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Commissioning of the LHCb Silicon Tracker using data from LHC injection tests

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LHCb is a single-arm forward spectrometer dedicated to the study of *CP* violation and rare decays in the *b*-quark sector. An efficient and high-precision tracking system is a key requirement of the experiment. The LHCb Silicon Tracker consists of two sub-detectors that make use of silicon micro-strip technology: the Tracker Turicensis located upstream of the spectrometer magnet and the Inner Tracker which covers the innermost part of the tracking stations downstream of the magnet. Together, these two detectors cover an area of 12 m^2 with silicon. In September 2008 and June 2009 injection tests from the SPS to the LHC were performed. Bunches of approximately 2–5 $\times 10^9$ protons were dumped onto a beam stopper (TED), producing a cone of secondary particles heading towards LHCb. This produced a spray of $\simeq$ 10 GeV/c muons in the LHCb detector. Although the occupancy in these events is significantly higher than that expected for normal running conditions, the TED runs have allowed a first space and time alignment of the tracking system. The results of these studies and the overall detector performance obtained in the TED running are discussed.

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1. The LHCb Detector

LHCb is an experiment at the Large Hadron Collider (LHC), dedicated to the study of *CP* violation and rare decays in the *b*-quark sector. It is designed to run with *pp* collisions at a center-of-mass energy of 14 TeV/c^2. Since the *b*-quark production cross-section is peaked at high pseudo-rapidity, the detector has been designed as a single-arm forward spectrometer. The layout of the detector is shown in Fig. 1. The acceptance covers an angle of 15–300 (15–250) mrad with respect to the beam axis in the bending plane (non-bending plane).

The tracking system includes the Vertex Locator (VELO), which is a silicon detector for primary vertex reconstruction surrounding the interaction region, the silicon Tracker Turicensis (TT) located before the dipole magnet, and three tracking stations (T1, T2, T3) located after the magnet. The tracking stations are are composed of the silicon Inner Tracker (IT) and the straw-tube Outer Tracker (OT). Other important detectors are the Ring Imaging Cherenkov (RICH) counters for particle identification, the Electromagnetic and Hadronic Calorimeters (ECAL/HCAL), and the Muon stations M1-M5. LHCb uses a cartesian coordinate system with its origin at the nominal LHC interaction point, the z axis along the beam axis, the x axis horizontal and the y axis vertical. A detailed description of the detector can be found in Ref. [2].

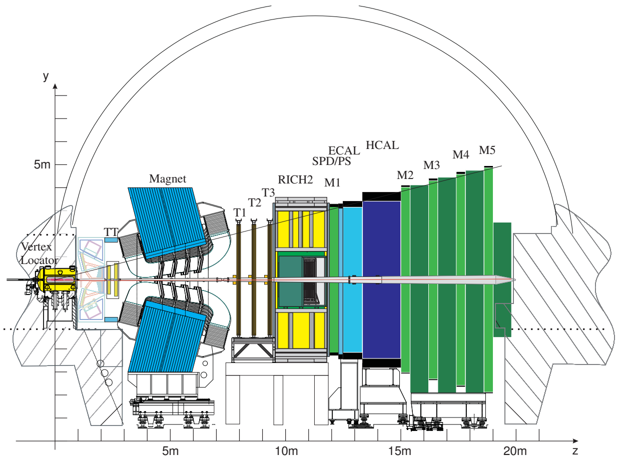

Figure 1: Layout of the LHCb detector in the non-bending (y-z) plane. The beam pipe crosses LHCb along the z axis at $y = 0$ and the interaction point is located at $z = 0$.

2. The Silicon Tracker

The Silicon Tracker consists of the Inner Tracker (IT) located downstream of the spectrometer magnet and the Tracker Turicensis (TT) situated upstream of the magnet. Both make use of silicon micro-strip technology. A total area of 12 m^2 is covered by 16 layers of silicon sensors. Due to their similarity the two detectors have been developed as a common project.

