PROCEEDINGS OF SCIENCE

Alignment of the Belle II Vertex Detector

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The Belle II experiment will start taking data in 2017. The SuperKEKB accelerator will deliver a factor 40 higher luminosity compared to its predecessor, KEKB, to acquire 50 times larger data sample of $B\bar{B}$ events. In order to manage higher occupancy and background, a new silicon vertex detector consisting of two inner layers of DEPFET pixel sensors surrounded by four layers of double-sided strip sensors will be installed. The high target performance of the detector, in particular its vertex and momentum resolution, motivated the development of a reliable alignment procedure. We present track-based alignment of the vertex detector using the Millepede II tool in combination with an advanced track parametrization by the General Broken Lines (GBL). The procedure is implemented within the software framework of the Belle II experiment and GBL has also been integrated into the experiment-independent track-fitting toolkit GENFIT.

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1. Introduction

The Belle II experiment is being prepared by the High Energy Accelerator Research Organization (KEK) in Tsukuba, Japan. It continues in the effort of the Belle experiment to fully exploit the potential of B-factories at the precision frontier. This goal is achieved by an upgraded accelerator, SuperKEKB, with peak luminosity of 8×10^{35} $\mathrm{cm}^{-2}\mathrm{s}^{-1}$, about 40 times larger than its precedestor, aiming at an integrated luminosity of 50 ab^{-1} [1]. The upgraded collider will pose significant challenges to the detector. Namely, the innermost part, the Vertex Detector (VXD) will be exposed to a much higher backgrounds and event rates. Therefore DEPFET pixel sensors will be used for the two innermost layers of the vertex detector, followed by four layers of double-sided strip sensors (SVD). The new vertex detector will offer improved tracking and vertexing performance, while keeping the material budget low.

For the experiment, the Belle II Software and Analysis Framework (basf2) is being developed [2, 3]. This framework covers most software tasks of the experiment, from full Monte Carlo simulation and simulation of the detector response to tracking and physics analysis. For track fitting, the GENFIT toolkit [4, 5], largely extended for the purpose of the Belle II tracking requirements, is integrated into basf2 and incorporates also vertexing features. It is described in the context of the Belle II detector in Ref. [6].

To achieve the required tracking performance, a stable and fast alignment method is being developed in basf2. It relies on the Millepede II tool [7], which is able to solve the alignment problem in an efficient way, while keeping all correlation among different alignment parameters. The input of Millepede II is prepared using another external tool integrated into basf2, the General Broken Lines (GBL) [8]. GBL is a track model and its implementation [9] allows for a fast refit of a particle trajectory treating multiple scattering effects as additional fit parameters. GBL is integrated into the GENFIT tollkit through an interface, which makes it an independent fitting method (along with Kalman filter algoritms) and uses many GENFIT features like extrapolation or generalized treatment of sensor measurements.

2. The Vertex Detector of Belle II

The first layer of PXD sensors is just 14 mm from the interaction point, which allows for very precise vertex reconstruction of B meson decays. To reach such a goal, the material budget has to be very low. At the same time, the large expected background requires very radiation-hard sensors. These requirements are pretty well fulfilled by the DEPFET (DEPleted Field Effect Transistor) technology [10]. The largest DEPFET matrices in PXD have 1600 rows and the full device can be read- out within 20 μs. The readout is done in parallel on four rows at the same time. Because PXD will have about 8 million pixels, it is not possible to read-out the complete device at the full trigger rate of 30 kHz with expected occupancy of 1 % [1]. Therefore, the background has to be reduced by selecting regions of interest using extrapolation from SVD.

PXD is composed of two sensor layers organized in a windmill structure. They are at radii of 14 mm and 22 mm and the support structure is mounted directly to the beam pipe, making PXD mechanically independent from the rest of the detector. There are 8 sensors in the first layer with pixel pitch 50 μm$\times$55$-$60 μm and 12 sensors in the second layer with 50 μm$\times$70$-$85 μm pixels,

