8 High-precision CP-violation Physics at LHCb

R. Bernet, F. Lehner, M. Needham, P. Sievers, O. Steinkamp, U. Straumann, A. Vollhardt, D. Wyler, M. Ziegler

in collaboration with:
The inner tracking group of LHCb: University of Lausanne; Max Planck Institute, Heidelberg, Germany; University of Santiago de Compostela, Spain; Budker Institute for Nuclear Physics (INP), Novosibirsk, Russia and Ukrainian Academy of Sciences, Kiev, Ukraine.

The full LHCb collaboration consists of 50 institutes from the countries Brazil, China, Finland, France, Germany, Italy, Netherlands, Poland, Romania, Russia, Spain, Switzerland, Ukraine and the United Kingdom.

(LHCb)

8.1 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 study of rare decays of B mesons. It will use a moderate luminosity of $2 - 5 \times 10^{32}\mathrm{cm}^{-2}\mathrm{s}^{-1}$ 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 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 (vertex detector VELO), to efficient particle identification over a wide momentum range, from 1 to 100 GeV/c (two RICH detectors), and to efficient triggering of B meson decays.

The efficient and precise reconstruction of the trajectories of charged particles and their momenta is one of the most challenging tasks in LHCb. A magnetic 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. In two layers the detector elements are oriented vertically. In the other two they are rotated by a small stereo angle, clockwise and counter-clockwise. 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 extends over a sensitive area of about $4.5{\times}6.5\,\mathrm{m}^2$. 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 $10^6\mathrm{cm}^{-2}\mathrm{s}^{-1}$ 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 area of each tracking station will be covered with a straw drift tube detector. However, close to the beam pipe particle densities are prohibitively high for the use of this detector technology. This region will be covered with 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 $5 \times 10^{13}\,\mathrm{cm}^{-2}$ 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.

8.2 Detector layout

The size and shape of the Inner Tracker are determined by the requirement of occupancies which should not exceed 15% in the straw tracker, while minimising the area covered by the expensive silicon technology. Our studies lead to the layout [2] illustrated in Fig. 8.1, in which the Inner Tracker covers a cross-shaped area around the beam pipe.

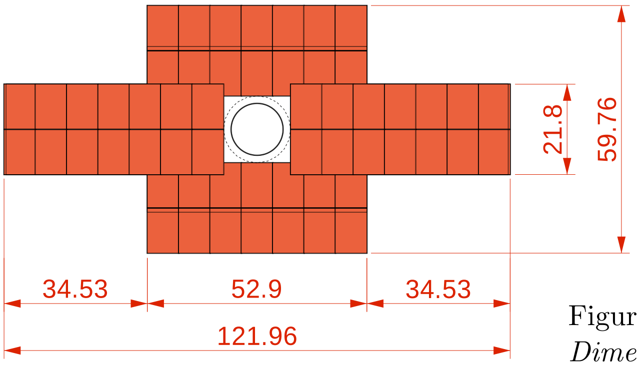

Figure 8.1: *Layout of an Inner Tracker station. Dimensions are in cm.*

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 m^2.

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.

8.3 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 minimise the multiple scattering of particles in the detector material. On the other hand, the LHC bunch-crossing frequency of 40 MHz forces 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 optimise this performance.

First prototype sensors [3] were designed and produced in single-sided $\mathrm{p}^+\mathrm{n}$ 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, were implemented on three different groups of strips. The read-out strips were AC coupled and biased through polysilicon resistors. The characterisation of these sensors in a laboratory setup in Zürich (P. Sievers) showed a typical depletion voltage of about 50–70 V and a total strip capacitance of 1.3–1.6 pF / cm depending on implant width. Unfortunately, all sensors exhibited rather low break-down voltages of typically 100–130 V.