The IT is composed of 336 silicon micro-strip modules arranged in three stations with four boxes each. The stations are separated by $\simeq$ 70 cm in z. The boxes are located at 7 mm from the beam pipe, covering the very forward region of the acceptance. Each box contains 28 modules arranged in four layers. Two of the four layers have vertical readout strips, the other two layers have readout strips tilted by a stereo angle of $+5^\circ$ and -5°. Although the IT covers only 1.5% of the geometrical acceptance, it covers about 20% of the pseudo-rapidity range, leading to high particle densities. The readout pitch is 198 μm, and the total number of channels is 129′000. The layout of a layer is shown in Fig. 2 (left). The 336 modules are of two types: "Short" modules (11 cm in length), built with one 320 μm-thick silicon sensor, used in upper and lower boxes and "Long" modules (22 cm in length), built with two 410 μm-thick silicon sensors, used in side boxes. The Signal-over-Noise ratio (S/N) of the IT modules is about 15.

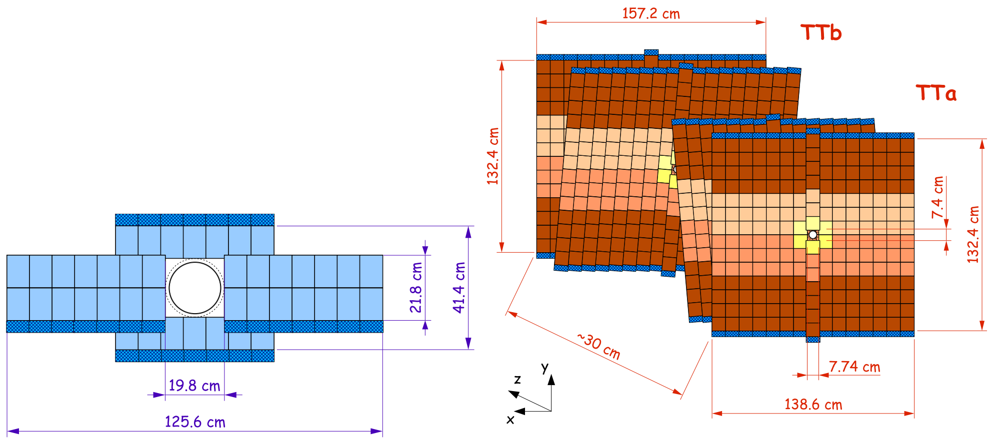

Figure 2: Silicon sensors arranged in x–y planes around the beam pipe (each rectangle represents one sensor). Left: one of the 12 IT detection layers. Right: the four TT layers.

The TT (Fig. 2, right) located just before the magnet is composed of 128 half-modules arranged in four layers. The four layers have the same orientation as for the IT: two layers are vertical, and the other two are tilted by $+5^\circ$ and -5°. In contrast to the IT it covers the full LHCb acceptance. The half-modules are made of seven 500 μm-thick CMS-OB2 sensors (each sensor is 9.4 cm long). The readout pitch is 183 μm, and the total number of channels is 143′000. The S/N of the TT modules is about 12.

After the installation was completed in early summer 2008, the commissioning of both IT and TT was started using data collected in cosmic runs as well as LHC injection test runs. Analysis of the data taken in the 2008 running period allowed to identify several readout channels faults, which were fixed for the 2009 run. Currently 99.7% of the channels are operational in each detector.

3. Cosmic Running

The probability for a cosmic particle triggered by the calorimeters to pass through IT or TT is extremely low because of the geometric configuration of the detector. In a sample of 2.6 million cosmic events triggered by the calorimeters, 1000 cosmics were observed for which track segments were reconstructed in at least one IT box. In the same sample three tracks were reconstructed through three IT boxes. Though the statistics were limited these events were useful to have a first coarse time and space alignment. An example of a "golden" cosmic event, hitting three IT boxes, is shown in Fig. 3.

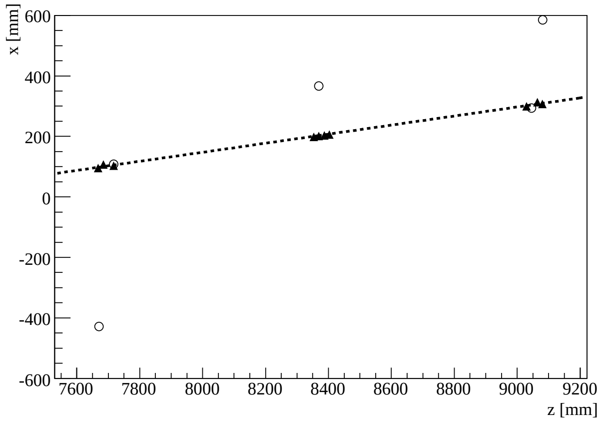

Figure 3: Position of the hits in an event with a cosmic particle traversing three IT boxes, shown in the x-z view (z: coordinate of the sensor, x: coordinate of the mid-point of the sensor). There are three groups of four aligned hits, corresponding to the four layers of one box in each of the three stations. Triangles are hits associated to the track while circles are other hits in the event.

