7 High-precision CP-violation Physics at LHCb

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The full LHCb collaboration consists of 48 institutes from Brazil, China, France, Germany, Italy, The Netherlands, Poland, Romania, Russia, Spain, Switzerland, Ukraine, the United Kingdom, and the United States of America.

(LHCb)

The LHCb experiment (1; 2) aims to perform high precision measurements of CP violating processes and rare decays in the B meson systems. The comparison of results from many different decay modes will permit to perform consistency tests of the Standard Model explanation of CP violation. In the Standard-Model picture, CP violating asymmetries are generated through processes involving internal loops of virtual particles and are therefore very sensitive to contributions from possible new particles, as they are predicted by almost all extentions of the Standard Model. Precision measurements of CP violating processes therefore provide a powerful tool to search for physics beyond the Standard Model, which is complementary to direct searches at the high energy frontier. Our group concentrates on the development, construction, operation and data analysis of the LHCb Silicon Tracker as well as on the preparation of physics analyses.

7.1 LHCb experiment

The LHCb experiment 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.

A vertical cut through the LHCb detector is shown in Fig. 7.1. Since the production of b quarks in proton-proton collisions at the LHC is strongly peaked towards small polar angles with respect to the beam axis, the 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 proton-proton interaction region.

The precise and efficient reconstruction of the trajectories of charged particles is a key requirement for the experiment. Many of the interesting decay channels require the reconstruction of several decay particles in a high-multiplicity environment. Furthermore, excellent