Several silicon ladders were assembled from these sensors and tested in laboratory setups in Zürich and Heidelberg, 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 beam test [4], using 9 GeV/c charged pions at the T7 facility, was performed using the HELIX read-out chip [5]. The shortest shaping time of the HELIX of about 70 ns (FWHM) is too long for LHCb, but its noise performance is quite similar to that expected for the final LHCb read-out chip (see Sec. 8.4). 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 analysis of the data, by P. Sievers, also demonstrated a significant charge loss in the inter-strip region that, for the 20 cm long ladder at fastest shaping, resulted in a sizeable efficiency loss. As illustrated in figures 8.2 and 8.3, 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 local 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 over-biasing the silicon sensor. Unfortunately, the low break-down voltage of the prototype sensors did not allow to test this hypothesis.

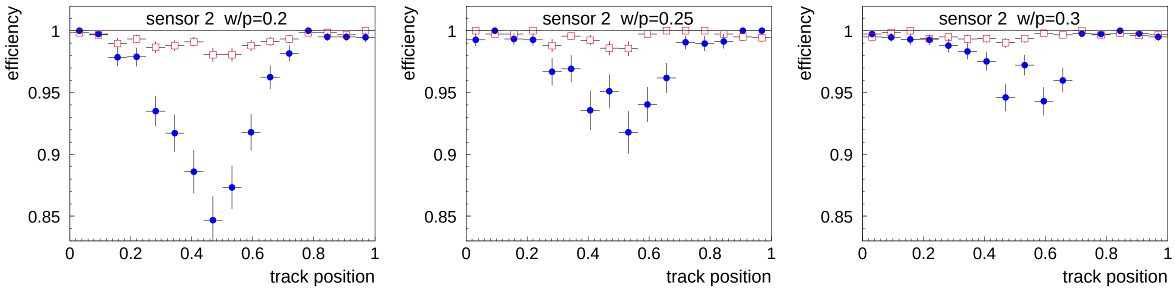

Figure 8.2: *Efficiency of 20 cm long ladder as function of the track position in between strips for w/p=0.2, 0.25, 0.3. The bias voltage was 90 V. Crosses are for shortest, open squares for a longer shaping time (about 120 ns FWHM) of the HELIX read-out amplifier.*

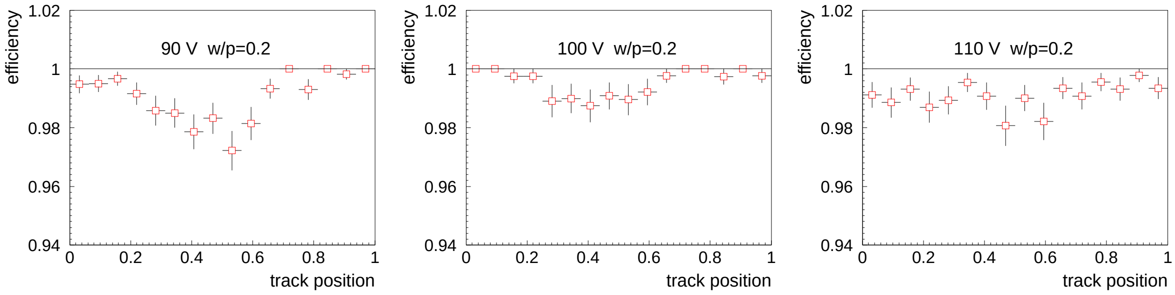

Figure 8.3: *Efficiency of 20 cm long ladder as function of the track position in between strips for w/p=0.2, for bias voltages of 90 V, 100 V and 110 V. Measurements were done with a 120 ns shaping time of the HELIX read-out amplifier.*

A second generation of prototype sensors have been produced by Hamamatsu in single-sided p^+n technology from 320 μm thick 6" wafers, according to specifications by F. Lehner and O. Steinkamp. 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 μm and 237.5 μm) 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 characterised 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 in Zürich and tested in a beam at CERN end of May 2002. The results of this test will provide the basis for the decision on the final strip geometry for the Inner Tracker.

