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Commissioning and performance of the LHCb Silicon Tracker

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Abstract

The LHCb Silicon Tracker is a silicon micro-strip detector with a sensitive area of 12 m^2 and a total of 272k readout channels. The Silicon Tracker consists of two parts that use different detector modules. The detector installation was completed by early summer 2008 and the commissioning without beam has reached its final stage, successfully overcoming most of the encountered problems. Currently, the detector has more than 99% of the channels fully functioning. Commissioning with particles has started using beam-induced events from the LHC injection tests in 2008 and 2009. These events allowed initial studies of the detector performance. Especially, the detector modules could be aligned with an accuracy of about 20 μm. Furthermore, with the first beam collisions that took place end of 2009 we could further study the performance and improve the alignment of the detector.

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1. Introduction

The Silicon Tracker [1] is part of the tracking system of the LHCb experiment [2]. LHCb is a single-arm, forward spectrometer with excellent tracking and particle identification capabilities, ideally suited to perform high-precision measurements of CP violation and rare decays of B hadrons. The Silicon Tracker (ST) consists of two detectors, both of which use silicon micro-strip detectors with p-on-n type sensors, built from 6 inch wafers.

The first of these detectors, the Tracker Turicensis (TT), is a 150 cm wide and 130 cm high planar tracking station that is placed upstream of the LHCb dipole magnet and covers the whole acceptance of the experiment. It has been constructed using sensors with a pitch of 183 μm and a thickness of 500 μm. It is composed of four layers arranged into two half stations separated 30 cm along the beam (z) axis, and in an orientation of $0°$, $+5°$, $-5°$, and $0°$ with respect to the vertical (y) axis. The total active area of the TT equals 7.8 m^2. The layers are made out of 14-sensor long modules, except directly above and below the LHC beam pipe where the module is split in two 7-sensor half-modules (see Fig. 1(a)). Up to four sensors are bonded together thereby forming readout sectors of 1-, 2-, 3-, and 4-sensors. This segmentation is indicated by the different shadings in Fig. 1(a) and is motivated by the falling particle density when moving away from the beam axis. There are 280 readout sectors with a total number of readout channels 143k.

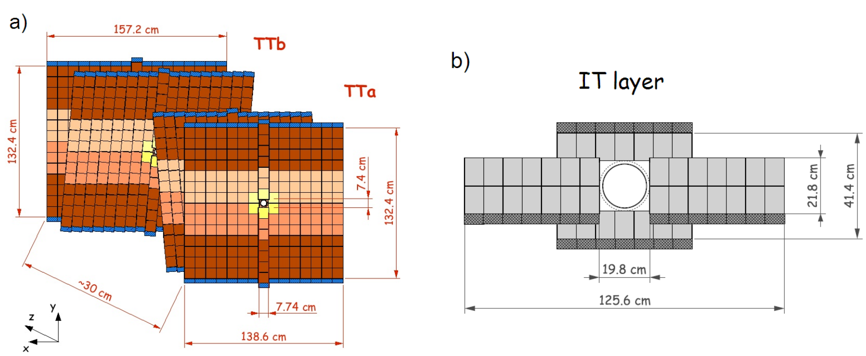

Figure 1: Layout of the full TT detector (a) and a single IT layer (b).

The second of the two detectors is the Inner Tracker (IT). It extends over a 120 cm wide and 40 high cross-shaped region in the center of the three planar tracking stations downstream of the magnet. Although the IT covers only 1.2% of the acceptance of these tracking stations, about 30% of the particles from the main interaction point are passing through the first IT station. Each IT station consists of four independent boxes arranged around the LHC beam pipe (see Fig. 1(b)), where each box contains four layers of silicon micro-strips again in an orientation of $0°$, $+5°$, $-5°$, and $0°$. The total active area of the IT equals 4.2 m^2. The detector modules placed left and right of the LHC beam pipe are 22 cm long with a thickness of 410 μm, while the modules above and below the beam pipe are 11 cm long with a thickness of 320 μm, in both cases the strip pitch is 198 μm. There are 336 readout sectors with a total number of readout channels 129k.

Both detectors use the same radiation-hard front-end chip (Beetle [3]) and readout electronics [4], operating at a clock frequency of 40 MHz. Clustering and zero-suppression are performed on a common off-detector readout board (TELL1 [5]), located in a zone accessible during LHC operation. The TT (IT) has been designed to withstand a radiation dose of 5 (8) x 10^{13} 1 MeV n/cm^2 equivalent to 10 years of nominal LHC operation. They can be cooled below 5 °C (with the coolant at -15 °C) in order to keep the effect from radiation damage to an acceptable level after 10 years of operation.

