# 4 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 main goal of the LHCb experiment is to perform systematic measurements of CP violating processes and rare decays in the B meson systems, with unprecedented precision. Measuring CP violation in many different decay modes of $\mathrm{B_d^0}$ and $\mathrm{B_s^0}$ mesons and comparing the results with predictions from the Standard Model of particle physics, the experiment will also search for new physics beyond the Standard Model. Our group concentrates on the development, construction, operation and data analysis of the LHCb Silicon Tracker as well as on physics analyses.

## 4.1 The LHCb experiment

The LHCb experiment [1] has been designed to exploit the large $\mathrm{b\overline{b}}$ production cross section at the Large Hadron Collider (LHC) at CERN in order to perform a wide range of precision studies of CP violating phenomena and rare decays in the B meson systems. The experiment will use a moderate luminosity of $2-5\times10^{32}\mathrm{cm^{-2}s^{-1}}$ and will be fully operational at the startup of the LHC, which is foreseen for 2007.

In particular, the copious production of $\mathrm{B_s^0}$ mesons, combined with the unique particle-identification capabilities of the LHCb detector, will permit 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.

Since the production of $b$ quarks in proton-proton collisions 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 of the experiment is limited by the LHC beam pipe that passes through the detector and follows a 10 mrad cone pointing back to the p-p interaction region.

In 2002, the LHCb collaboration decided to revise the layout of the LHCb detector in general, and of the tracking system in particular. The goal of this revision was to further improve the physics potential of the experiment by reducing the material budget of the detector and by improving the performance of the Level-1 trigger. A large part of the year 2003 was dedicated to studying the physics potential of the revised detector and to working out the technical design of the revised detector components. The results of these efforts are summarised in the so-called “LHCb re-optimised detector Technical

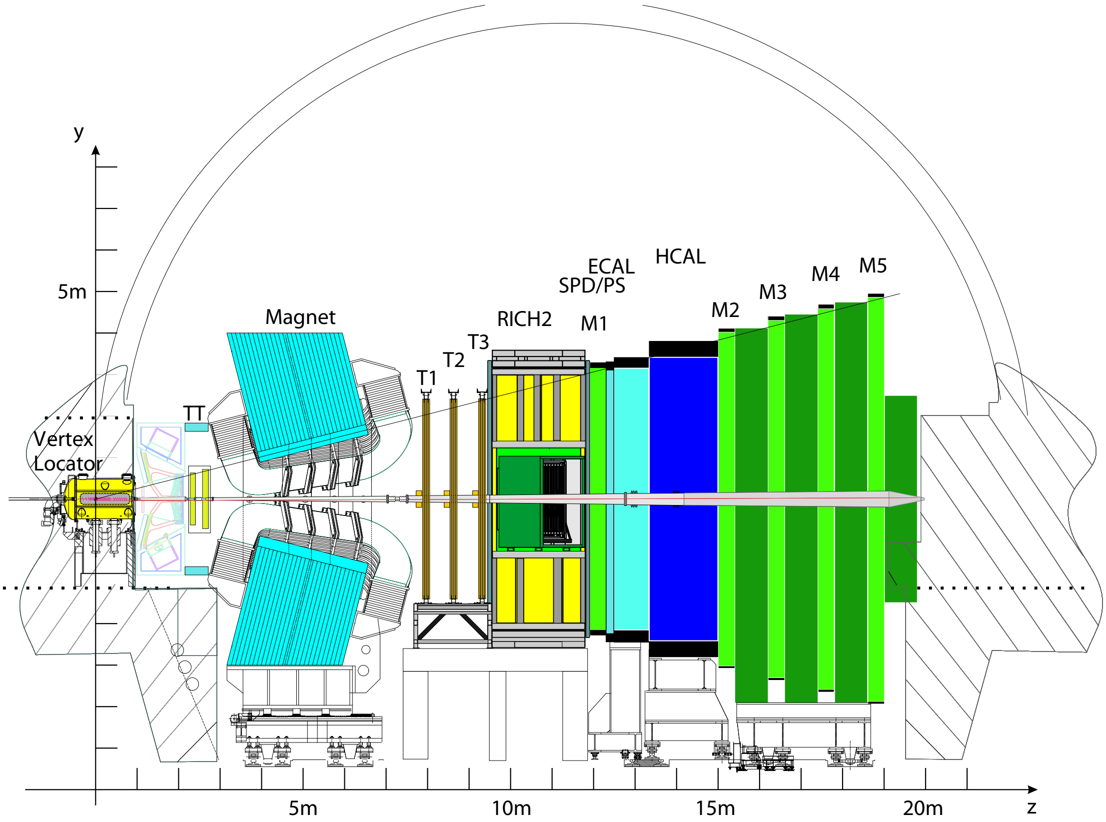

Figure 4.1: *Vertical cross section through the revised LHCb detector.*

Design Report" [2] that was submitted to the CERN LHCC committee in September 2003. It was well received by the committee and has been recommended for approval.