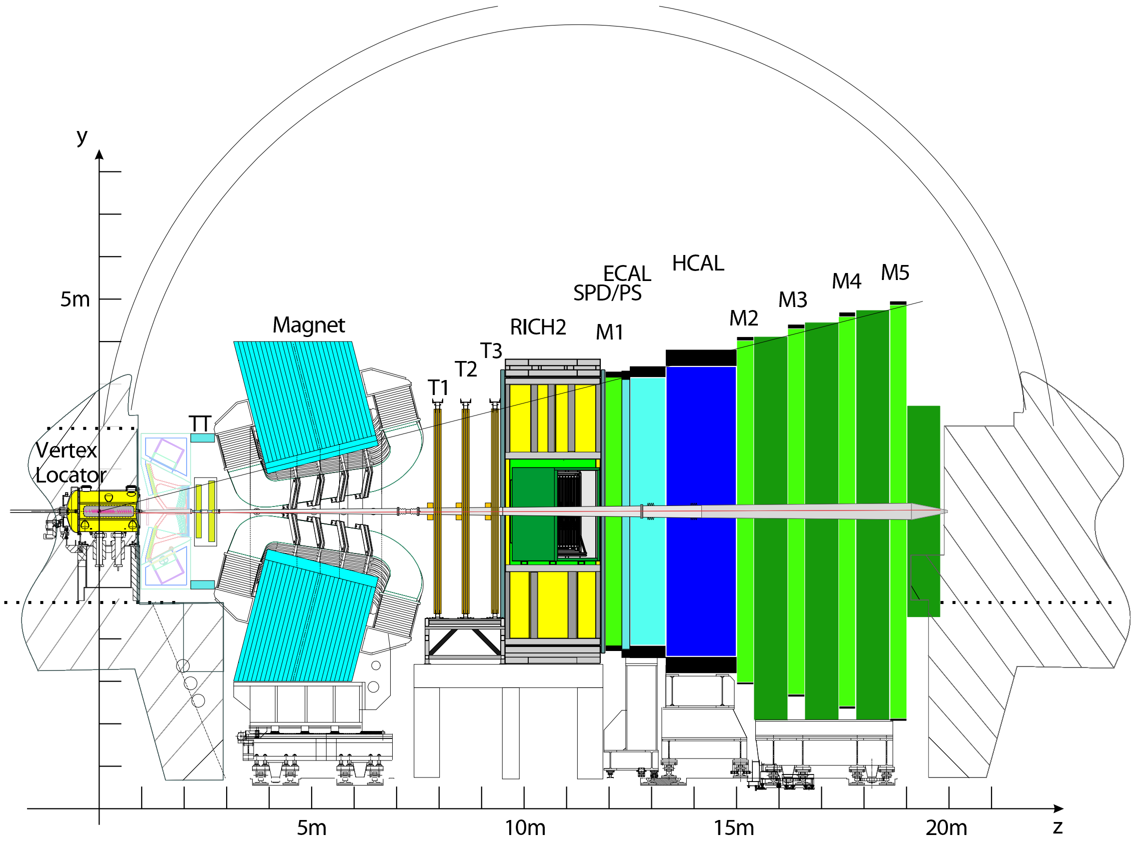

Figure 7.1: Vertical cross section through the LHCb detector.

momentum resolution is mandatory to resolve the fast flavour oscillation of B_s^0 mesons, which is required for time-dependent CP violation analyses. The LHCb tracking system consists of a silicon vertex detector (VELO), the Trigger Tracker (TT) upstream of the dipole magnet and four tracking stations (T1-T3) downstream of the magnet. The Trigger Tracker (2; 4) covers the full acceptance of the experiment with long silicon micro-strip detectors, whereas two detector technologies are employed in the large tracking stations T1-T3. Here, the innermost region around the beam pipe is covered by silicon micro-strips (Inner Tracker (3)) whereas the outer part of these stations is covered by straw drift-tubes (Outer Tracker).

Other components of the LHCb detector are two ring-imaging cherenkov (RICH) detectors, calorimeters (SPD,PS,ECAL,HCAL) and muon chambers (M1-M5).

7.2 Silicon tracker

Our group has taken a leading rôle in the development, production and operation of the LHCb Silicon Tracker, which consists of the Trigger Tracker and the Inner Tracker described above. Both these detectors employ silicon micro-strip technology but differ in important details of the technical design. The Silicon Tracker project is led by O. Steinkamp with U. Straumann as his deputy.

The main responsibility of the group is the design and construction of the Trigger Tracker. A large fraction of our efforts in 2005 were spent in launching the detector module production and quality assurance (QA) and in designing and preparing the various parts of the detector box and support frames. In addition, our group is responsible for the procurement and quality assurance of the silicon sensors for Inner Tracker and Trigger Tracker, and for design and production of the optical digital readout link for both these detectors. Almost all silicon sensors have been delivered to us and a large fraction of these have passed the QA programme. A full readout system, using the final components, has been set up and is routinely operated as part of the detector module quality assurance programme.

7.3 Trigger tracker

The Trigger Tracker fulfills a two-fold purpose: It will be used in the Level-1 trigger (hence its name) to assign transverse-momentum information to large-impact parameter tracks, and it will be used in higher-level triggers and 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 Trigger Tracker consists of four detection layers (4). Its active area is approximately 160 cm wide and 130 cm high and will be covered entirely by silicon micro-strip detectors with a strip pitch of 183 μm. An isometric drawing of the basic detector module is shown in Fig. 7.2 (5). It consists of seven silicon sensors that are electronically organised into either two or three readout sectors. All readout electronics and associated mechanics are located at one end of the module, 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. The layout of a detection layer is illustrated in Fig. 7.3, where the different readout sectors are indicated by different shadings. The areas above and below the beam pipe are each covered by a single detector module, the areas to the left and to the right of the beam pipe are covered by 14-sensor long ladders that are assembled by joining two detector modules together at their ends.

Including 15% spares, a total of 148 detector modules with about 165′000 readout channels has to be produced. A rigorous quality assurance programme has to be carried out in order to ensure that each module fulfills the strict mechanical and electrical acceptance criteria.