2. Commissioning without beam

The installation of the ST was completed by early summer 2008, followed by an extensive commissioning period. Readout channels that are not fully functioning were identified by comparing measured noise levels with the expected ones. Problems in the readout chain could be fixed, mostly by replacing the faulty component (e.g. electronics board, patch panel, cable, connector). Currently, the TT has 99.7% and IT has 99.2% of the channels fully functioning. Below we highlight two of the problems encountered during the commissioning without beam.

2.1. Broken bond wires (TT)

Soon after the installation of the first detector modules in the TT in June 2008 it was observed that in a few readout sectors every fourth channel started to show a lower noise than expected. Examining the affected readout hybrids under a microscope showed that this problem was caused by broken bond wires between the readout chip (Beetle) and the pitch adapter that leads to the sensor. These bond wires are staggered in four rows of which only the innermost row of bond wires was broken, thereby explaining the low-noise pattern of every fourth channel. In total 9 out of 280 readout sectors are (partially) affected. Despite many investigations, it was not possible to reproduce the bond wire breaking in the lab. Our current understanding is that material fatigue, induced by stress on the wire, e.g. vibrations and thermal cycling, has probably initiated the process. In addition the low loop height of the innermost bond wires is not ideal and might have accelerated the breaking process. Nevertheless, the total number of broken bond wires is still very low and the number of new broken bond wires has been decreasing over time. There are no new broken bond wires seen since July 2009. Six out of the nine affected sectors have been replaced and currently, the TT has 99.7% of the channels fully functioning.

2.2. Header cross talk

The analog data from the Beetle is sent via four output ports. Each port corresponds to 32 channels (silicon strips). This data is preceded by 4 header bits, which are encoded as analog signals. The first few data channels are affected by cross talk from these header bits, which effectively gives rise to higher noise in these channels. A small amount of cross talk was indeed expected in the first channel only, due to an internal feature of the Beetle chip. However, the cross talk affects not only the first channel, but the first 4 (2) channels in the TT (IT). The amount of cross talk and the number of affected channels depends mainly on the length of the output cable going from the Beetle to the digitizer board. The effect can be corrected for in the LHCb readout board (TELL1) before the zero-suppression. The correction values can be obtained from a calibration run by calculating the correlation between a high or low header bit and the readout value in the first strips in each port. This correction is then subtracted from the readout values in the FPGA on the TELL1. In the current FPGA implementation the correction can be applied to the first 6 strips in each port. Figure 2 shows the effect of the header correction on the noise level in a readout port.

3. Commissioning with beam

3.1. Data from the LHC injection tests

During the summer of 2008 commissioning with particles started using cosmic rays, albeit at a low rate due to the geometry of LHCb. The IT participated in these cosmic runs, however, there were only about 100 cosmic tracks crossing two IT stations. A much larger data set was obtained using beam-induced particles from the injection tests of the LHC machine in 2008 and 2009. As part of these tests, the 450 GeV proton beam was directed on a beam dump, called TED, in the SPS-LHC transfer line, 350 meter behind

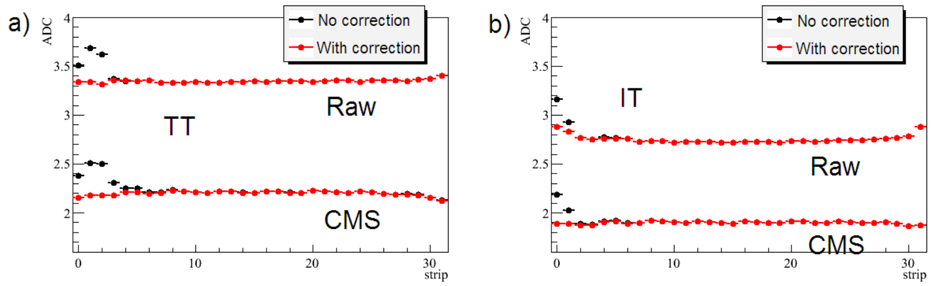

Figure 2: Raw noise and common-mode-subtracted (CMS) noise in the 32 data channels of a port for TT (a) and IT (b). It shows the effect of the header correction on the noise in the first few data channels.

the LHCb experiment. This produced splashes of secondary particles in the detector with an average momentum of about 10 GeV/c. The strip occupancy in the IT was typically about 6%, while in the TT it was about 10%, which is a factor 20 higher than expected in a typical beam collision event. Since the TED is located behind the LHCb detector, the secondary particles are coming from the *wrong direction* compared to particles from beam collisions.