A vertical cut through the revised LHCb detector is shown in Fig. 4.1. The tracking system consists of four planar tracking stations (TT and T1-T3), complemented by the Vertex Detector (VELO) that surrounds the p-p interaction region.

## 4.2 Silicon tracker

Our group has taken a leading rôle in the development, production and operation of the Silicon Tracker. The Silicon Tracker project is led by U. Straumann and O. Steinkamp (deputy). It consists of two detectors that both employ silicon microstrip technology but differ in important details of the technical design: The Inner Tracker covers the innermost region around the beam-pipe in the three large tracking stations T1-T3 downstream of the spectrometer magnet; the Trigger Tracker (TT) is located upstream of the spectrometer magnet and covers the full acceptance of the experiment.

The technical design of the Inner Tracker is described in the Inner Tracker Technical Design Report [3]. After the submission of the Inner Tracker TDR in November 2002, a large fraction of our efforts over the year 2003 was taken up by design work and R&D for the TT station. The resulting technical design of the TT station is described in Chapter 5, written by O. Steinkamp, of the "LHCb re-optimised detector TDR" [2] and in a subsequent technical note [4]. Furthermore, our group is responsible for the development of the optical digital readout link for Inner Tracker and TT station.

A full prototype link using final components has been set up and tested in the laboratory. Several irradiation tests of critical components have been carried out during the last year.

## 4.3 TT station

The Trigger Tracker (TT station) fulfills a two-fold purpose: First, it will be used in the Level-1 trigger to assign transverse-momentum information to large-impact parameter tracks. Secondly, it will be used in the offline analysis to reconstruct the trajectories of low-momentum particles that are bent out of the acceptance of the experiment before reaching tracking stations T1-T3.

The TT station consists of four detection layers. Its active area is approximately 160 cm wide and 130 cm high and will be covered entirely by silicon micro-strip detectors. The layout of a detection layer is illustrated in Fig. 4.2. The areas above and below the beam pipe are each covered by a single seven-sensor long silicon ladder, the areas to the left and to the right of the beam pipe are covered by seven or eight staggered 14-sensor long ladders. Electronically, each ladder is split into several readout sectors, indicated by different shadings in Fig. 4.2. All readout electronics and associated mechanics are located at the top end or the bottom end of a ladder, outside of the acceptance of the experiment. The inner readout sectors are connected to their readout electronics via approximately 39 cm long Kapton interconnect cables. An isometric drawing of the basic detector unit, consisting of seven silicon sensors, a Kapton interconnect, and two staggered front-end readout hybrids, is shown in Fig. 4.3. The 14-sensor long ladders that cover the areas to the left and to the right of the beam pipe are assembled from two such detector units that are joined together at their ends. A readout strip pitch of 183 $\mu$m will be employed everywhere. In simulation studies, M. Needham has demonstrated that this layout provides adequate spatial resolution and acceptably low detector occupancies. For four detection layers, the TT station employs 896 silicon sensors, arranged in 128 modules and 256 readout sectors. It covers a total sensitive area of approximately 8 m$^2$ and counts 131k readout channels.

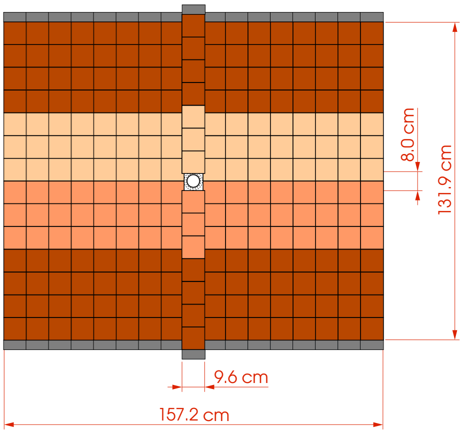

Figure 4.2: *Layout of one detection layer of the TT station. Readout sectors are indicated by different shading.*

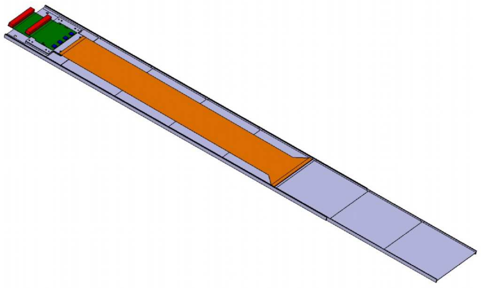

Figure 4.3: *Drawing of a silicon module, consisting of seven silicon sensors, a Kapton interconnect cable and two staggered readout hybrids attached at one end of the module.*

A substantial R&D effort has been carried out in our group in order to validate this layout and develop the mechanical design of the long detector modules and of the station frames.

