Experience with LHCb alignment software on first data

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Abstract. The LHCb (Large Hadron Collider beauty) experiment is designed to perform high precision measurements of B-meson decays. The construction and installation of the LHCb detector was finished early summer 2008, followed by intensive testing and commissioning of the system in order to be ready for the first data taking. Despite the forward geometry of the LHCb detector over 1 million cosmic events were collected and in addition beam dumps during the LHC synchronisation tests provided very useful data. These data allowed for first calibration and spatial alignments of several subdetectors. This note describes the alignment procedure and its underlying mathematics and will give results of the first spatial alignment of the tracking system done with the collected data.

1. Introduction
At the Large Hadron Collider (LHC), protons will collide at an energy of $\sqrt{s} \approx 14$ TeV. The $b\bar{b}$ cross section at this energy is expected to be $\sigma_{b\bar{b}} \sim 0.5$ mb. The LHCb detector is designed to operate with an average luminosity of $2 \times 10^{32}$ cm$^{-2}$ s$^{-1}$, one year of running corresponds to $\sim 10^{12}$ $b\bar{b}$ pairs produced in the spectrometer which makes the LHC collider an ideal facility to study B-meson decays. Given that the $b\bar{b}$ pairs are mostly produced in the forward and backward direction, the LHCb detector has been conceived as a forward spectrometer. It is designed to reach excellent performance in precision measurements of specific B-meson decays in order to resolve small CP asymmetries. However, such precision measurements can only be achieved with a well calibrated and aligned spectrometer. For that, a very accurate determination of the relative position of the subdetectors to each other (global alignment), as well as an internal alignment of components of the subdetectors (local alignment) is necessary. Local alignment parameters are obtained by survey measurements and by track based alignment algorithms, whereas the latter ones give the most accurate results and can optionally use the survey data as input. A global alignment, however, can only be achieved with tracks traversing the whole detector. Last year’s commissioning of the detector consisted of the collection of data from dumped proton beams and the measurement of cosmic muons. Both data types allow for a local alignment of subdetectors. The Vertex Locator (VELO) [1] and the Inner Tracker (IT) [2], both covering a rather small area around the beam pipe, are calibrated using beam dump events, whereas the large Outer Tracker (OT) [3] can be aligned with tracks of muons from cosmic showers.
Figure 1. The LHCb detector layout showing the Vertex Locator (VELO), the dipole magnet, the tracking system with TT and the main tracking stations T1-T3, two Ring Imaging Cherenkov detectors (RICH) [6], the Scintillating Pad Detector (SPD), the Preshower (PS), the Electromagnetic (ECal) and Hadronic Calorimeter (HCal) [7] and the Muon Stations M1-M5 [8].

2. The LHCb experiment
The LHCb detector [4] is designed as a single arm spectrometer (see figure 1) with a 4Tm dipole magnet [5] and subdetectors for tracking, particle identification (PID) and muon track reconstruction. The spectrometer covers an acceptance of 10-300 mrad in the horizontal plane and 10-250 mrad in the vertical plane. The VELO and the tracking system placed downstream of the magnet consisting of IT and OT are described here since these are aligned with the collected data.

Vertex Locator: The VELO consists of two retractable halves placed close to the beam axis around the interaction point. They are positioned 8 mm close to the beam during stable running conditions. Each halves comprises 21 silicon strip modules of R and Φ sensors with a pitch of 40 – 100 µm, measuring the radial and azimuthal coordinates (see figure 2). The design precision for reconstructing primary vertices is 10 µm in the transverse and 60 µm in the parallel direction to the beam axis. However, this accuracy implies the determination of O(500) alignment parameters for the detector [9].

Main Tracking System: The tracking system comprises the TT, IT and OT. TT and IT are both silicon strip detectors covering an area close to the beampipe, whereas the OT reconstructs the particle trajectories in the outer part. Each of the three tracking stations (T1-T3) consists of four IT and four OT layers in a ‘xuxu’ arrangement. The x layers are vertically orientated and provide precise measurements of particle trajectories in the horizontal plane, i.e. the bending plane of the magnet. The u and v layers are rotated by −5° and +5° with respect to the y-axis and provide information in the vertical plane.
Figure 2. The VELO R (red) and Φ (blue) sensors in closed position. Each sensor comprises 1024 strips with a pitch of 40 – 100 µm.