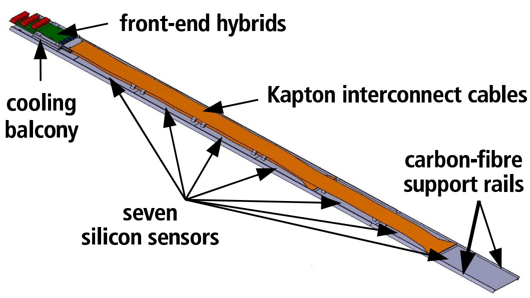

Figure 7.2: Isometric drawing of a detector module for the Trigger Tracker.

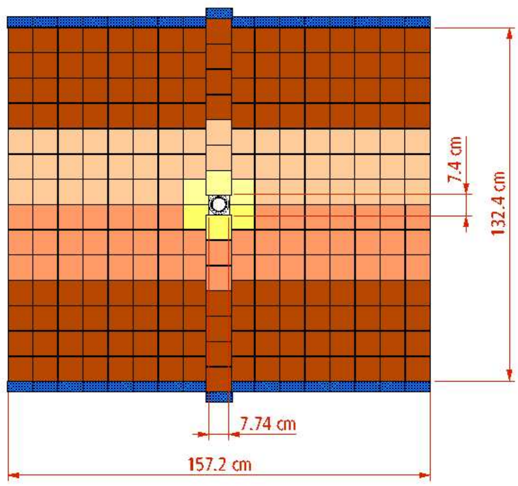

Figure 7.3: Layout of one detection layer of the Trigger Tracker.

7.3.1 Module production

The production of detector modules for the Trigger Tracker is proceeding under the responsibility of F. Lehner and T. Sakhelashvili. A laboratory at the Physik Institut has been converted into a clean room and equipped with the required infrastructure and equipment, such as microscopes for visual inspections and an automatic ultrasonic wire-bonding machine. In a pre-series production, that took place between May and August 2005, seven modules were assembled and thoroughly tested after each production step. This permitted to refine various details of the module assembly procedure (6) and to identify and improve a few weak points in the module design. For instance, the high voltage insulation between the carbon fiber support rails and the backplane of the silicon sensors was significantly improved to prevent sparking. Improvements to the alignment jigs used in the module assembly permitted to achieve an accuracy of the silicon sensor placement well within the tight specifications (Fig. 7.4).

The series production of detector modules was launched in September 2005. The production of a module proceeds in two stages. The first production stage includes the initial alignment of the seven silicon sensors and the lower readout hybrid under the control of an optical metrology machine, the glueing of the two suppport rails onto the edges of the hybrid and the sensors, the attachment of high-voltage and ground connections with silver epoxy glue, the wire bonding of the outer four silicon sensors to the readout hybrid, and the attachment of Kevlar protection caps over the wire bonds. After this first stage, the outer readout sector is fully operational and the module undergoes a first burn-in cycle as described in the quality assurance programme below. After the module has successfully passed the burn-in, it is completed in the second stage of the production. This consists of mounting and bonding the second (and third, where applicable) readout hybrid and Kapton interconnect cable(s) to the inner readout sector(s). The completed module then undergoes a second and final burn-in cycle.

The production of a detector module involves several gluing steps, each of which requires over-night curing of the glue. Several modules are produced in parallel to achieve an average module production rate of five modules per week. By the end of March 2005, about 60 modules were completed after the first production stage and twelve modules were fully completed (see Fig. 7.5 and 7.6).

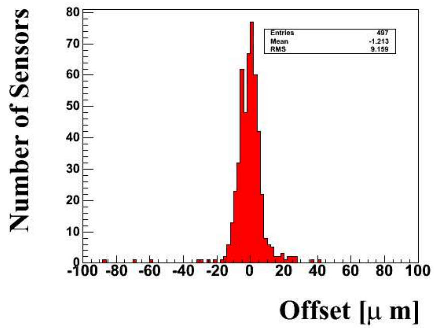

Figure 7.4: Distribution of the measured offsets of silicon sensors. Offsets should be small compared to the expected spatial resolution of 50 μm.