Key issues in our R&D effort have been the optimisation of silicon sensors and the design of the interconnect cables. The long readout strips and interconnect cables employed in the TT station result in expected load capacitances of up to 55 pF at the input of the front-end readout amplifier. In order to maintain sufficiently high signal-to-noise ratios for full particle detection efficiency, thicker sensors have to be used for the TT station than for the shorter ladders of the Inner Tracker. Several proto-

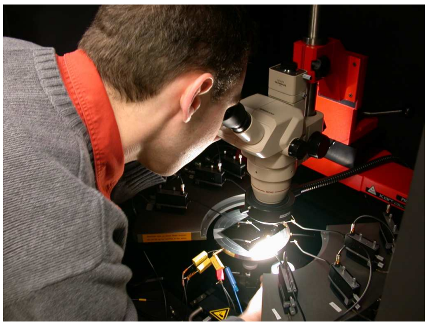

Figure 4.4:
*Manual probe-station.*

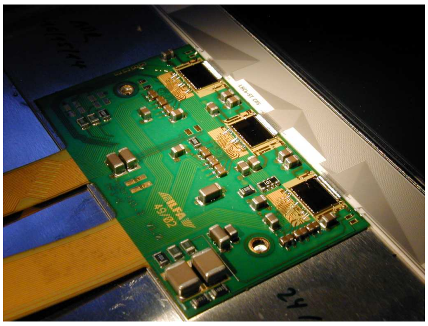

Figure 4.5: *Readout hybrid with Beetle 1.2 chips.*

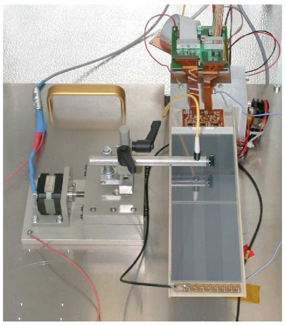

Figure 4.6:
*Laser test stand.*

type ladders were constructed from 320 $\mu$m, 410 $\mu$m and 500 $\mu$m thick silicon sensors. Before being assembled into ladders, all sensors were characterised by C.Lois, using manual (see Fig. 4.4) and automatic probe-stations in our laboratory [5]. Each prototype ladder consisted of three silicon sensors bonded in series, for a total readout strip length of approximately 30 cm. All ladders were equipped with a prototype version of the LHCb front-end readout chip, called Beetle 1.2. A photograph of a front-end readout hybrid carrying three Beetle 1.2 chips and bonded to one of the prototype ladders is shown in Fig. 4.5.

Initial tests on the prototype ladders were performed in an infra-red laser test stand [6] that has been set up in our laboratory by P.Bernhard, St.Heule and A.Vollhardt. A photograph of the setup is shown in Fig. 4.6. It employs a focussed 1064 nm laser beam to generate charges at well-defined locations in the silicon bulk and permitted systematic studies of signal pulse shapes as a function of various operation parameters of the detector and of the location of the charge deposition. A detailed description of the setup and the results obtained in the laser tests is given in [6].

Further measurements were then performed at the X7 test-beam facility at CERN, in collaboration with our colleagues from Lausanne and Heidelberg. The analysis of the collected data was coordinated by M.Needham. A detailed description of the test-beam setup and the obtained results is given in [7]. As shown in Fig. 4.7, for all prototype ladders a significant drop of the charge collection efficiency was observed in the central region in between two readout strips. The effect was observed both in the laser setup and in the test-beam and confirmed an earlier result from measurements on Inner Tracker prototype ladders [3]. It was also reproduced in a detector simulation developed by St.Heule as part of his Diploma thesis in our group [8]. It is mainly attributed to a loss of charge carriers at the