4. LHC injection tests

In September 2008 and June 2009, injection tests were performed with the LHC machine. These tests consisted of injecting 450 GeV/c^2 protons in the transfer line from the SPS to the LHC. Bunches of $2\text{–}5 \times 10^9$ protons were dumped onto a beam stopper (TED), located in the transfer line. Since LHCb is located 350 m downstream of the cone of secondary particles produced by the beam dump, it was possible to observe these particles, about 1000 to 2000 per event in the LHCb acceptance. Monte Carlo simulations indicated that the particles reaching the detector are mainly $\simeq$ 10 GeV/c muons. The data were collected without magnetic field. The analysis of the TED events was challenging, since particle densities in the Silicon Tracker were about ten times larger than expected in a typical $b\bar{b}$ event, leading to strip occupancies up to 8%.

5. Time Alignment

The goal of the time alignment was to synchronize the maximum of the signal amplitude from the output of the front-end electronics, with the sampling time given by the LHC clock at 40 MHz. Different timings had to be set for each specific part of the IT or TT. The timings depend on three parameters: the time of flight between the tracking stations, the signal cable lengths which are different for various parts of the detector, and the different capacitances between the detector modules due to the different readout strip lengths.

The method used to find the time of the maximum signal was to reconstruct the pulse shape as a function of time, by taking several data points with different time delays between the LHC clock and the signal sampling time. The signal amplitude for each delay was determined from the measured charge distribution of all the clusters (not only the ones associated to a track) as described below. Although we will show the figures for IT, the TT was time-aligned in the same way. Details can be found in [3].

The charge distribution of $\simeq 10$ GeV/c muons passing through a given thickness of silicon can be described by the convolution of a Landau with a Gaussian. The Gaussian width takes into account the effect of detector noise and atomic binding. A typical distribution is shown in Fig. 4 (left). The region around the maximum of the distribution is well described by the fitting function. The small peak just above $\simeq 10$ ADC counts is the tail of the noise distribution. There is a knee in the tail of the curve around 80 ADC, which is due to merged clusters coming from two distinct particles[1]. The value used to measure the signal from the charge distribution is the most probable value (MPV).

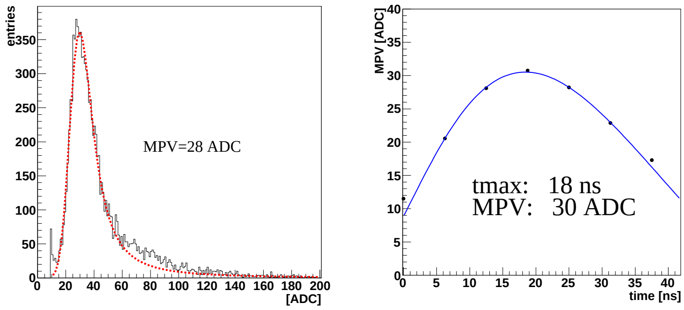

Figure 4: Left: Charge distribution fitted with the convolution of a Landau and a Gaussian. The Most Probable Value (MPV) is given by the fit, which was performed between 15 and 50 ADC. Right: Pulse-shape scan. The MPV of the charge distribution is plotted versus delay time, and fitted by a function describing well the expected signal pulse shape.

Several sets of data were taken with different delays between trigger and signal sampling time, in steps of 6.25 ns[2]. For each delay, the Landau was fitted to the charge distribution and the MPV was extracted. The MPV was then plotted against the different delays, allowing to reconstruct the shape of the pulse in steps of 6.25 ns over more than 50 ns (Fig. 4, right).

