9 High-precision CP-violation Physics at LHCb

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The full LHCb collaboration consists of 51 institutes from Brazil, China, Finland, France, Germany, Italy, The Netherlands, Poland, Romania, Russia, Spain, Switzerland, Ukraine, and the United Kingdom.

(LHCb)

The LHCb experiment [1] is designed to exploit the large $\mathrm{b\overline{b}}$ production cross section at the LHC in order to perform a wide range of precision studies of CP violating phenomena in the B meson systems. The experiment 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, which is foreseen for 2007.

The copious production of all flavours of B mesons and of b hadrons, combined with the unique particle-identification capabilities of the LHCb detector, will allow the experiment to perform sensitive measurements of CP violating asymmetries in a variety of decay channels that are beyond the reach of the current generation of CP-violation experiments. In particular, the possibility to investigate the decays of $\mathrm{B_s}$ mesons gives access to an important field of research that is not accessible to the successfully operating “B factories”, BaBar and Belle. Both these experiments have recently presented first precision measurements of a CP violationg asymmetry in the decay $\mathrm{B_d} \rightarrow \mathrm{J}/\psi\mathrm{K_s}$. However, $\mathrm{B_s}$ mesons are not produced at the $\mathrm{e^+e^-}$ colliders at which these experiments operate.

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. Its acceptance extends out to 300 mrad in the horizontal bending plane of the 4 Tm dipole magnet and to 250 mrad in the vertical plane. The forward acceptance is limited by the LHC beam pipe which follows a 10 mrad cone.

In order to fully exploit its exciting physics potential, the LHCb apparatus must ensure high trigger and event reconstruction efficiencies for all interesting physics channels. An efficient and precise reconstruction of the trajectories of charged particles is a key ingredient towards achieving this aim, since many of the interesting B meson decay channels are characterised by final states that involve multiple charged particles. On the other hand, track reconstruction is one of the most challenging tasks in the high-rate environment of LHCb, where charged particle fluxes of up to $5 \times 10^5\,\mathrm{cm}^{-2}\mathrm{s}^{-1}$ are expected in the very forward region.

Our group has taken a major responsibility for the design and development of the silicon tracking system for LHCb.

9.1 Silicon tracker

In the original design of the LHCb detector, the tracking system consisted of nine planar tracking stations, each of which employed two different detector technologies: silicon microstrip detectors covered the region of highest particle fluxes close to the beam pipe and straw drift tube detectors were employed for the remainder of the acceptance. Extensive simulation studies, in which M. Needham took a leading role, demonstrated that the required reconstruction efficiency and momentum resolution were reached in this setup.

Further investigations, to which M. Needham again contributed significantly, showed that a comparable tracking performance could be achieved [2] in a reduced setup using only one station (TT) upstream of the dipole magnet and three stations (T1-T3) downstream of the magnet. A smaller number of tracking stations is advantageous for several reasons, one of the most important being that the loss of particles due to nuclear interactions in the material of the detector is reduced significantly.

In addition, the reduction of the number of tracking stations liberated resources that permitted to envisage a layout of the relatively small TT station, in which the acceptance of this station is entirely covered by silicon microstrip detectors. This station is going to be used not only in the offline track reconstruction but also in the Level-1 trigger. Here, it is employed in order to assign transverse momentum information to high-impact parameter tracks reconstructed in the vertex detector. Simulation studies [3] have shown that an all-silicon layout for the TT station provided for a significantly better trigger performance than the original layout with silicon microstrips close to the beam pipe and straw drift tubes in the outer region of the station.

In the revised layout of the LHCb tracking system, silicon microstrip detectors thus cover the entire TT station and the innermost part of stations T1-T3 (Inner Tracker). TT and Inner Tracker together form the so-called Silicon Tracker system, which is led by U. Straumann (coordinator) and O. Steinkamp (deputy coordinator).

The design of the Inner Tracker is well advanced. The Techical Design Report (TDR) for this detector [4], written by O. Steinkamp, was submitted to the CERN LHCC on November 8, 2002. It was well received by the committee and has been recommended for general approval. The Inner Tracker TDR is based to a large extent on design and R&D efforts carried out in our group, as described below.