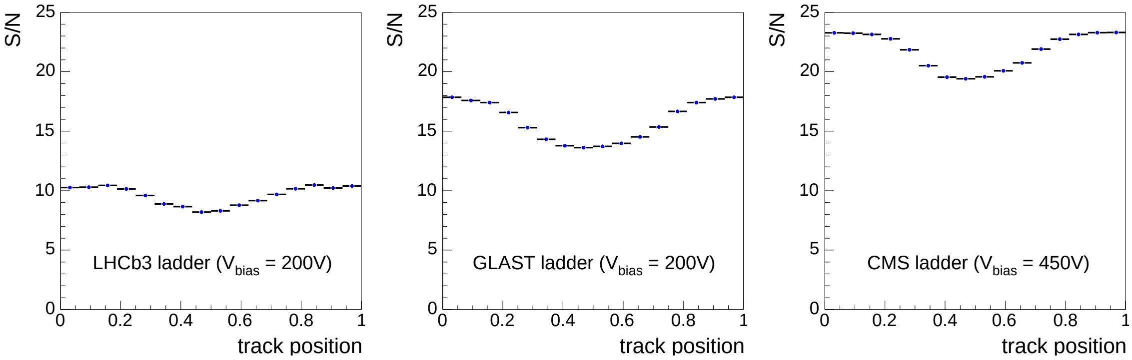

Figure 4.7: *Most probable signal-to-noise ratios as a function of the relative interstrip position of the charge deposition.*

boundary between the silicon bulk and the silicon oxide layer in between the two readout strips.
For the ladder built from 320 $\mu$m thick silicon sensors, this charge loss led to a significant loss of particle detection efficiency in the central region in between two strips. For the ladders using 410 $\mu$m and 500 $\mu$m thick silicon sensors a particle detection efficiency in access of 99.8% was maintained over the full interstrip gap. Readout strips in the TT station will be slightly longer than those on the prototype ladders and in order to ensure a robust operation of the detector it was decided to employ 500 $\mu$m thick silicon sensors for the TT station.
Low-mass interconnect cables of approximately 39 cm in length will be employed in order to connect the inner readout sectors on a ladder to their front-end readout hybrid. The design of these cables is the resonsibility of J.Gassner. Several prototype cables were developed in collaboration with the company Dyconex, Bassersdorf, and characterised in our laboratory. A prototype ladder has then been constructed consisting of three 500 $\mu$m thick silicon sensors, a 39 cm long interconnect cable and a readout hybrid carrying three Beetle 1.2 chips. Laboratory measurements on this prototype ladder, using the infra-red laser setup, are ongoing and show promising results. Further tests on this prototype ladder will be performed in a test-beam at CERN later this year.
The mechanical design of the silicon ladders for the TT station and of the station frames is advancing well, in close collaboration with the engineers and the mechanical workshop at the Physik-Institut. An isometric drawing of a silicon module is shown in Fig. 4.3, a drawing of one half of the TT station is shown in Fig. 4.8.
The production of the complete TT station, including all silicon modules and station mechanics is the responsibility of our group. The preparation of production and test facilities has started under the supervision of F.Lehner, a detailed production plan and quality assurance procedures are being defined.

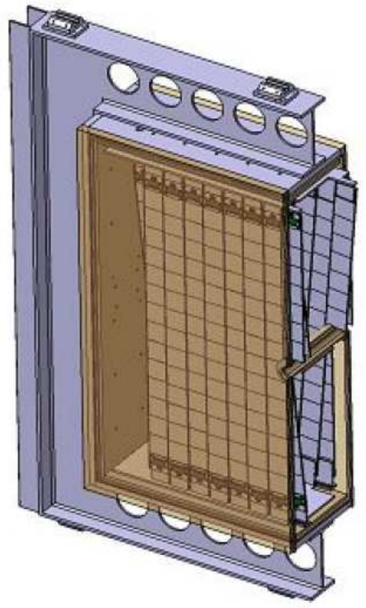

Figure 4.8: *Isometric drawing of one half of the TT station.*

## 4.4 Optical readout link

The Beetle front-end chip samples detector data at the LHC bunch crossing frequency of 40 MHz and stores the analog data for the latency of the Level-0 trigger. At a trigger accept, the analog data are multiplexed, read out, digitised and transmitted 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 maximum accept rate of 1.1 MHz, up to 2.6 Tbit/s of digitised detector data have to be transmitted for the Silicon Tracker. A low-cost digital optical link using commercially available components is being developed for this purpose by A.Vollhardt as part of his PhD thesis work in our group. A full prototype link using final components has been set up and is working in the laboratory [9]. Similar developments are underway for other LHCb subsystems and the formation of a common working group has been initiated by A.Vollhardt. He organizes regular group meetings, in which common solutions are discussed and the selection of commercial components is coordinated.