The measured pulse shape was then fitted with a function which describes the expected behaviour of the front-end amplifier, in order to extract parameters such as the time of the maximum and the signal amplitude in the maximum of the pulse. This analysis was performed per detector module. Distributions of the fitted parameters are shown in Fig. 5. The distribution of the time of the maximum shows several peaks corresponding to different data cable lengths. The distribution of the error on the time of the maximum shows that the average precision is about 1 ns. The errors are bigger for short-sensor modules due to their lower signal amplitude, as seen on the third plot of the figure. A few of the short-sensor modules have a higher signal than the rest (the cluster around 37 ADC), due to the fact that these special modules have been built with 410 μm sensors, instead of 320 μm for the other short modules. The higher signal observed on these modules compared to the long modules of the same thickness is consistent with the expected higher gain of the front-end amplifier for the lower capacitance in this case.

[1]This structure will be smaller during normal data taking due to the lower occupancy.

[2]This corresponds to a quarter of the time between two bunch crossings at 40 MHz.

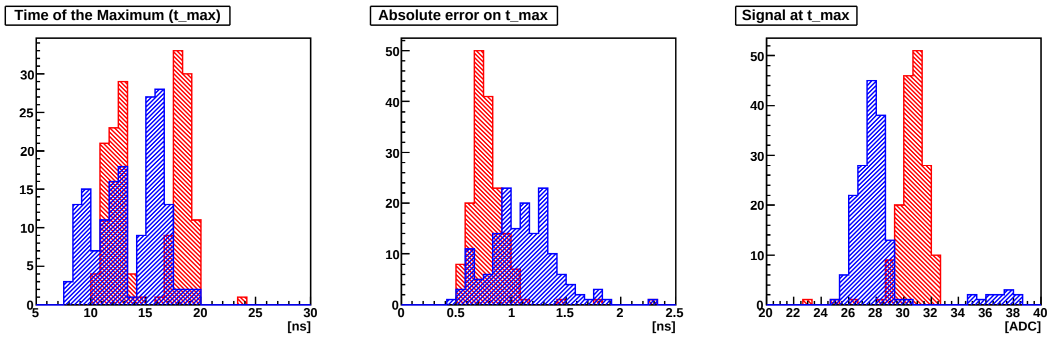

Figure 5: Parameters extracted by the pulse-shape fits per IT-detector module, for the short IT modules (blue/dark grey) and the long IT modules (red/light grey). Left: Time of the maximum. Middle: Error on the time of the maximum. Right: Signal amplitude in the maximum.

6. IT Space Alignment

The alignment performed in the TED runs which is decribed here is an internal alignment: no alignment with other detectors was performed. The space alignment procedure consists of two steps: pre-alignment and alignment. In the pre-alignment step, two boxes are fixed and the third one is aligned with respect to these two. This step is needed to ensure that the box position in x is known to a sufficient precision to allow a reliable pattern recognition to be performed. In the alignment step, two layers are fixed, and the others are aligned with respect to these. Details can be found in Refs. [4, 5, 6].

6.1 Pre-alignment

The pre-alignment consisted of estimating the position of the T2-station boxes with respect to the boxes in station T1 and T3. Firstly, a line was defined with a hit in the last layer of the last box (station T3) and a hit in the first layer of the first box (station T1). This line was required to be consistent with a particle originating from the TED. A second layer in one of the boxes was used to confirm the track candidate. Secondly, the distance between the line and the hits in station T2 was calculated and histogrammed. Fitting a Gaussian plus a flat background to this histogram allowed to extract the position of the middle box in T2 relatively to the fixed T1 and T3 stations (see Fig. 6). The observed offsets (700 μm, average over all four boxes) were consistent with the precision of the survey ($\simeq 1$ mm).

6.2 Alignment

The full alignment procedure was run after the pre-alignment. A sub-set of 16′000 isolated[3] tracks were selected in the TED events where the occupancy was lowest. Tracks were reconstructed in the IT in a standalone way, and then passed to the full LHCb alignment framework[4]. The boxes were aligned for x, y translations and z rotations, the layers for x translations and z rotations, and the detector modules for x translations. An iterative procedure was used in which tracks were

[3]An isolated track is defined as having less than four hits in a 1 mm window around it.