Figure 3. The double layer structure inside an OT module. Sketched is the profile of the straw tubes with the anode wire in the center.

The cross shaped IT covers only 1.3% of the sensitive surface of the tracking station but is traversed by approximately 20% of the charged particles produced at the interaction point. A silicon sensor has a dimension of 110 mm × 78 mm and a strip pitch of 198 µm. The 504 sensors are mounted on so called ladders, each comprising one or two sensors and the readout hybrid. 28 ladders are then grouped together in a detector box, arranged in four detection layers (‘xuvx’). In total, 336 modules have to be aligned in order to obtain the design resolution of better than ∼ 70 µm.

The area covered by an OT layer is 27m². This acceptance, the expected occupancy and the requirement of a long radiation length lead to a modular design and the use of straw tube technology. A module comprises 64-128 straw tubes arranged in a double layer structure (see figure 3). The 2.5 m long straws have a diameter of ∼ 5 mm and a hit resolution of 200 µm. In total, O(2000) parameters have to be determined in order to align all 432 modules of the OT.

The tracking system allows to measure the momentum of charged particles with a precision of 0.4% and provides the impact parameter with a resolution down to 14 µm.

3. The Alignment Formalism

The mathematical principle of the alignment algorithm is presented in this section. The alignment procedure is a minimization of a total χ². The definition of the residual and the χ² is given, discussing a linear problem, i.e. a straight line fit. Any nonlinear problem, however, can be treated the same way after being linearized, e.g. with the Newton-Raphson approach. Assuming a measurement xₘ is associated with a theoretical prediction xₚ of the measured parameter, e.g. the prediction of the position of a hit in the detector using a track model. The difference between prediction and measurement is called the residual r and can be expressed as

\[ r = xₘ - xₚ = xₘ - a^T d, \] (1)

where a denotes the vector of parameters of the prediction, e.g. the offset and slope of the track, and d the vector of the partial derivatives \( d_i = \frac{\partial x_p}{\partial a_i} \) of the i-th parameter. By summing over the squared residual of each measurement j and normalizing it with the variance of the measurement \( \sigma_j^2 \), one gets

\[ \chi^2 = \sum_j \left( \frac{x_{m,j} - a^T d_j}{\sigma_j^2} \right)^2. \] (2)

For the alignment, there are two different vectors of parameters, namely the vector for the track parameters and the vector for the alignment parameters. Since the track parameters are different
for each track, they are called local. The alignment or global parameters on the other hand are the same for each track.

The minimization of the $\chi^2$ with respect to local and global parameters simultaneously requires the solution of a large linear system, with a size proportional to the number of tracks. To reduce the complexity, a set of normal equations can be calculated that explicitly only contains the global parameters and implicitly the information of the local parameters [10], leading to the expression

$$\begin{pmatrix} \Gamma' \end{pmatrix} \begin{pmatrix} \Delta \end{pmatrix} = \begin{pmatrix} \beta' \end{pmatrix}. \quad (3)$$

The matrix $\Gamma'$ includes the complete information of the local parameters and therefore all correlations between the tracks and the global parameters $\Delta$. The vector $\beta'$ as well contains both local and global information (e.g. see [10]). By inverting $\Gamma'$ the alignment parameters are determined in one single step, i.e. no iteration is required. In LHCb two different implementations of the $\chi^2$ minimization are applied. One based on the Millepede [10] algorithm using a standalone track fit, the other based on the standard LHCb track fit algorithm [11, 12]. Both algorithms are capable of fitting tracks bent in a magnetic field, the latter one includes multiple scattering corrections. Both implementations give comparable performances, the IT results presented in this note are obtained with the algorithm using the standard LHCb track fit, the parameters for the VELO and OT are determined with the Millepede based approach.