Figure 7.5: Storage of produced detector modules.

Figure 7.6: Two stage-I modules and two completed modules on their way from the production lab to the burn-in test stand.

A bottleneck during the start-up of the module production was caused by the late delivery of the Kapton interconnect cables, which are used to connect the inner readout sectors to their front-end readout hybrids. These cables were produced in industry and their delivery was delayed several times due to unexpectedly low production yields at the company. J. Gassner spent a significant amount of time and effort in discussions and tests with the company in order to overcome this problem. He recently managed to retrieve a sufficiently large number of cables of acceptable quality, so that all necessary components for the TT module production are now in hand. The production schedule foresees the completion of the module production by the end of October 2006.

7.3.2 Module quality assurance

Each module undergoes two extensive burn-in programmes, one after the first production stage and another one when the module is completed. A dedicated test stand that can hold up to four detector modules in parallel has been set up for this purpose by M. Needham and A. Vollhardt, with help from D. Volyanskyy and A. Wenger.

The burn-in programme takes two days and runs fully automatic, controlled by LabView running on a Linux PC. It includes measurements of sensor leakage currents as a function of the applied bias voltage as well as searches for interrupted and shorted readout strips and pinholes. A pulsed infra-red laser system is used to generate charges at well-defined locations on each silicon sensor and permits to measure signal pulse shapes and charge collection efficiency as a function of the applied bias voltage. Each module undergoes several temperature cycles between room temperature and +5°C, the latter being the operating temperature foreseen in LHCb.

As final readout electronics are employed to read out the detector modules, the burn-in test stand also serves as a full system test. Furthermore, the box that holds the modules during the tests uses many components of the final detector box (described below) and therefore serves as a small-scale prototype of that box.

So far, the quality of the tested modules is excellent. The fraction of non-working readout channels is in the sub-permille range and only a small number of modules showed operational problems and had to go through a repair cycle.

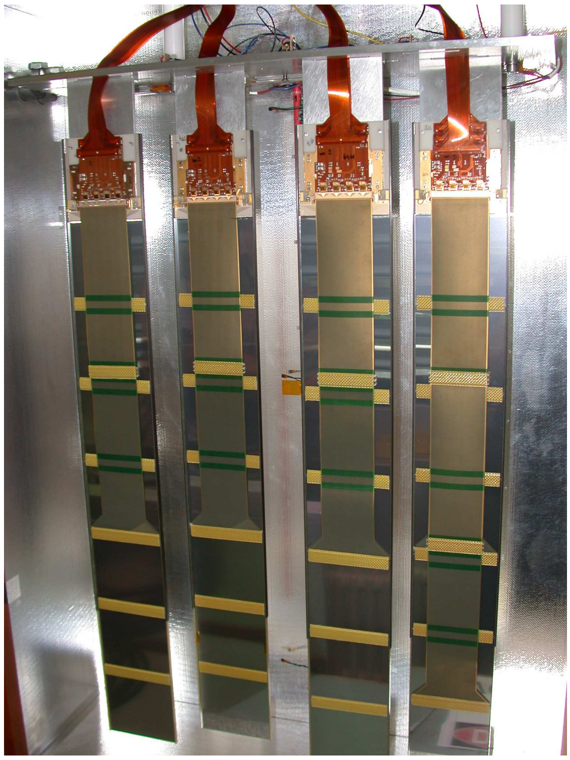

Figure 7.7:
Four completed detector modules installed in the burn-in test stand. The readout-hybrids can be seen at the upper end of the modules.

7.3.3 Station mechanics

All detector modules will be housed in a single light-tight and thermally insulating box, which also provides electrical insulation to the environment (5). Each module will be mounted into one of two C-shaped aluminum frames. These two frames will be mounted onto precision rails and can be retracted from the beam pipe for detector maintenance and for bake-outs of the beam pipe (Fig. 7.8). The frames include a cooling plate through which C_6F_{14} will be circulated as cooling agent to remove the heat generated by the readout hybrids and to create the desired ambient temperature of around 5°C inside the detector box. The design and production of the station mechanics has been the responsibility of S. Steiner. Almost all parts and pieces have been produced and are currently being assembled in a laboratory at our institute. Here, detailed mechanical and thermal studies will be performed on the detector box, before it will be shipped to CERN in autumn 2006.

