7 High-precision CP-violation Physics at LHCb

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in collaboration with:
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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)

7.1 Introduction

The LHCb experiment aims to perform high precision measurements of CP violating processes and rare decays in the B meson systems. By measuring CP violation in many different decay modes of B_d^0 and B_s^0 mesons the experiment will over-constrain the picture of CP violation given by the Standard Model of particle physics and possibly reveal the effect of new physics. Our group concentrates on the development, construction, operation and data analysis of the LHCb Silicon Tracker as well as on physics analyses.

7.2 The LHCb experiment

The LHCb experiment (1; 2) is designed to exploit the large $b\overline{b}$ 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 operate at a moderate luminosity of 2×10^{32} cm^{-2}s^{-1} and will be fully operational from the start of LHC operation in 2007.

In particular, the copious production of 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.

A vertical cut through the LHCb detector is shown in Fig. 7.1. The most important elements are: a silicon vertex detector, tracking system and ring-imaging Cherenkov (RICH) detectors. Excellent particle identification is a key requirement for the experiment. The ability to

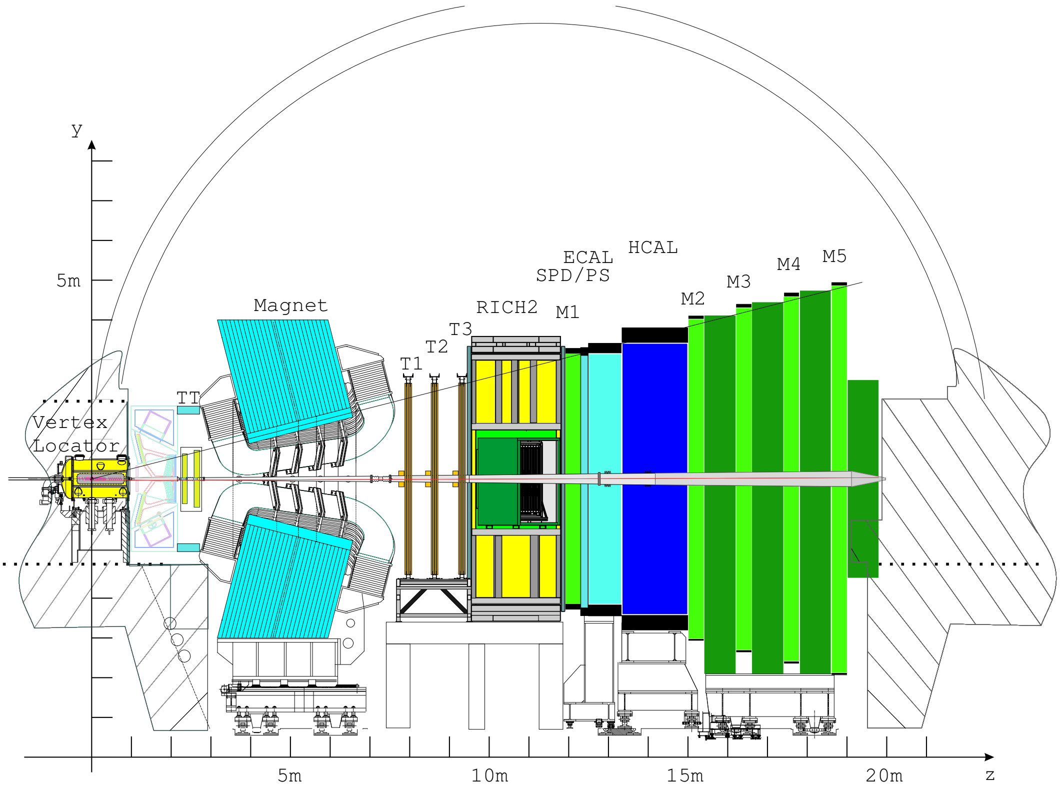

Figure 7.1:Vertical cross section through the LHCb detector.

distinguish final state with kaons and pions is essential in order to suppress specific backgrounds in many channels of interest and also to be able to select kaons for flavour tagging. Since measurements of particle trajectories are used as an input to the RICH reconstruction a highly efficient and well understood tracking system is essential to achieve good particle identification.

7.3 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 with O. Steinkamp as his deputy. It consists of two detectors that both employ silicon micro-strip technology but differ in important details of the technical design: The Inner Tracker (3) 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, (4) is located upstream of the spectrometer magnet and covers the full acceptance of the experiment.