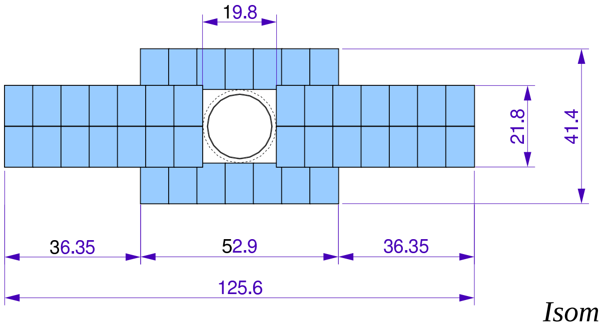
The design of the TT station is, by comparison, in an early stage. A conceptual layout for the all-silicon station has been proposed [5] by O. Steinkamp, but a significant R&D effort is still required in order to validate this layout and develop a technical design for the station. After the submission of the Inner Tracker TDR, our group has taken a leading role in this effort.

9.1.1 Inner tracker

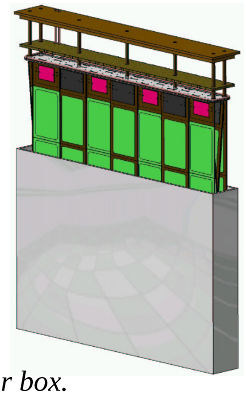
The size and shape of the area covered by the Inner Tracker was determined from the requirement of acceptably low occupancies in the straw tracker [6], while keeping the area covered by the expensive silicon technology as small as possible. Optimisation studies lead to the layout illustrated in Figure 9.1.

Each Inner Tracker station consists of four independent detector boxes, above, below and to both sides of the beam pipe. A detector box contains four detection layers and each detection layer consists of seven staggered ladders of silicon sensors. Silicon ladders are two sensors (22 cm) long in the side boxes, and one sensor (11 cm) long in the top/bottom boxes. All silicon ladders within a detector box are mounted on a common cooling plate that removes the heat generated by the front-end readout chips and cools the silicon sensors. The detector box is housed in an enclosure that provides thermal, optical and electrical insulation. In total, the Inner Tracker employs 12 detector boxes and 504 silicon sensors arranged in 336 ladders. It covers a sensitive area of approximately 4.2 m^2 and

Figure 9.1: *The inner tracker.*



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



Isometric view of a detector box.
The box enclosure is partially removed to show
the silicon sensors and box mechanics.

has 130k readout channels.

R&D for the Inner Tracker is to a large extent driven by the effort to minimise detector material. Any active or passive material inside the acceptance of the experiment reduces the performance of the detector, due to multiple scattering and inelastic interactions of the particles. Minimising detector material implies on the one hand that silicon sensors should be as thin as possible, and on the other hand that light-weight materials have to be used for the mechanical support of the detectors.

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. A detailed R&D program, involving laboratory tests and test beams at CERN has been carried out in order to optimise the detector geometry and demonstrate that a sufficiently high signal-to-noise ratio and full particle detection efficiency can be ensured. P. Sievers contributed significantly at all stages of these investigations and in January 2003 obtained his PhD degree for his excellent work [7].

First measurements [8], performend on prototype sensors produced at the company SPA Detector, Kiev, had demonstrated a significant reduction of charge collection efficiency in the central region in between readout strips. For a 22 cm long ladder at LHC-compatible shaping time, this signal loss would result in a sizeable loss of particle detection efficiency. However, these measurements were hampered by a relatively low breakdown voltage of the sensors. Subsequently, a second generation of prototype sensors were produced by HPK Hamamatsu from 320 μm thick 6” wafers, according to specifications by F. Lehner and O. Steinkamp. These sensors are 110 mm long and 78 mm wide, which are the dimensions foreseen for the final detectors. They contain 352 read-out strips with five different strip geometries, namely two strip pitches (198 μm and 237.5 μm) and different strip widths corresponding to w/p values between 0.25 and 0.35.

After an extensive characterisation of their electrical and mechanical properties [9], these sensors were assembled in one- and two-sensor long detector ladders and equipped with a prototype version of the LHCb readout chip, called Beetle 1.1. Measurements in a beam test at the CERN X7 facility in May/June 2002 confirmed [10] the occurance of a reduced charge collection efficiency in the central region in between readout strips. However, as illustrated in Figure 9.2, the observed signal loss was reduced to an acceptably low level for the smaller strip pitch of 198 μm and sufficiently high sensor bias voltages. Furthermore, the measurements demonstrated that a signal-to-noise level of eleven could be obtained for the 22 cm long silicon ladders, whereas a signal-to-noise level of ten was shown to be sufficient to ensure full particle detection efficiency. It was thus decided to adopt the proposed layout of the Inner Tracker, using the smaller strip pitch of 198 μm.

