PROCEEDINGS OF SCIENCE

Real-time alignment and temperature dependency of the LHCb Vertex Detector

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The accuracy of the LHCb Vertex Locator (VELO) position has ensured excellent detector performance, with a track reconstruction efficiency above 98%, and a vertex resolution along the beam axis of about 70 μm. The real-time alignment and calibration procedure developed by the LHCb experiment for Run 2 (2015-2018) for the full detector, including the VELO, provided extremely stable conditions during the full data taking period. In 2010, a significant shrinkage of the VELO modules was observed at the operating temperature of -30 degrees with respect to survey measurements made at ambient temperature. This has been confirmed by the following laboratory measurements of different tmeperatures on a single module. In a recent study, using a dedicated LHCb data sample taken over a range of VELO temperatures, the variation of the detector position as a function of temperature has been evaluated. An overview of the VELO alignment procedure and its performance during Run 2 will be presented, with an emphasis on the study of the temperature dependence.

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1. Introduction

The LHCb experiment [1] was designed to investigate the difference between matter and antimatter by studying decays of beauty and charm hadrons. It is part of the LHC (Large Hadron Collider) situated at CERN (European Center for Nuclear Research). As the production of the b-mesons is concentrated in the forward direction, the LHCb experiment was constructed as a single arm forward spectrometer which covers the pseudorapidity region of $2 < \eta < 5$. The Vertex Locator (VELO) is situated in the region of the proton-proton interaction. It provides reconstruction of particle trajectories passing through and of primary and secondary vertices. The detector operates in secondary vacuum conditions separated from the LHC vacuum by a thin aluminium foil. The VELO [2] consists of 42 silicon strip modules arranged perpendicularly operating at a set temperature of -30°. The modules have radial geometry (with R and a ϕ sensor each) and are mounted in two halves that approach the beam line to a minimum distance of 8 mm during stable beams. The movable system allows to open/close the two halves when there are stable beams with an accuracy of 10 μm. For charged particles that pass through the modules tracks are reconstructed using the hits on the modules (sensors). The current VELO design operated up to the end of 2018 when it will be replaced by a new detector in 2020.

2. The VELO alignment

One of the key elements to achieve the best physics performance is the detector alignment accuracy. The correct VELO alignment contributes to correctly distinguishing primary and secondary vertices and improving the quality of the impact parameter [1]. The alignment of the VELO is determined by a method based on Kalman filter [3] track fit. It uses in a minimum χ^2 algorithm to determine the position of the detector elements (halves, modules and sensors) from a sample of reconstructed tracks. The position of each detector element is stored in a database that is being used in the reconstruction. This algorithm estimates the misplacement of a set of positions of detector elements with respect to their expected positions. The software aligns for three translations $(\mathrm{T_x}, \mathrm{T_y}, \mathrm{T_z})$ and three rotations $(\mathrm{R_x}, \mathrm{R_y}, \mathrm{R_z})$ around the x, y or z axis of the VELO. These are known as alignment constants. The process of performing an alignment starts with collecting the particles' hits associated to the reconstructed tracks in the detector. After the track reconstruction a difference between the hit and the intersection between the track and the sensor is calculated. This difference is called a residual. A sign of good alignment is that all the residuals are centered to zero. While aligning the detector several constraints can be used such as the vertex and mass constraints.

2.1 Real time alignment

The accuracy of the LHCb VELO has ensured excellent detector performance, with a track reconstruction efficiency above 98%, a vertex resolution along the beam axis of about 70 μm, and a decay time resolution of about 45 fs [4] [5]. A key ingredient to achieve such performance is the real-time alignment of the VELO, included in the full-detector real-time alignment and calibration procedure developed by the LHCb experiment for Run 2 (2015-2018) [6]. In the process of data

[1] Impact parameter is the transverse distance of closest approach between a particle trajectory and a vertex, mostly referring to the primary proton-proton interaction vertex.

taking when stable beams are declared the VELO halves are closed around the beam. The closing and opening of the VELO repeats for each fill of the LHC, which can lead to alignment changing in each fill. The alignment has to be run at the beginning of each fill to check for an update of the alignment constants for which uses certain data sample. If there is a significant difference between two previous alignments the alignment constants are updated. The whole alignment procedure can run over several iterations until it converges. A convergence is reached if a certain condition for the χ^2 of tracks is fulfilled. The process starts by selecting a data sample in the HLT1 trigger (first level of the software trigger). The alignment procedure is run online on the computing clusters to produce an alignment for the fill. If the variations are significant and the procedure converges after several iterations an update is needed and the new alignment (providing the new conditions) obtained in the last iteration is used. The new conditions are used immediately in HLT1 (and consequently in HLT2). This maximises the selection efficiency and ensures the quality of the reconstruction at trigger level. In the online alignment procedure the VELO halves are aligned for all degrees of freedom (translations and rotations). If the variation of the alignment constants is above a certain threshold an automatic update is triggered. The thresholds for the online update ,shown on Table 1, are evaluated using data and simulation samples. Any variation below that threshold is considered as fluctuation/accuracy of the alignment.

dof	Threshold
$T_x, T_y (\mu m)$	1.5
$T_z (\mu m)$	5
$R_x, R_y (\mu rad)$	4
$R_z (\mu rad)$	30

Table 1: Thresholds for the alignment constants used for the online update.