Nevertheless, these events could be used to perform a first relative time alignment of the different parts of the detector and to measure the pulse shape of the Beetle output signal. First, the coarse time alignment is determined by reading out (triggering) 15 consecutive clock cycles (events). The event with the highest occupancy determines the correct delay of the trigger signal. After that the fine time adjustment is performed. This can be done by setting the delay of the 40 MHz sampling clock, which can be adjusted in steps of 104.17 ps for each set of 12 or 16 readout sectors. The full pulse shape could be measured by taking non-zero-suppressed data with different clock delays. Only one-strip clusters were considered to avoid bias from capacitive coupling and charge sharing between neighbouring channels, which is present in two-, three-, and four-strip clusters. By reading out five consecutive events (separated by 25 ns) around the maximum of the pulse, it was possible to follow the pulse shape including its undershoot without relying on external information (e.g. without the need reconstruct tracks). For each event and setting of the sampling clock the most probable value (MPV) of the signal-over-noise (S/N) distribution is determined. Figure 3 shows the pulse shape obtained when plotting the MPV versus the total, effective trigger delay (i.e. sampling clock delay plus coarse trigger delay).

The data from the TED runs could also be used to obtain an initial

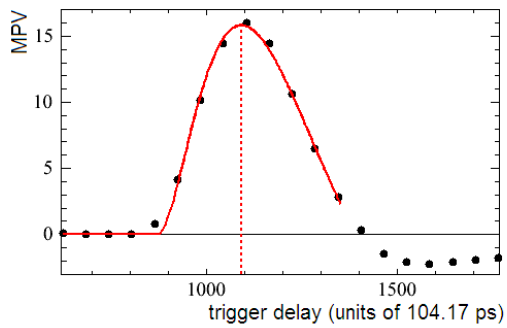

Figure 3: Pulse shape for a set of short IT ladders from the TED data. The most probable value (MPV) for each trigger delay is obtained from a fit to the S/N distribution. The overlaid curve is from a fit to a function [6] that is expected from the output of the Beetle chip.

spatial alignment of the IT [7]. For this purpose, a robust, standalone track reconstruction code was developed [8] to deal with the high occupancies. The track finding is based on straight line trajectories since the LHCb dipole magnet was not turned on during the TED runs. In order to select isolated tracks, only the low occupancy runs (with an occupancy of about 3%) were used for the alignment and tracks were required to point back to the position of the TED, resulting in a total of 16k isolated tracks. The initial position of the detector is taken from survey measurements (c.f. Ref. [9] and [10]). Then, a pre-alignment is done by connecting hits in the first and last layer of the IT and calculating the distances to the hits in the other 10 layers. The distributions of these distances shows clear peaks due to real tracks on top of a large combinatorial background. This allows to coarse align the layers for the most sensitive axis (x-axis). After this pre-alignment, the track finding algorithm and the actual alignment are performed. The alignment of the IT is based on a closed-form alignment method [11] using tracks fitted with a Kalman filter. Each of the twelve detector boxes were aligned for translations along x (horizontal) and y (vertical) and rotations around the z axis, each of the four layers within a box for translations along x and rotations around z and the individual modules only for translations along x. An estimate for the alignment accuracy is obtained from the distribution of the mean of the unbiased track-hit residuals for each detector module, taken from an independent data sample. The width of this distribution indicates that the IT modules could be aligned with an accuracy of about 20 μm (see Fig. 4). Even though the IT boxes were moved between the TED runs, it was shown that the internal alignment within each of the boxes remained valid.

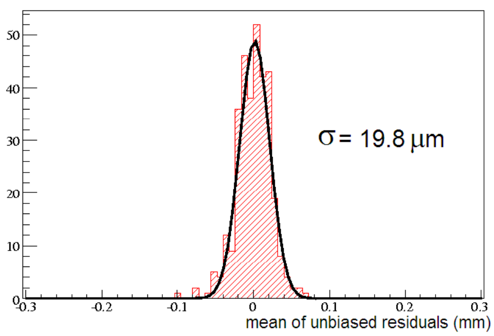

Figure 4: Offset of each ladder in IT taken from the mean of the unbiased residual distributions. The unbiased residual distributions are obtained from an independent sample of the TED data. The width of this distribution (20 μm) is a measure for the alignment precision.