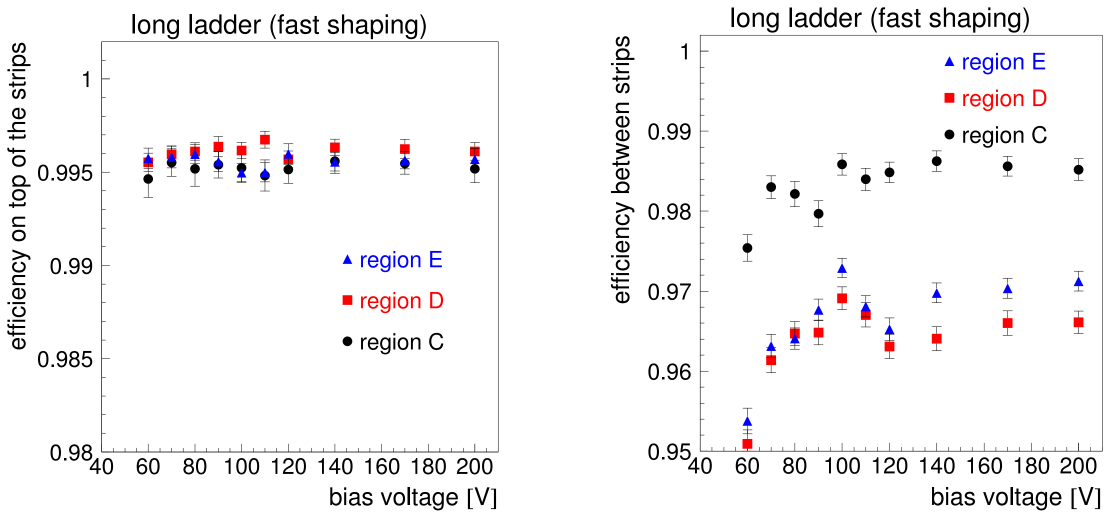


Figure 9.2: *Particle detection efficiency close to a readout strip (left) and in between two strips (right). Region "C" has a strip pitch of 198 μm, regions "D" and "E" have a strip pitch of 237 μm.*

In order to study the origin of the observed loss of charge collection efficiency in between readout strips, a dedicated simulation program was developed by St. Heule as part of his Diploma thesis. The simulation includes the charge transport and signal generation in silicon, as well as the response of the Beetle readout chip. In addition, a laboratory test stand that employs a focussed infra-red laser beam to generate charges at well-defined locations on the silicon sensors has been set up in our laboratory by P. Bernhard, St. Heule and A. Vollhardt.

In parallel to the studies on silicon sensors, an extensive R&D program was carried out [11] in order to identify suitable lightweight materials for the detector box mechanics. These materials must be precisely machinable, have to exhibit high thermal conductivity and should have as long as possible radiation length and nuclear interaction length. The R&D program was led by F. Lehner and carried out both in our laboratory and in collaboration with several outside institutes. In particular, a new type of metal matrix composite material, using high-tensile carbon fibres embedded in a Magnesium matrix, was developed and characterized in a joint effort with the EMPA/Thun. This material was shown to exhibit all properties required for the various pieces of the Inner Tracker mechanics.

9.1.2 TT station

The acceptance of the TT station covers an area of approximately 140 cm × 120 cm. The proposed layout [5] for this station is illustrated in Figure 9.3. It employs long silicon ladders that span the full height of the active area. All readout electronics and associated mechanics are located above and below the active area and outside of the acceptance of the experiment. Electronically, each ladder is split into five readout sectors, with the inner sectors being connected to their readout electronics via 33 cm and 55 cm long kapton interconnects, respectively. For four detection layers, the TT station employs 832 silicon sensors, arranged in 80 ladders and 376 readout sectors. It covers a sensitive area of approximately 6.8 m^2 and counts 144k readout channels.