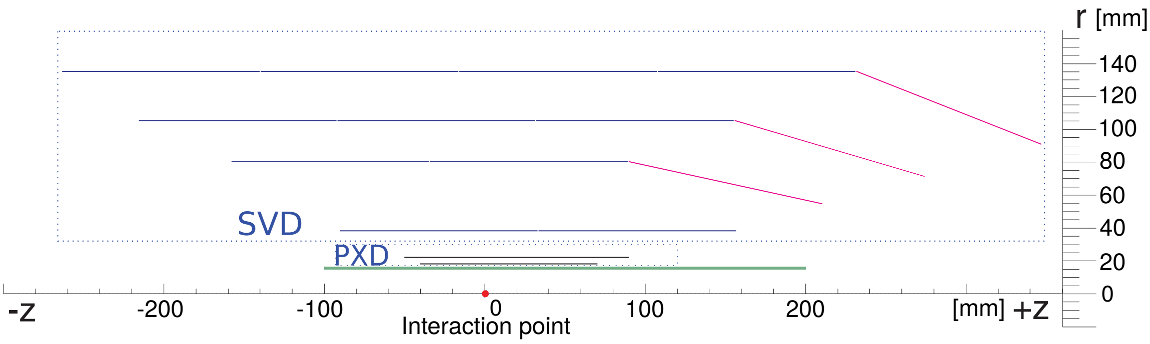

Figure 1: Layers of the vertex detector. Two layers of the PXD detector are located just above the beam pipe (bottom green line). The drawing is shown in milimeters in coordinates relative to the interaction point. The coordinate system of Belle II is also shown.

with the smaller pitch in the one third of each ladder closest to the interaction point. All sensors have sensitive area thinned to 75 μm. [1]

SVD consists of 187 double-sided silicon strip sensors with readout chips with fast shaping time of O(50 ns), which allows to suppress background hits. The sensors of SVD are organized into four layers and 49 ladders at radii of 38, 80, 115 and 140 mm, covering the full acceptance region of Belle II. Two kinds of sensor shapes are used. Rectangular sensors are used in the barrel part (pitch 75 μm along z and 240 μm in $r-\phi$ direction), with smaller sensors (pitch 50 and 160 μm) in the innermost layer. In the forward region, slanted sensors with trapezoidal shape with varying pitch size along z are installed. The thickness of the detectors is 320 μm for barrel and 300 μm for slanted sensors.

3. Track Fitting with General Broken Lines

GBL is a track model, where effects of multiple scattering at charged particle trajectory are treated as additional fit parameters. The trajectory is constructed from points with meaurement and/or thin scatterer. A thin scatterer represents a source of track slope variance at a particular arc length. The resulting parametrization allows for kinks in the particle trajectory at the position of scatterers. The implementation of the fitting algoritm is thoroughly described in Ref. [11]. At each point, a local coordinate system is constructed by means of the GENFIT virtual planes technique [4]. These virtual planes correspond to pixel or strip planar sensors for points with a measurement, or in case of a point with only a scatterer, the plane is constructed perpendicular to the propagation direction of the particle. The projection of track states at the planes, as well as calculation of the propagation Jacobians relies on GENFIT and its Runge-Kutta extrapolation method.

The implementation of the interface between GENFIT and GBL constructs the trajectory from measurements and scatterers automatically, from a given list of hits in a track candidate. To model the multiple scattering, the initial trajectory seed is propagated in the detector material. The trajectory is split into segments between measurement planes and for each such segment, the inverse radiation length[1] at each propagation step is used to calculate the total crossed radiation length (and the corresponding variance in track slopes θ^2), its mean $\bar{s}$ and variance Δs^2:

$$\bar{s} = \int \frac{s\,ds}{X_0(s)} \Big/ \int \frac{ds}{X_0(s)}, \qquad \Delta s^2 = \int \frac{(s-\bar{s})^2\,ds}{X_0(s)} \Big/ \int \frac{ds}{X_0(s)}. \tag{3.1}$$