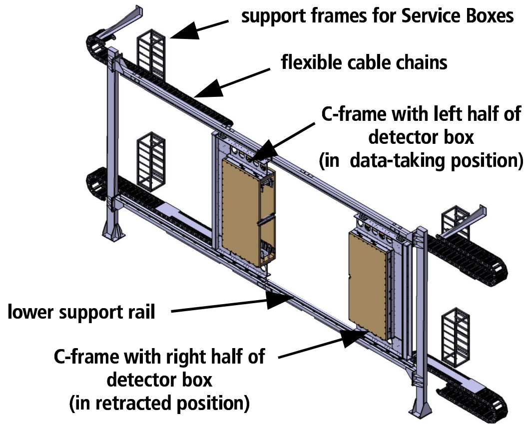

Figure 7.8:
Isometric drawing of the Trigger Tracker support frames and detector box. One half of the detector box is shown in the retracted position that is used for detector installation and maintenance.

7.4 Silicon sensors

The different types of silicon sensors that are used for the Inner Tracker and the Trigger Tracker have been described in earlier reports. The design specifications for the Inner Tracker sensors were defined in our group, whereas an existing design developed for the Outer Barrel of the CMS silicon tracker could be used for the Trigger Tracker. All types of silicon sensors have been produced by Hamamatsu Photonics, Japan. Upon arrival in Zürich, the sensors undergo a detailed quality assurance programme, which includes visual inspection, electrical characterisation and metrology. The largest part of this work has been carried out by students working under the supervision of F. Lehner (7). The last batch of sensors has been delivered recently and their testing is expected to be completed soon. The quality of the sensors is excellent and well within the strict mechanical and electrical specifications.

7.5 Readout system

The detector modules are equipped with Beetle front-end chips, which sample the detector data at the LHC bunch crossing frequency of 40 MHz and store the analog data for the latency of the Level-0 trigger. On reception of a trigger accept, the data are transmitted to a so-called Service Box, which is located close to the detector but outside of the acceptance of the experiment. Here, they are digitised, multiplexed and prepared for optical transmission to the LHCb electronics barrack. The Service Boxes and the optical links have been designed by A. Vollhardt, who is also responsible for the production and commissioning of the readout system. All relevant components have been radiation qualified for the expected radiation dose of up to 15 kRad for 10 years of operation at the location of the Service Boxes. Digitizer boards from a pre-production run are used to read out the data of the module burn-in stand described above, and in a similar setup used in the Inner Tracker module production at CERN. The series production of the boards is scheduled for summer 2006.

7.6 Detector simulation and reconstruction software

In preparation for data taking, a considerable software effort has been undertaken in our group to provide a detailed description of the Silicon Tracker and its performance in the framework of the LHCb Monte-Carlo and reconstruction programs. As input for the GEANT4-based LHCb detector simulation, a detailed XML description of the geometry of the Trigger Tracker, including sensitive detector elements as well as dead material, has been prepared by D. Volyanskyy and A. Wenger under the guidance of M. Needham. A refined description of the signal generation in the detector has been implemented and tuned to reproduce the detector performance measured in various test beams and laboratory tests. Furthermore, the final detector readout partitioning and data format have been defined and Monte-Carlo generated events are now stored in the same data format in which data will later be provided by the detector. This will permit more precise estimates of the expected data volumes and will significantly simplify the transition of the reconstruction code from Monte-Carlo to "real" data. The development and optimisation of track reconstruction algorithms is continuing.

