unfortunately, the low break-down voltage of the prototype sensors did not allow to test this hypothesis.

A second generation of prototype sensors have been produced by Hamamatsu
Fig. 2. Efficiency of 20 cm long ladder as function of the track position in between strips for \( w/p = 0.2, 0.25, 0.3 \) (from left to right). The bias voltage was 90 V. Crosses are for fastest, open squares for a slower shaping time (about 120 ns FWHM) of the HELIX read-out amplifier.

Fig. 3. Efficiency of 20 cm long ladder as function of the track position in between strips, in the \( w/p = 0.2 \) region, for bias voltages of 90 V, 100 V and 110 V (from left to right). Measurements were done with a slow shaping time of the HELIX read-out amplifier.

in single-sided \( p^+n \) technology, from 320 \( \mu \)m thick 6” wafers. They have the same overall dimensions as is foreseen for the final detectors, 110 mm long and 78 mm wide, and contain 352 read-out strips with five different strip geometries, namely two strip pitches (198 \( \mu \)m and 237.5 \( \mu \)m) and \( w/p \) values between 0.25 and 0.35. Read-out strips are AC coupled and biased through polysilicon resistors. These sensors are currently being characterized in the laboratory and have been biased up to more than 300 V without breakdown. As a next step, they will be assembled to ladders and tested in a test beam end of May 2002. The results of this test beam will provide the basis for the decision on the final strip geometry for the Inner Tracker.

4 Front-End Electronics

A radiation hard read-out chip in 0.25 \( \mu \)m CMOS technology, called BEETLE \([7]\), is being custom developed for the LHCb vertex detector and Inner Tracker. It provides a 128-channel preamplifier, and a 168 cells deep analog pipeline that matches the latency of the LHCb L0-trigger. The chip operates at a sampling rate of 40 MHz, and four analog output ports allow to read out the 32-fold multiplexed signals within 900 ns.
The analog output signals of the BEETLE will be transmitted via 10 m long low-mass copper cables to a service box located on the frames of the tracking station. Here, the signals will be digitized by 8-bit FADCs and fed via 32-bit serializer chips (CERN GOL) and 12-channel VCSEL optical converters into parallel optical cables that will transmit the digitized data at a rate of 19.2 Gbit/s per 12-fibre cable over a distance of about 100 m to the LHCb counting room.

A first working version of the full read-out chip, the BEETLE v1.1, was connected to Inner Tracker prototype sensors and operated successfully in a test beam [8], using 120 GeV/c muons at the CERN–X7 facility in October 2001. Two test ladders were assembled, using one respectively three prototype sensors produced by SPA Detector, Kiev, and read out with two BEETLE chips each. Although the setup did not allow new insights into the S/N performance of the ladders, the chip could be shown to operate reliably throughout the test. BEETLE v1.1 chips were also submitted to a total ionizing dose irradiation at the CERN X-ray facility and showed full functionality up to an integrated dose of 45 Mrad, with only minimal deterioration of the analog performance.

The BEETLE v1.1 chip will also be used in the next Inner Tracker test beam in May 2002, together with the new full-size prototype sensors from Hamamatsu. A new version of the read-out chip, the BEETLE v1.2, will be submitted in April 2002. Major improvements for this new version will be the use of SEU-resistant logics and the implementation of a further optimized front end.

The front end has to provide a fast pulse shape and at the same time give good noise performance at the expected load capacitance of about 30 pF. A number of different front ends, implemented in two test chips, have been investigated [9] in order to optimize for these somewhat contradictory requirements. The finally selected front end was measured to have a fast enough phase shape, with a rise time of below 20 ns and a remainder of less than 30% of the amplitude 25 ns after the maximum, together with an ENC noise of 450 e− + 47 e−/pF. This should allow the operation of a 22 cm long ladder at an acceptable S/N ratio of about 13.

5 Detector Boxes

The silicon sensors have to be operated at a temperature of about -5 °C, in order to minimize additional noise from radiation-induced leakage currents. Efficient cooling of the sensors is thus an important parameter in the design of detector mechanics. Since the detector boxes are completely located inside the acceptance of the spectrometer, the amount of material must be minimized everywhere.
Within a detector box, all silicon ladders will be individually mounted onto a common cooling plate, as indicated in figure 4. The cooling plate will be constructed from either beryllium or a light-weight carbon-carbon composite. It will carry alignment pins for precise positioning of the ladders and will be kept at typically -10°C. Liquid C₆F₁₄, running through a cooling pipe attached to the plate, will be used as cooling agent.

![Diagram of detector box]

Fig. 4. Isometric view of a detector box. The housing is not shown.

Detector ladders will be assembled on a U-shaped carbon-fibre support, as sketched in figure 5. This support frame provides mechanical stiffness to the ladder and will be composed of a highly thermal conductive fibre in order to remove the heat generated by leakage currents in the sensors. The support frame will be attached to a cooling balcony from either beryllium or a metal matrix composite material being custom developed in cooperation with the swiss federal institute EMPA/Thun. This balcony will provide the mechanical and thermal contact to the cooling plate. The read-out hybrid will be directly attached to this cooling balcony and will not be in direct thermal contact with the carbon support frame. This construction avoids possible heat flow from the hybrid to the sensors.

The detector box will be enclosed in a housing from thermally insulating polyurethane foam, covered with a thin aluminium foil to provide electrical insulation.

First prototypes of detector box and ladder mechanics have been produced.
Fig. 5. Sketch of a 2-sensor ladder.

and their thermal and mechanical properties are currently being investigated.

6 Summary and Outlook

The Inner Tracker for LHCb will be produced in single-sided silicon strip technology, using up to 22 cm long ladders with a read-out pitch of 200-240 µm. In the current design of the LHCb tracking system, it will cover a sensitive surface of 14m².

Within the framework of a general re-optimization of the LHCb detector that aims at a significant reduction the amount of material in front of the calorimeters, a reduction of the number of tracking stations from nine to four is currently being discussed. Studies of tracking algorithms for the new layout are under way and show promising results. The resulting reduction, in size and cost, of the tracking system would allow the possibility to construct the first tracking station, in between the interaction point and the magnet, completely from silicon. The main motivation for this upgrade would be to use information from this station in the Level-1 trigger decision. If both changes are implemented, the overall size of the silicon tracker would remain approximately unchanged. However, the need for the mentioned all-silicon tracking station has still to be proven.

A technical design report for the silicon inner tracker is going to be submitted by the end of this year. The construction of the detector is foreseen to take about 18 months and will be scheduled such that the detector can be installed and fully commissioned before the startup of LHC.
References

[1] LHCb technical proposal, CERN/LHCC 998-4
[3] F. Lehner et al., Description and Characterization of Inner Tracker Silicon
Prototype Sensors, LHCb-2001-036
[4] C. Bauer et al., Test Beam Results on Inner Tracker Silicon Prototype Sensors,
LHCb-2001-135
Using the BEETLE v1.1 Readout Chip, LHCb-2002-018