The main responsibility of the group is the design and construction of the TT station. A large fraction of our efforts in 2004 were spent in the construction of final prototypes for the TT station and preparation for the detector production. In addition, our group is responsible for the L0 electronics and the development of the optical digital readout link for Inner Tracker and TT station. A prototype of the full readout system, using the final components has been set up and successfully tested in the laboratory.

7.4 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 layers are arranged into two half stations, referred to as TTa and TTb, split in z by a distance of around 30 cm. The layout of a detection layer is illustrated in Fig. 7.2. 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 (TTa) or eight (TTb) 14-sensor long ladders. Electronically, each ladder is split into several readout sectors, indicated by different shadings in Fig. 7.2. In the outer part of the detector, where the fluence is low the readout sectors consist of four and three sensors chained together. In the innermost three columns where the the fluence is highest the three sensor sector is split into a one and two sensor sector. M. Siegler has has shown that this layout gives adequate performance in terms of radiation induced leakage currents and shot noise, even after ten years operation in the harsh environment of the LHC, whilst minimizing the number of readout channels (5).

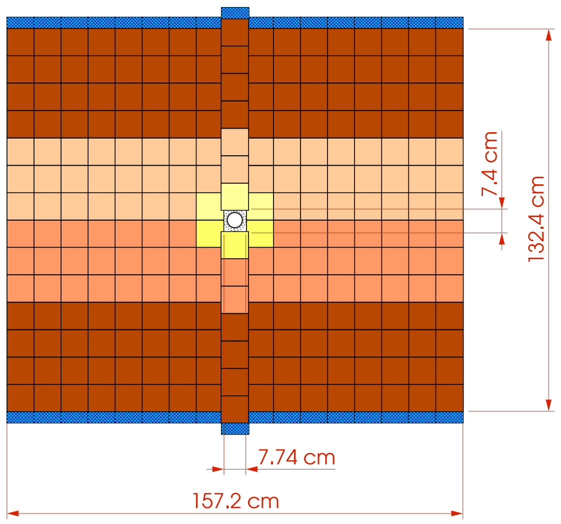

Figure 7.2:
Layout of one detection layer of the TT station. Readout sectors are indicated by different shading.

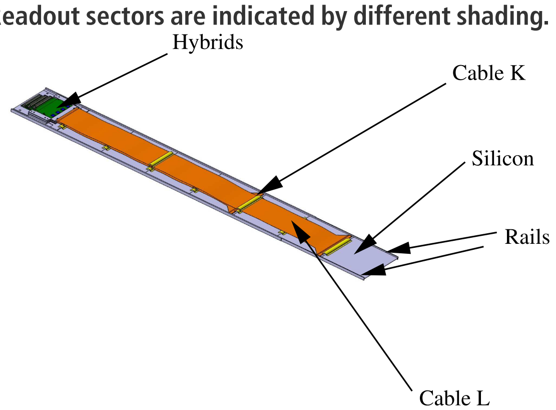

Figure 7.3:
Layout of a half module with two interconnect cables.

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 and 58 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. 7.3. 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 μm will be employed.

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.

7.5 Prototype tests

To verify the performance of the ladders equipped with interconnect cables two prototype modules have been built (see Fig. 7.4). Initial tests on the prototype ladders were performed in an infra-red laser test stand (6) in our laboratory by D. Volyanskyy and J. Gassner. A focussed 1064 nm laser beam is used 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 on the CMS3+Flex ladder 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).

Figure 7.5 shows the S/N distribution obtained for this ladder in the testbeam for tracks passing close to a readout strip. In Fig. 7.6 the dependence of the most likely S/N value on the inter-strip position is presented. It can be seen that for tracks passing close to a readout strip a S/N of 16 is obtained whilst for tracks passing midway between two readout strips a S/N of 14 is found. Such a charge loss has been observed in earlier tests of prototype modules and reproduced in a detector simulation (8). It is mainly attributed to loss of charge carriers at the boundary between the silicon bulk and the silicon oxide layer in between the two readout strips. These results are in good agreement with previous observations. Despite this charge loss full cluster finding efficiency is found across the entire inter-strip region.