The triplet of values $(\theta^2, \bar{s}, \Delta s^2)$ represents[2] a thick scatterer - a realistic material distribution in between two measurements. A thick scatterer is represented by a doublet of thin scatterers, such that the original continous distribution becomes $1/X_0(s) \propto \delta(s)\theta_1^2 + \delta(s-s_2)\theta_2^2$. The first thin scatterer is placed at the measurement plane at the begining of the segment with slope variance θ_1^2. The second scatterer is placed at arc length s_2 with variance of θ_2^2. The situation is illustrated in Fig. 2. Using

$$\theta_1^2 = \frac{\theta^2 \Delta s^2}{\Delta s^2 + \bar{s}^2}, \qquad \theta_2^2 = \frac{\theta^2 \bar{s}^2}{\Delta s^2 + \bar{s}^2} \qquad \text{and} \qquad s_2 = \frac{\Delta s^2 + \bar{s}^2}{\bar{s}},$$

the effect of the doublet is equivalent to the thick scatterer, having the same mean and variance (3.1). The trajectory is populated with scattering points, where a scatterer is at the position of each measurement, except the last, and in between each pair of consecutive measurements.

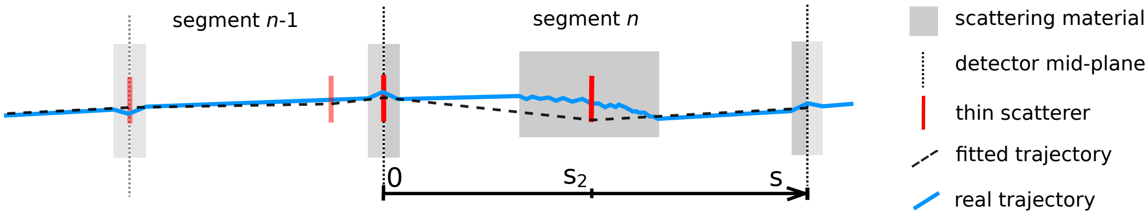

Figure 2: The trajectory is split into segments between detector mid-planes. The image illustrates the situation for a single segment n. The material distribution (including detector planes) is replaced by the doublet of thin scatterers (red), at which the fitted track (dashed line) is allowed to change its slope. The particle goes from left to right and undergoes many scattering events in the segment n. The doublets are chosen such that the track slopes and positions have the same covariance as for the realistic material distribution at the end of each segment (at each detector plane)[12].

The interface to GBL allows for arbitrary detector geometries, sensor orientation and material distribution. Measurements of different detectors with different dimensions can be freely combined in the track fit. GBL allows to include additional data to meaurement points, which contain the derivatives of track residuals w.r.t. alignment parameters relevant for a given measurement. GENFIT was extended by an interface which allows each detector to provide its own set of alignment parameters and corresponding derivatives. The derivatives are calculated using a fitted state at the measurement plane. In the current implementation, PXD and SVD provide six rigid body alignment parameters per sensor. A trajectoty fitted by GBL is directly written to a binary file in a format used by Millepede II.

[1] It is assumed that the change of the momentum of the particle can be neglected within a segment of the trajectory. This a limitation of the current implemenation.

[2] The logarithmic correction to the multiple scattering angle is only considered in evaluation of θ^2 and in this correction, the total radiation length crossed in the segment is used.

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4. Alignment with Millepede II

For the alignment of the vertex detector, the Millepede II method is integrated into basf2. The task of the detector alignment is solved by linear least squares minimization of normalized residuals. Each track is fitted by GBL and if it passes a set of simple cut-off criteria (length, p-value, ...), it is written to a binary file which can be directly loaded by Millepede II. The expression to be minimized by Millepede II is the sum of squares of the normalized residuals of independent scalar measurements

$$\chi^2(\vec{p},\vec{q}_1,\vec{q}_2,\ldots) = \sum_i^{tracks} \sum^{measurements} \left(\frac{measurement - prediction(\vec{p},\vec{q}_i)}{resolution} \right)^2$$

as a function of the alignment parameters $\vec{p}$ and a set of local parameters $\vec{q}_i$ for each track. The function is linearized around initial (assumed) values of the alignment and track parameters. The linearized expression is minimized w.r.t. all local and alignment parameters which results in a special bordered block-diagonal structure of the matrix equation to be solved. Millepede II utilizes this structure to reduce the dimension of the problem to the number of alignment parameters.

The method is described in Ref. [7] and its implementation [13] is explained in Ref. [14]. As a result, the alignment task can be solved in a single step without any approximation except linearization. Non-linearities can be treated by iteration of the alignment procedure with an updated linearization point. All correlations among alignment parameters are kept in the solution, which is computed by standard matrix inversion, diagonalization or other more advanced methods available in Millepede II.