Since the TT contains only 4 layers, it is hardly possible to do a standalone track reconstruction. Hence, the alignment of the TT relies on extrapolated tracks from the other tracking detectors. With the TED data it was only possible to align to the level of the whole TT station for translations in x and rotations around y.

3.2. Data from the first beam collisions

In November and December 2009 the LHC detectors saw the first collisions. In total about 540k events were collected at a beam energy of 450 GeV with all detectors, including the silicon detectors, and the magnet turned on. In addition, 3k events were recorded during a run when the LHCb dipole magnet was turned off. The first data with stable beam conditions was used to perform a fine timing of the TT and IT. With the experience and internal timing from the TED runs, the adjustment could be done in only 3 hours. Compared to the TED run, only zero-suppressed data was available. Although this means it is not possible to see the full pulse shape it is more than sufficient to find the time of the maximum signal with an accuracy of the order of one nanosecond. At the maximum height of the pulse shape the signal-over-noise is found to range between 11.1 and 16.8 as shown in Table 1. These numbers are consistent with expectations from test-beam measurements [12]. The timing adjustment of the ST will be repeated for

Sector type type	TT1	TT2	TT3	TT4	IT long	IT short
S/N	14.5	13.7	11.1	11.9	15.4	16.8

Table 1: Measured signal-over-noise (S/N) in 2009 collision data for the different readout sector types. TT1, TT2, TT3, and TT4 denote, respectively, the 1-, 2-, 3-, and 4-sensor sectors in the TT, while the IT long and IT short denote the long, 2-sensors ladders and short, 1-sensor ladders in the IT.

the 2010 run, since the cooling temperature is lowered. The coolant temperature has changed from 15 °C to 5 °C, which is considered to be sufficient for the low amount of radiation expected in the 2010-2011 LHC run.

The collision data also provides a wealth of data for spatial alignment. In contrast to the TED data the occupancies are much lower and more homogeneous throughout the detector. In addition, standard LHCb tracking algorithms could be deployed to find particles passing through all tracking detectors. The alignment of the IT with collision data is similar to the alignment with TED data. This time the starting point is the resulting alignment from the TED run. Tracks are required to point back to the interaction point and have a momentum above 6 GeV/c and χ^2 per degree of freedom below 7. It was found that the modules in the IT could be aligned with an accuracy of about 15 μm in x. However, not all degrees of freedom have been included in the alignment yet. Another issue concerns the alignment of the IT boxes with respect to each other. This inter-box alignment relies on tracks passing through the overlap region of two adjacent boxes in the same station. The number of these tracks is limited since the physical overlap between the boxes is small. Significant differences are also seen between the alignment of magnet-on and magnet-off data. It is known that some of the detectors are moving when the magnet is turned on. However, the reconstructed differences are larger than the expected movements. More studies are needed to understand these differences.

With the beam collision data it is also possible to perform an alignment of the TT to the module level. After this alignment the unbiased hit residual is found to be 75 μm, which can be compared to the 51 μm that is found in the Monte Carlo simulation.

4. Conclusions

The Silicon Tracker has been successfully installed in the underground area. During the commissioning without beam several problems in the readout chain were identified and solved. The fact that the cause for breaking bond wires in the TT has not been understood remains a concern, however, the total number of affected channels remains low and the rate at which new broken bond wires are observed has gone down significantly over the last two years, without any new broken bond wires in the last six months. Currently, both the IT and TT have more than 99% of working channels. Another achievement was the removal of the additional noise in the first data channels of each Beetle output port. Data from the TED runs have allowed us to gain a valuable experience in aligning the detectors both in time and space. Nevertheless, the real test case is coming from the data from the first collisions in 2009. With this data we could align the detectors with an accuracy of the order of one nanosecond. For the 2010 run the timing will be re-tuned because of the change in temperature, but also other scans are envisaged as for instance charge-collection-efficiency versus the bias voltage. With the 2009 collision data we have verified the expected signal-over-noise from test-beam results. Also the spatial alignment has started and the first successes have been made with an alignment to the module level for both the IT and TT. This effort will continue with more statistics becoming available in order to include more degrees-of freedom and to understand discrepancies between the magnet-on and magnet-off data. With the first collisions the LHCb spectrometer has reconstructed its first K^0_S, Λ, and ϕ peaks with the masses in very good agreement with expectations. The mass resolution will improve with a better alignment.

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