The LHCb experiment is expected to operate for ten years in the harsh hadronic environment of the LHC. With time the radiation dose will significantly alter the electrical properties of the sensors. In particular it is known that after irradiation changes in the effective doping concentration and hence the depletion voltage occur (9). In addition, the increased leakage current leads to higher noise and heat dissipation. It is important to test the impact of these changes on the detector performance. To investigate the performance of IT sen-

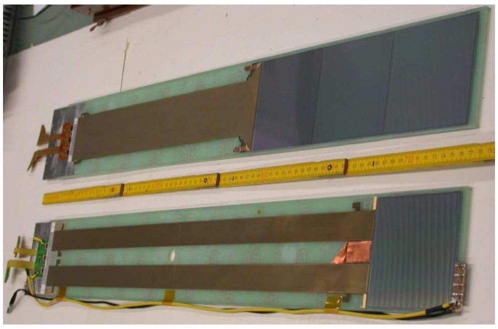

Figure 7.4:
Prototype ladders equipped with Kapton cables: CMS1+Flex (bottom) and CMS3+Flex (top).

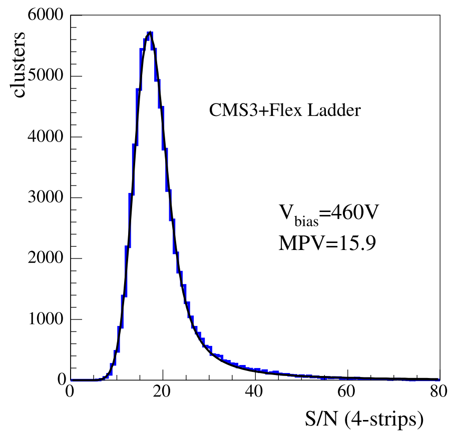

Figure 7.5:
Distribution of S/N derived from the sum of the four strips closest to the extrapolated track impact point for tracks passing close to a readout strip.

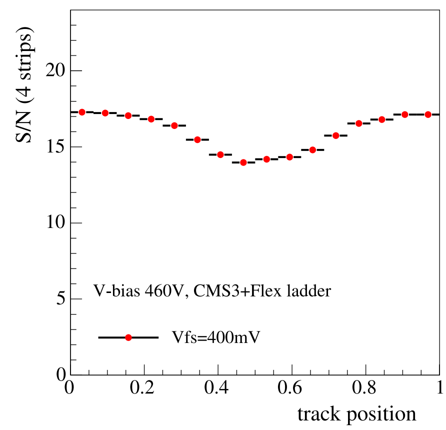

Figure 7.6:
Most likely S/N as a function of the inter-strip position.

sors after irradiation three LHCb multi-geometry prototype sensors were irradiated in a 24 GeV/c proton beam at the CERN PS with proton fluences in the range $2-6\times10^{13}$ cm^{-2}. The latter corresponds to the expected radiation dose after 20 years of LHCb operation. After irradiation the sensors were electrically characterized by C. Lois (10). Further tests were then carried out in the laser setup in Zürich (11). After irradiation the depletion voltage of the ladder irradiated up to 6×10^{13} cm^{-2} had increased from 70 V to 140 V. At room temperature a sizeable radiation induced leakage current is observed. This current leads to additional shot noise. As expected, both the leakage current (Fig. 7.7) and the shot noise could be suppressed by operating the ladders at temperatures around 5 °C. From these tests it is concluded that even after ten years operation at the LHC the detector will give adequate performance.

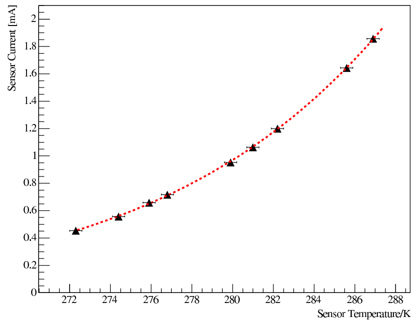

Figure 7.7:
Leakage current versus temperature for the irrad2 ladder

7.6 Preparation for the module production

Work has started in preparation for the final detector production which starts in May 2005. Sensors for both the IT and TT detectors will be first delivered to Zürich. A detailed test program including visual inspection, electrical characterization and metrology will then be carried out to assure the quality of the sensors. The majority of this work will be carried out by students working within our group. Procedures to be followed in this step have been produced by F. Lehner and tested on a preseries of sensors for the TT and IT (12).
Several prototype modules for the TT station have been produced in order to test the procedure to be followed. Bonding tests have also been made and adequate pull strengths achieved.
After production all modules will be tested in a 'burn in' stand being set up by M. Needham together with D. Volyanskyy and A. Wenger. Four TT modules will be tested at a time in a custom built box (Fig. 7.8). Electronics needed to control and readout the system is presently being prepared (Fig. 7.9).