4. The alignment cycle

An alignment cycle, as shown in figure 4, starts with reading the raw data and closes with the determination of the alignment parameters. In case nonlinear degrees of freedom have to be determined, e.g. pattern recognition effects, or a non-linear measurement model (Eq. 1), several alignment cycles have to be executed iteratively until a stable minimum of the $\chi^2$ is found.

![Figure 4. The dataflow during an alignment cycle, divided into two main tasks. First step is the reconstruction of all available tracks and the preparation of the matrix, second the constants are obtained by inverting the matrix.](image)

The first step in running the alignment is the pattern recognition which is accomplished using the default algorithm of the LHCb software framework. Each track is refitted with a robust $\chi^2$ track fit, and the alignment matrix is set up considering correlations between track and alignment parameters. Finally the matrix is inverted and the alignment constants and their errors are obtained. These are then stored in the new geometry database. If necessary, a subsequent alignment cycle can be processed using the updated database.

5. Vertex Locator alignment

Protons from the LHC injection line stopped at a beam dump (‘TED’) at the entry point of the LHC ring provide a large flux of nearly parallel particles in LHCb. In two periods, August and
September 2008, these so called 'TED' events were recorded by the VELO, IT and TT detectors. For the VELO 1400 collected tracks are sufficient to determine the positions of the modules in $x$ and $y$-direction. Figure 5 shows the constants obtained with the software alignment with respect to survey information. The majority of the constants are below $10\,\mu m$. Given a survey accuracy of $\approx 10\,\mu m$ the results obtained by the two methods are in agreement confirming the reliability of the algorithm. Comparing the constants obtained in August and September, no significant changes can be seen. As expected, the modules are in steady positions and the software gives stable and reproducible output. Furthermore the track residuals in the $R$ and $\Phi$ sensors were studied (see figure 6). The achieved resolution matches the binary resolution $(= \frac{\text{pitch}}{\sqrt{12}})$. This is expected because $\sim 90\%$ of the used clusters are one strip clusters. The 2006 Test Beam resolution will be reached after optimization of the thresholds for each strip and time alignment.

6. Alignment of the main tracking system

The first alignment of the main tracking system is done using TED data (see Section 5) for the IT and cosmic muon data for the OT. Hardly any cosmic muon traverse the IT because of its relatively small acceptance, therefore it could only be aligned with TED data. The occupancy in the detector was $\sim 20$ times larger than the occupancy expected for normal LHCb running conditions. This leads to a high rate of wrongly reconstructed tracks ($\sim 10\%$) giving large tails in residual distributions (see figure 7). In total 800 tracks are used for the IT alignment that is done stepwise. First the alignment of the boxes in $x$-direction and $y$-direction and in the rotation around the $z$-axis $(=\text{angle } \gamma)$

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**Figure 5.** Misalignments in $x$ and $y$-direction with respect to survey measurements. A side denotes the left and C side the right half of the VELO. The results for data collected in August (squares) and September (circles) are shown.
Figure 6. The resolution of the track residuals for (a) the R sensors and (b) the Φ sensors matches the binary resolution. This is expected since \( \sim 90\% \) of the clusters are one strip clusters.

is performed, followed by the layer alignment in \( x \) and \( \gamma \). Finally shifts of the ladders in \( x \) are determined. Figure 7 shows the improvement of the unbiased track residuals in a ladder of station T2. Before alignment, the mean of the fitted Gaussian is shifted to +30 \( \mu m \) and the width of the core Gaussian is \( \sigma_{\text{core}} \approx 120 \mu m \). These values improve significantly after alignment with \( \sigma_{\text{core}} \approx 96 \mu m \) and a mean at 3 \( \mu m \).

The alignment of the OT is done using 20k reconstructed tracks of cosmic muons. The statistics allow to resolve possible shifts in the main measurement direction, the \( z \)-direction and rotations around the \( z \)-axis. By reconstructing the tracks without drift time information the constants obtained are independent of a complete detector calibration. The improvement on the residuals’ mean of each module due to the software alignment can be seen in figure 8. The left plot (a) shows the spread of the means with an RMS \( \approx 0.3 \) mm and maximal shifts from zero of up to 1mm.