8.4 Front-End electronics

A radiation hard read-out chip in 0.25 μm CMOS technology, called BEETLE [7], is being custom developed in Heidelberg 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 service boxes located on the frames of the tracking station. Here, the signals will be digitised 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 digitised 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 prototype data link is currently being assembled by A. Vollhardt in Zürich.

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 beam of 120 GeV/c muons at the CERN–X7 facility in October 2001 [8]. The Zürich group was strongly involved in all phases of this test. 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 operated reliably throughout the test. BEETLE v1.1 chips were also exposed to a total ionising 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 a test of the new full-size prototype sensors from Hamamatsu. Beam time at the X7 facility is scheduled for May 2002.

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-resistent logics and the implementation of a further optimised 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 Zürich (A. Vollhardt) and Heidelberg in order to optimise for these somewhat contradictory requirements. The finally selected front end was measured to have a fast enough response, 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 $450\,e^- + 47\,e^- / \mathrm{pF}$. This should allow the operation of a 22 cm long ladder at an acceptable S/N ratio of about 13.

8.5 Detector boxes

The silicon sensors have to be operated at a temperature of about -5°C, in order to minimise 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 minimised everywhere. F. Lehner plays a leading role in the design of the detector box and the choice and development of low-mass materials for its components.

Within a detector box, all silicon ladders will be individually mounted onto a common cooling plate, as indicated in Fig. 8.4. 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 C_6F_{14}, running through a cooling pipe attached to the plate, will be used as cooling agent.

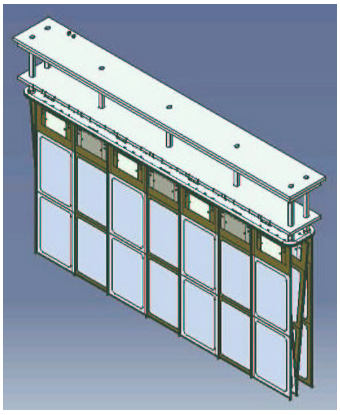

Figure 8.4: *A detector box. The housing is not shown.*

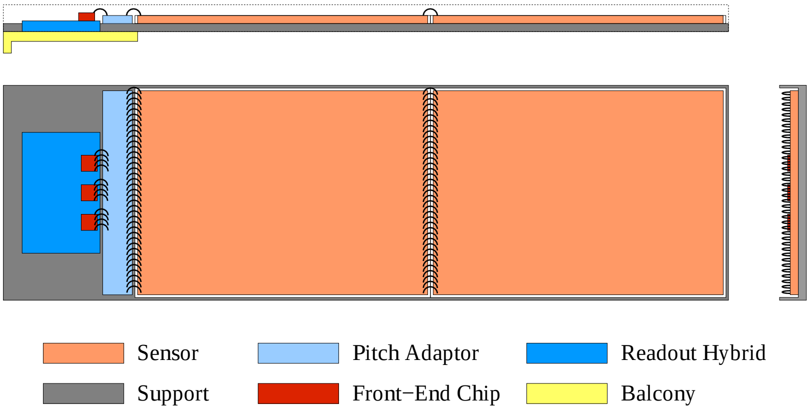

Figure 8.5: *Sketch of a 2-sensor ladder.*

Detector ladders will be assembled on a U-shaped carbon-fibre support, as sketched in Fig. 8.5. 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 and their thermal and mechanical properties are currently being investigated in Zürich and Lausanne, respectively.

8.6 Outlook

Within the framework of a general re-optimisation 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. M. Needham, who has made significant contributions to the development of the LHCb tracking code, has recently joined the Zürich group and will play an important role in further optimisation studies.

The reduction of the number of tracking stations would allow the possibility to construct the first tracking station, in between the interaction point and the magnet, completely from silicon. The overall size and cost of the silicon tracker would then remain approximately unchanged. The main motivation for this upgrade would be to use information from this station in the Level-1 trigger decision.

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.

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