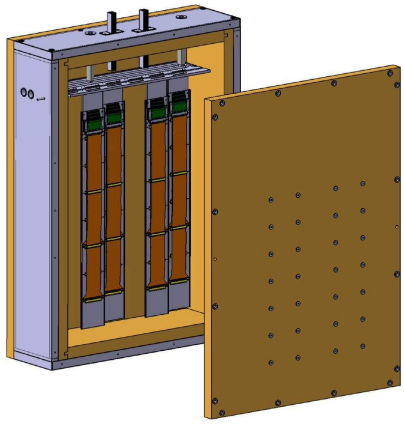

Figure 7.8:Detail of the burn-in box.

Figure 7.9:Detail of the electronics.

7.7 Readout system

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. On receipt of a trigger accept, the analog data are multiplexed, read out, digitised and transmitted to the LHCb electronics barrack. For the Silicon Tracker, the design and production of the electronics to do this is a responsibility of our group. Further processing of the data then occurs in the electronics barrack before the data is transmitted to the data acquisition system.

After transmission of the data from the Beetle the first step in the processing chain is to digitize the data. This occurs on digitizer boards located in service boxes placed close to the detector in the LHCb cavern. This electronics has been designed by A. Vollhardt as part of his Ph.D thesis work. This work has included qualifying all the components used for the expected radiation dose of 10 kRad after 10 years at the location of the service boxes (13). Prototypes for the digitizer boards have been produced and successfully tested in the laboratory. Data from the service boxes is transmitted to the electronics barracks using an optical link. Since the L0 Trigger operates at an 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. Vollhardt has designed and tested a low-cost digital optical link using commercially available components for this purpose. Similar developments are underway for other LHCb subsystems and a common working group has been formed by A. Vollhardt. He organizes regular group meetings, in which common solutions are discussed and the selection of commercial components is coordinated.

After transmission to the electronics barracks the data will be processed using L1 electronics boards developed by EPFL, Lausanne. Prototypes of this board have recently become available and have been integrated with the optical link setup in Zurich. This has allowed a first test of the complete readout chain to be carried out.

7.8 Simulation studies

The group is also active in studies of expected LHCb performance in preparation for LHCb startup. This work takes two forms. The first is the studies of LHCb physics reach described in the next section. The second is in the on-going studies of the performance of the tracking system. M. Needham has written a fast and efficient algorithm for searching track seeds in the Inner Tracker ('Tsa') (14). This algorithm is now being extended to Outer Tracker. Work has also been undertaken by A. Wenger and M. Needham to provide and up-to-date estimates of the material budget of the TT station for the LHCb Monte Carlo simulation.

7.8.1 Physics studies

In preparation for data taking the group has started to work on physics simulation studies. Such studies are important in order to understand the physics reach of LHCb, to investigate possible sources of systematic uncertainty and to optimize the performance of the trigger. We have chosen to concentrate our efforts in the area of B_s physics, which is beyond the reach of the current generation of B factories. Currently we are studying two decay modes. The first is the rare decay $B_s \to \phi\mu^+\mu^-$. The measurement of the forward-backward asymmetry of the lepton pair in this decay mode constitutes an important test of the standard model (15). As part of his Ph.D work A. Wenger, supervised by M. Needham, investigates this decay mode. He works to develop an analysis for this decay mode and to determine the annual expected yield and signal-to-background ratio. This work is being undertaken in close co-operation with R. Bernhard who is undertaking a search for this decay at D0 (see Sec.3).

The second decay mode being studied is $B_s \to J/\psi\eta'$. This decay mode can be used to measure the CKM angle χ via a time dependent CP asymmetry measurement. A high precision measurement of this angle is an important check of the standard model (16). This work is being jointly undertaken by D. Volyanskyy as part of his Ph.D. thesis and M.Regli as part of his Diploma studies. They investigate the physics sensitivity of LHCb for this decay mode by estimating the annual expected yield and the signal-to-background ratio.

7.8.2 Summary and outlook

Tests of final detector modules and preparation for the final detector production 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 completed. Preparations for the production of the detector are ongoing. Series production will commence in May of 2005. Detailed testing and quality assurance will be performed in a burn-in stand being set up in Zurich. The detector will be installed and fully commissioned before the startup of LHC, foreseen for 2007.

A full system test of the final readout electronics has been performed in the laboratory. The system will now be used to test modules in the burn-in stand.

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

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

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[6] **Measurements of Prototype Ladders for the TT station with a Laser**, J. Gassner *et al.*, LHCb-2004-102.

[7] **Measurements of a prototype ladder for the TT station in a 120 GeV/c π^- beam**, M. Agari *et al.*, LHCb-2004-103.

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