Figure 7. The unbiased residual in a ladder of a \( x \) layer in station T2. (a) The residual before the ladder alignment. The mean is shifted to +30 \( \mu m \), \( \sigma_{\text{core}} \approx 120 \mu m \). The tails of the distributions are due to wrongly reconstructed tracks. (b) After alignment the mean and the width of the core Gaussian improve significantly to 3 \( \mu m \) and \( \sigma_{\text{core}} \approx 96 \mu m \) respectively.
Figure 8. The mean of track residuals measured in the modules. (a) No software alignment applied. (b) After alignment of the modules in $x$-direction and rotation around the $z$ axis the RMS of the distribution improves to RMS $\approx 100\mu$m.

Before alignment. After the correction the RMS shows a significant improvement and reduces to $\sim 0.1$ mm, figure 8 (b). The constants are then used to get the correct correlation between the drift time and the flight path of the particle through the straw. This correlation is expressed in the two dimensional space drift-time relation shown in figure 9. The distance between the fitted track and the wire inside a straw is called distance of closest approach and plotted on the $x$-axis. The $y$-axis shows the drift time measured with the time to digital converter (TDC). As the alignment improves the precision of the measurements the shape of the function becomes considerably narrower. An additional confirmation of the algorithm’s performance is shown by comparing the software results with survey measurements. These measurements determined the $z$-positions of elements of the OT which are called C-frames. Each frame supports two layers. Since the survey measures the position of frame 1 and 5 to be at $z = (0 \pm 0.5)$mm, the two corresponding layers were constrained to the same positions in the software. The alignment

Figure 9. The space drift-time function: Distance Of Closest Approach (DOCA) between fitted track and wire inside the straw tube plotted against the measured drift time. (a) The obtained function without software alignment. (b) The space drift-time relation improves significantly with module alignment as the shape becomes narrower.
was done for each layer, therefore 12 layer parameters have to be compared to six C-frame parameters, figure 10. The alignment parameters agree perfectly with the survey within the accuracy of the survey measurement.

7. Conclusion
After finishing the construction and installation of the LHCb detector early summer 2008, over 1 million cosmic events were collected with the spectrometer. Additional data were provided by beam dumps during the LHC injection tests. Events of the dumped beam were measured with the VELO and were used to align its modules in $x$-direction and $y$-direction. The results show that the modules are, as expected, in steady positions inside the vacuum vessel and prove the stability of the alignment software. Using data from cosmic muons, shifts and rotations of the OT modules were determined. The obtained constants improved the track parameters and therefore the space drift-time calibration significantly. In addition the successful confirmation of survey parameters were shown. The alignment software is ready for first beam data.

References
[1] The LHCb Collaboration 2001 *LHCb Vertex Locator technical design report* CERN/LHCC/2001-011
[2] The LHCb Collaboration 2002 *LHCb Inner Tracker technical design report* CERN/LHCC/2002-029
[3] The LHCb Collaboration 2001 *LHCb Outer Tracker technical design report* CERN/LHCC/2001-024
[4] The LHCb Collaboration 2008 The LHCb detector at the LHC 2008 *JINST* 3 S08005
[5] The LHCb Collaboration 2000 *LHCb Magnet technical design report* CERN/LHCC/2000-007
[6] The LHCb Collaboration 2000 *LHCb RICH technical design report* CERN/LHCC/2000-037
[7] The LHCb Collaboration 2000 *LHCb calorimeters technical design report* CERN/LHCC/2000-0036
[8] The LHCb Collaboration 2001 *LHCb Muon System technical design report* CERN/LHCC/2001-010
[9] Viret S, Gersabeck M, Parkes C 2008 *Nucl. Instr. and Meth. A* 596 157-163
[10] Blobel V and Kleinwort C 2002 A new method for high-precision alignment of track detectors Contribution to the Conference on Advanced Statistical Techniques in Particle Physics, Durham, hep-ex/0208021
[11] Hulsbergen W D 2009 *Nucl. Instr. and Meth. A* 600 471-477
[12] Amoraal J et al 2009 Alignment of the LHCb detector with Kalman fitted tracks Proc. CHEP2009