Compared to the Inner Tracker detectors, the longer readout strips and the kapton interconnects employed in the TT station will give rise to higher load capacitances at the input of the front-end readout chips, resulting in larger noise. Thicker silicon sensors need thus to be employed here, in order

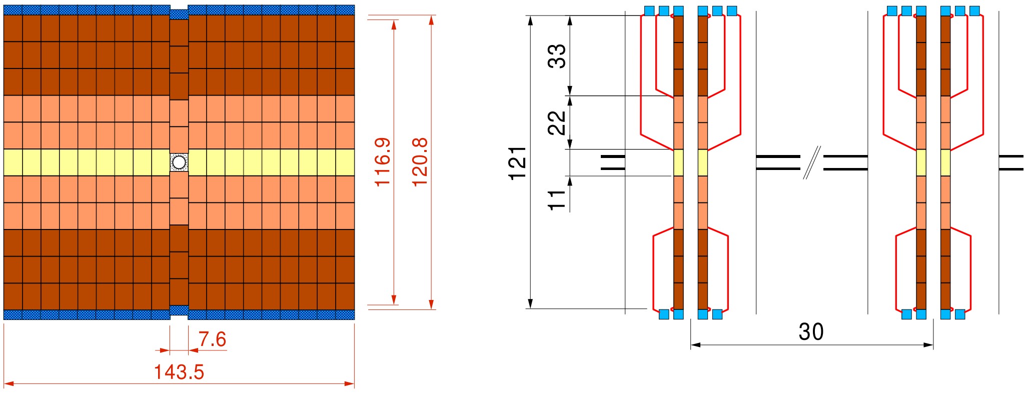


Figure 9.3: *Front (left) and side (right) views of the proposed layout for the TT station.*

to maintain sufficiently high signal-to-noise ratios. First estimates show that 500 μm thick sensors should provide large enough signals to ensure full particle detection efficiency. However, these estimates do not take into account ballistic deficits, which could become sizeable at the fast shaping times required for operation at LHC.

Our group has started an intensive R&D program in order to investigate signal collection in thick silicon sensors and particle detection efficiencies for long ladders using fast signal shaping times. Several, approx. 30 cm long test ladders have been assembled from sensors of different thicknesses between 320 μm and 500 μm. One test ladder is equipped with a 33 cm long kapton interconnect that has been produced in cooperation with the company Dyconex, Bassersdorf. All ladders are equipped with an improved version of the read-out chip, the Beetle 1.2. The ladders are being tested in the infra-red laser setup in our laboratory, while a beam test at CERN is under preparation. In addition, the simulation studies mentioned above are being extended to include thicker sensors and kapton interconnects.

In parallel, we have started to work on the mechanical design of the station.

9.2 Optical readout link

The front-end chip samples detector data at the LHC bunch crossing frequency of 40 MHz. At a Level-0 trigger accept, the analog data are read out, digitised, multiplexed and transmitted via 100 m long optical fibres to the LHCb electronics barrack. Here, the data are processed and transmitted to the higher-level triggers and the data acquisition system.

The L0 Trigger operating at a rate of 1.1 MHz, a total of 2.6 Tbit of digitised detector data have to be transmitted per second. A low-cost digital optical link, using commercially available components is being developed [12] for this purpose by Achim Vollhardt. A prototype link has been set up and is working in the laboratory. Bit error tests are under way and radiation tests for those components that are located close to the detector are being prepared. Expected radiation doses at the location of the readout link electronics do not exceed 10 krad after ten years of LHCb operation at nominal luminosity.

9.3 Summary and outlook

In the revised layout of the LHCb detector, the main tracking system consists of four stations. In three stations downstream of the magnet, silicon microstrip detectors cover the innermost region close to the beam pipe. A Technical Design Report for this detector, called Inner Tracker, has been submitted to the CERN LHCC committee, which has recommended it for approval. The fourth station, called TT, is covered entirely by silicon microstrip detectors. Work on the design of this station has started, including R&D on silicon detectors and readout, as well as a mechanical design of the station. Work on the TT station will be the major occupation of our group for the year 2003. A prototype digital optical readout link is operational in the laboratory, detailed tests are in progress.

The construction of the detector is estimated to require approximately 18 months and will be scheduled such that the detector can be installed and fully commissioned before the startup of LHC, foreseen for 2007.

[1] LHCb technical proposal, CERN/LHCC 998-4.
[2] M.Needham, LHCb-2002-043.
[3] H.Dijkstra et al., LHCb-2002-045.
[4] LHCb Inner Tracker Technical Design Report, CERN/LHCC 2002-029.
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[9] F.Lehner et al., LHCb-2002-038.
[10] M.Agari et al., LHCb-2002-058.
[11] K.Bösiger et al., LHCb-2002-061.
[12] A.Vollhardt, LHCb-2002-062, LHCb-2002-068.