Some components of the readout link are located close to the detector, where an accumulated radiation dose of up to 10 kRad is expected after ten years of LHCb operation at nominal luminosity. All relevant components have been radiation qualified by A.Vollhardt and Y.Ermoline in total ionizing dose irradiation campaigns at PSI and in a neutron irradiation at the Prospero nuclear reactor at CEA Valduc, France [10].

First components of the Low-Voltage supply system for the Silicon Tracker have been received and characterised [11] by A.Vollhardt and A.Gafner, the latter working in our group as a technical student.

## 4.5 Event simulation

The group has played a major part in simulation studies of the LHCb tracking system performance that were described in the LHCb reoptimized detector TDR [2]. In particular, M.Needham has shown that the proposed detector design leads to high tracking efficiency, low ghost-rates and good momentum resolution. In addition the proposed design has been shown to be robust in the case the simulation of the detector is overly optimistic. For the forthcoming LHCb data challenge (DC '04) M.Needham has provided software to encode and decode the data in the format that it is expected to come from the detector.

## 4.6 Physics studies

In preparation for Physics data taking the group has recently started to work on physics simulation studies. Such studies are important in order to understand the CP reach of LHCb, to investigate possible sources of systematic uncertainty and to optimize the performance of the trigger. In the area of $B_s$ decays which are beyond the reach of the current generation of B factories LHCb will make a large impact. Therefore, we have chosen to study the decay mode $B_s \to J/\psi\eta'$. This decay mode can be used to measure the CKM angle, $\chi$ via a time dependent CP asymmetry measurement. A high precision measurement of this angle is an important check of the standard model [12]. Under the supervision of M.Needham and as part of his Ph.D. thesis work in our group, D.Volyanskyy currently works to develop an analysis for this decay mode and to determine the annual expected yield and signal-to-background ratio. These numbers will then be used to investigate the physics sensistivity of LHCb for this decay mode. In April 2004, M.Regli will join this project as a Diploma student.

## 4.7 Summary and outlook

R&D and design work for the TT station of the LHCb Silicon Tracker has been the major occupation of our group over the last year. Successful prototype tests have been performed in the laboratory and in test-beams and a mechanical design of the station has been developed. Preparations for the production of the detector are ongoing, a pre-series production is scheduled to begin in Autumn 2004, series production will commence beginning of 2005. The detector is foreseen be installed and fully commissioned before the startup of LHC, foreseen for 2007.

The digital optical readout link is operational in the laboratory and all relevant components have been radiation qualified.

In preparation for Physics data taking, the group has started to work on simulation studies, studying the decay mode $B_s \to J/\psi\eta'$. These studies will continue over the next years and will permit the group to build up experience for Physics analyses.

[1] *LHCb technical proposal*, CERN/LHCC 998-4.

[2] *LHCb Reoptimised Detector Technical Design Report*, CERN/LHCC 2003-030.

[3] *LHCb Inner Tracker Technical Design Report*, CERN/LHCC 2002-029.

[4] J.Gassner, M.Needham, O.Steinkamp, *Layout and expected performance of the LHCb TT station*, LHCb-2003-140.

[5] J.Gassner *et al.*, *Capacitance Measurements on Silicon Micro-Strip Detectors for the TT Station of the LHCb Experiment*, LHCb-2003-081.

[6] R.Bernhard *et al.*, *Measurements of Prototype Ladders for the Silicon Tracker with Laser*, LHCb-2003-075.

[7] M.Agari *et al.*, *Test-Beam Measurements on Prototype Ladders for the LHCb TT Station and Inner Tracker*, LHCb-2002-032.

[8] St.Heule, *Simulation und Messung von Silizium-Streifen-Detektoren*, Diplomarbeit, Universität Zürich, 2003;
see also: St.Heule and F.Lehner, *Simulation of Signal Generation in Silicon Micro-strip Detectors for the Silicon Tracker of the LHCb Experiment*, LHCb-2003-159.

[9] A.Vollhardt, *A Prototype for the LHCb Silicon Tracker Data Readout System*, LHCb-2003-045.

[10] A.Vollhardt, *Neutron Irradiation Results for the LHCb Silicon Tracker Data Readout System Components*, LHCb-2003-049.

[11] A.Vollhardt and A.Gafner, *Characterization and Sample Testing of the LHC4913 Positive Voltage Regulator for the LHCb Silicon Tracker*, LHCb-2003-049.

[12] J.P.Silva and L.Wolfenstein, Phys.Rev.**D 55** (1997) 5331.