M. Needham having left our group in November 2005, his responsibilities in these areas have been taken over by J.v. Tilburg, who joined us in February 2006. J.v. Tilburg has also started to participate in the development of alignment algorithms for the LHCb tracking system.

7.6.1 Workshop on tracking in high multiplicity environments

Members of our group organised a workshop on Tracking in High Multiplicity Environments, which took place at our institute in October 2005. The workshop brought together about 50 physicists working on hardware and software aspects of tracking devices, with the aim of transferring experience from running High Energy Physics experiments to those currently under development. Topics covered in the workshop included operational and system aspects, tracking and vertexing algorithms, radiation environments and aging, and detector technologies. Introductions to these topics were given by invited keynote speakers. All presentations are available on the conference web page, the proceedings will be published in a special edition of Nucl. Instr. and Meth. A.

Figure 7.9: Conference poster for the TIME 2005 workshop.

7.7 Physics studies

In parallel to our detector-related activities, work on physics simulation studies has also continued in our group. Such studies are required to understand the physics reach of the experiment, to investigate possible sources of systematic uncertainty and to optimize trigger selection criteria. We have chosen to concentrate our efforts on the decay mode $B_s \rightarrow J/\psi\eta'$. A time-dependent measurement of the CP asymmetry can be used to determine the phase of $B_s\overline{B_s}$ oscillations (i.e. the CKM angle χ). Since this phase is predicted to be very small in the Standard Model, a high precision measurement provides a sensitive search for contributions from "new" physics beyond the Standard Model (8).

This work is being undertaken by D. Volyanskyy as part of his Ph.D. thesis, under the guidance of M. Needham and U. Straumann. An initial optimisation of selection cuts has been performed and, for these cuts, a background-to-signal ratio of around one and an annual signal yield of about 5.3 k reconstructed events have been estimated, respectively. Specific background studies have been carried out to test the performance of the selection cuts in suppressing events from b hadron decays with similar event topologies to that of the signal decay. Invariant-mass, primary-vertex and secondary-vertex resolutions have been estimated and a proper-time resolution of (34.8 $\pm$ 1.2) fs has been found. This resolution is sufficient to perform a precise measurement of the time-dependent CP asymmetry. In the near future, an overall re-optimisation of selection cuts will be performed using a random grid search. This will allow to better take into account correlations between the different cuts. Larger samples of Monte-Carlo events will be processed in order to obtain more precise estimates of the expected background-to-signal ratio. Based on the results of these investigations, a study of the sensitivity of LHCb to the CP-violating parameters will finally be performed.

7.8 Summary and outlook

The series production of detector modules for the Trigger Tracker has been launched in 2005 and will be completed in autumn 2006. A detailed testing and quality assurance programme is performed on all modules. For this purpose, a burn-in stand has been set up in our laboratory. The setup uses final readout electronics and also serves as a small-scale prototype for the final detector box. All silicon sensors for the Silicon have been received from industry, the quality assurance programme on these sensors is close to being completed. The Trigger Tracker detector box is being assembled and will soon be commissioned in our institute. The detector will be shipped to CERN and installed in the experiment in autumn 2006. The final readout electronics are routinely used in the module testing, the series production of the electronics boards will start very soon.

Software developments for detector simulation and reconstruction algorithms are ongoing. In preparation for physics analyses, the group continues its work on simulation studies, especially concentrating on a study of the decay mode $B_s \rightarrow J/\psi\eta'$ and the sensitivity of LHCb to the phase of $B_s\overline{B_s}$ oscillations in this decay mode.

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

[5] **The Mechanical Design of the LHCb Silicon Trigger Tracker**, J. Gassner, F. Lehner, S. Steiner, LHCb note 2004-110.

[6] **The Production, Assembly and Testing of the LHCb Silicon Trigger Tracker**, J. Gassner, F. Lehner, S. Steiner, LHCb note 2004-109.

[7] **Pre-Series Sensor Qualification for the Inner Tracker of LHCb**, G. Baumann et al., LHCb note 2005-037.

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