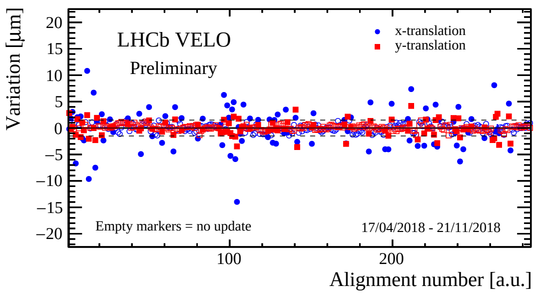

Figure 1: Stability of the alignment of the VELO halves during all Run 2 fills. Each point is obtained running the online alignment procedure and shows the difference between the initial alignment constants (the ones used in the previous fill) and the new ones computed by the alignment.

Fig. 1 shows the stability of the tracking system alignment for translations in x and y for the VELO. The threshold is indicated by the horizontal line. The points show the difference between the new alignment constant and the alignment constant from the previous alignment. The alignment proved to be stable over Run 2 and the constants are updated every few fills, as expected.

3. Temperature dependency

The temperature at which the VELO operates is set to -30° and remains constant during data taking. During a series of runs in October 2018 the set point temperature has been changed from -30° to -20° with data taking at temperatures of -20°, -24°, -26°, -30°. Dedicated data samples, collected at each temperature, have been used to study the detector movements as function of the temperature by using the alignment procedure. The variation of the alignment constants is evaluated with respect to the alignment constant evaluated at the operation temperature of the VELO (-30°). The variations have been analysed as a function of temperature for the VELO halves and modules. The construction of the VELO modules employs a carbon fiber support for which has been confirmed that is prone to shrinkage. Thus the largest variation of alignment constants is expected to occur at the alignment constants along x-axis due to the shrinkage of the support in carbon fiber of VELO. The alignment for the VELO halves is evaluated for all degrees of freedom (translations and rotations) at each temperature. Two alignment configurations are used: 1) only the 2 halves alignment is evaluated; 2) both the halves and modules alignment are evaluated. On Fig. 2

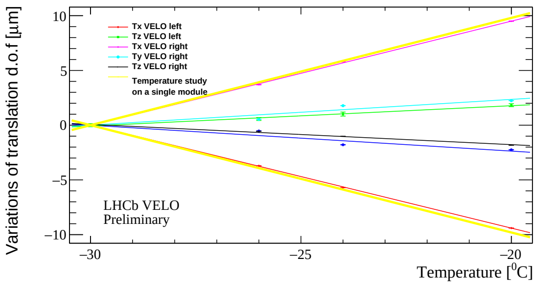

Figure 2: Variations of the VELO half translations as a function of temperature (obtained by aligning both the 2 halves and the modules), compared with the temperature measurements on a single module made in 2010 (yellow line).

the variations of the translations in all directions (x, y and z) are shown as a function of temperature. A linear trend is visible for all translation degrees of freedom. The variations of T_x for the both right and left side of the VELO (Fig. 2) are largest compared with T_y, and T_z. The variations are up to 10 μm for a temperature variation of 10 degrees. T_y and T_z variations are very small and up to 2 μm. The measured variations are compared to the measurements on a single module in laboratory and is shown on Fig. 2. The previous studies that involved temperature performance of the VELO are shown in yellow. The two studies are consistent.
The alignment procedure has been run for the VELO modules and the variations are being studied as a function of their z position. This allows to study the stability of the variations due to the change of temperature. To consider the overall movement one can evaluate the module position in the global reference system. Fig. 3 shows the variation of each modules versus their z position at different temperatures. The variations are small of the order of 1 μm with a maximum variation of 4 μm.

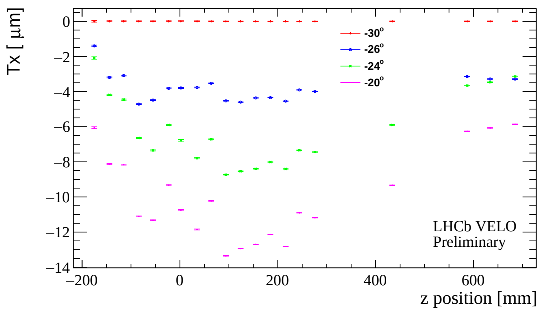

Figure 3: Variations of the translation along x of the VELO modules in the left VELO half, as a function of z position of modules for the different set temperatures. This variation take into account both variation of the module position and variation of the VELO half.

4. Conclusions

Since 2015 at LHCb a new model for the software trigger has been developed that allowed the alignment and calibration to be performed in real-time. Within the Run 2 data taking period the alignment of the LHCb VELO proved to be stable with updates for the alignment constants each few fills. The variation of alignment constants at different temperatures between -30° and -20° for the VELO has been studied. The alignment procedure was used to evaluate how the different temperatures affect the positions of the VELO. It has been confirmed that the alignment variation as a function of temperature for the VELO halves is a linear function, significant only for T_x. The modules variations as a function of z position are within few μm with a nonlinear behaviour. The variations of the halves in T_y are small and within the alignment accuracy. These results have been compared with the measurements performed on a single module and the variation observed for T_x is compatible with those measurements.

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