[4]Based on Kalman Filter, see Refs. [5, 6]

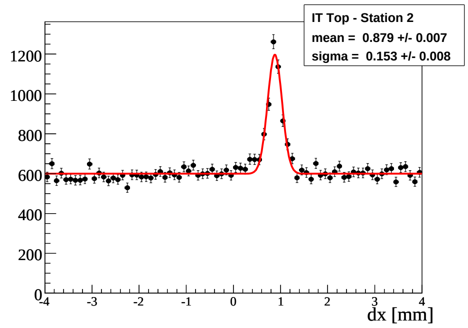

Figure 6: Pre-alignment: residuals in the Top box of IT-station T2.

selected with low χ^2. In order to give a reliable estimate of the χ^2 in the absence of misalignment, a momentum must be assigned in the track fit. Therefore all tracks were assumed to be $\simeq$ 10 GeV/c muons. To avoid biases, the χ^2 cut was initially kept loose, and gradually tightened after each iteration. After each iteration the new alignment constants were taken as an input for the next iteration. The procedure converged after three iterations.

The quality of the alignment was validated with an independent data sample from the TED run. Reconstructed tracks were used to calculate residuals in every module, without using the hits in this particular module (unbiased residuals). A Gaussian was then fitted to the unbiased residuals, and the mean (module bias) and the width (resolution) were extracted from the distribution. In Fig. 7, the distributions of the mean (left) and width (right) of the unbiased residuals are shown for all long-sensor modules. The distribution of the mean is centered around zero and has an rms of 9 μm, which is an indication of the remaining misalignment. The distribution of the width is centered around 80 μm for x-measuring layers, and 120 μm for stereo layers. The wider distribution of the width for stereo-layers is expected since there are only six measurements of this type compared to twelve x measurements. Both numbers are consistent with reconstructed tracks being $\simeq$ 10 GeV/c muons. The intrinsic resolution of the detector modules was determined in test beams to be around 50 μm.

7. TT Space Alignment

The TT has only four layers, therefore no standalone tracking can be done. In order to estimate the misalignment, residuals in TT with respect to extrapolated tracks from IT and VELO were calculated. Since the TED is located 350 m away from LHCb, the tracks were almost parallel, and due to the large acceptance of TT with respect to VELO and IT, the region of TT illuminated with VELO or IT tracks was small. This prevented a complete alignment of TT. The residuals obtained from IT tracks extrapolated to the TT are shown in Fig. 8.

8. Summary

The LHC injection tests have provided a wealth of data for the Silicon Tracker. The time alignment could be done up to 1 ns, and an initial space alignment of IT modules was performed in

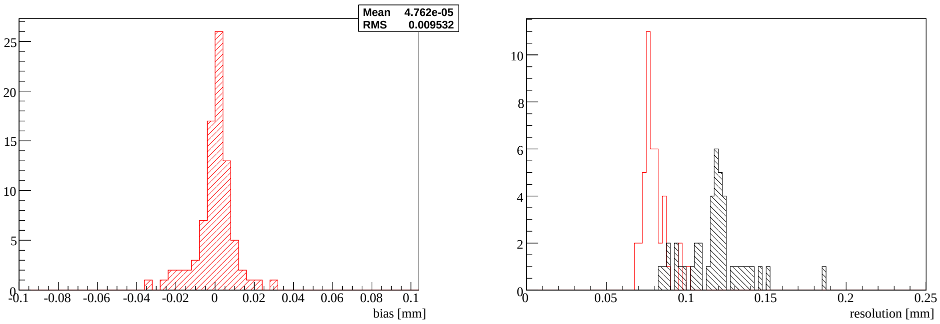

Figure 7: Left: Module bias (distribution of the mean of the unbiased residuals per detector module). Right: Resolution in x (distribution of the width of the unbiased residuals) for x hits (open histogram) and stereo hits (hatched histogram).

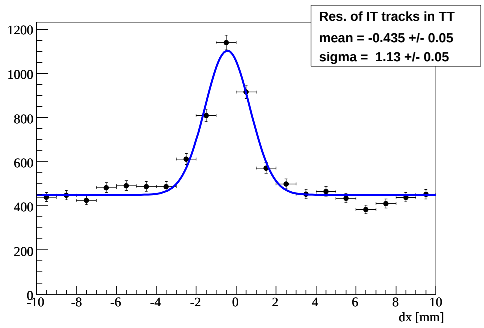

Figure 8: Residuals from IT tracks in TT.

which x translations could be determined to a precision of 13 μm. Tracks were observed in all three silicon detectors of LHCb (VELO, TT, IT). The Silicon Tracker is operational, and the outcome of these tests have provided a good starting point for data taking with the first LHC collisions.

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