5. Examples of Results

5.1 Beam Test Alignment

The developed fitting and alignment procedure is not specific to teh Belle II detector. It can be therefore easily used for alignment of VXD as well as for beam test setups. It was successfully used in the combined beam test [15] of one section of VXD with single PXD sensor (second layer in 1) and four SVD sensors inside a three-plus-three pixel telescope configuration. The distances between sensors and their size corresponded to Belle II design. The setup, visualized in Fig. 3, was iluminated with electron beam at DESY in January 2014. The test used electrons with momentum up to 5 GeV/c, with runs with 1 T magnetic field and without. The maturity of the complete Belle II VXD infrastructure, from data aquisition, slow control and cooling, up to tracking and data reduction systems was successfully demonstrated for the first time.

A new beam test package was developed and included into basf2, covering all the testbeam-specific software tasks while using common parts of the framework, developed for the "big" detector, including full Monte Carlo simulation. The package uses a slightly modified version of the Belle II VXD track finding software and a measured field map of the magnet within a user-defined geometry. One can define simple setups and instantly run full-scaled simulations or reconstruction, including the alignment.

Alignment corrections determined for sensor displacements and rotations in their planes had typical uncertainties below 3 μm / 0.5 mrad. A slightly better precision is achieved in magnetic field

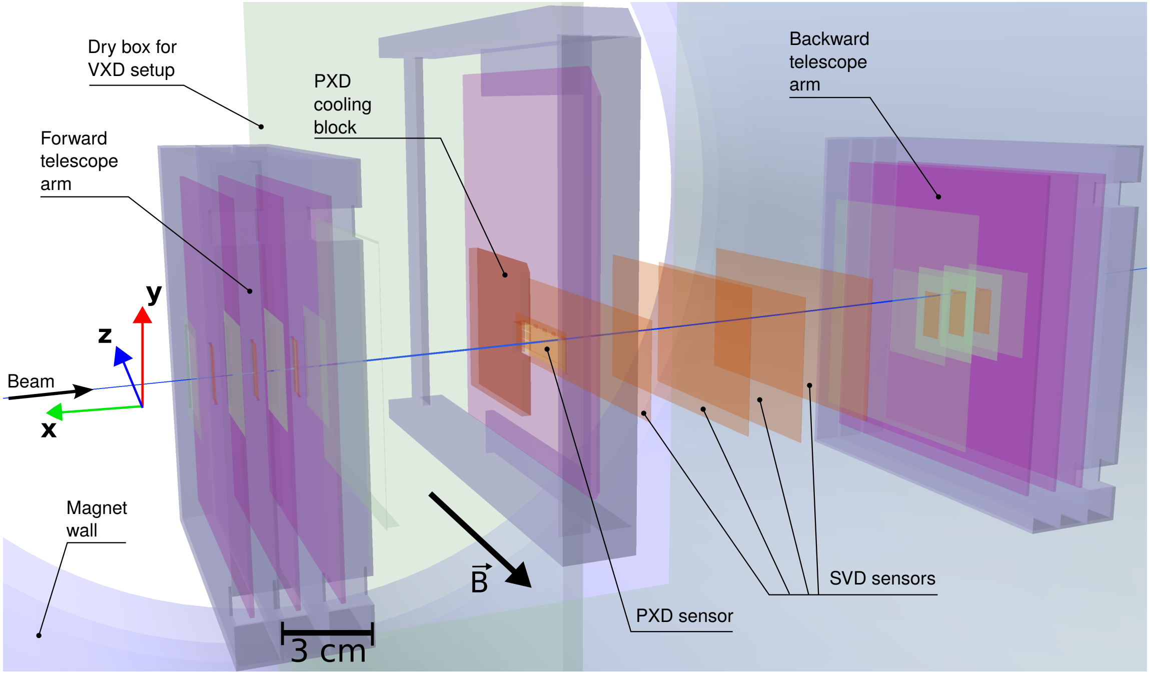

Figure 3: The geometry of the DESY beam test in basf2 event display. A simulated track going from left to right is shown. The colors distinguish different materials: silicon (orange), electronic boards (magenta), plastic parts (greenish), copper cooling block (dark orange) and other metalic parts (blue and gray).

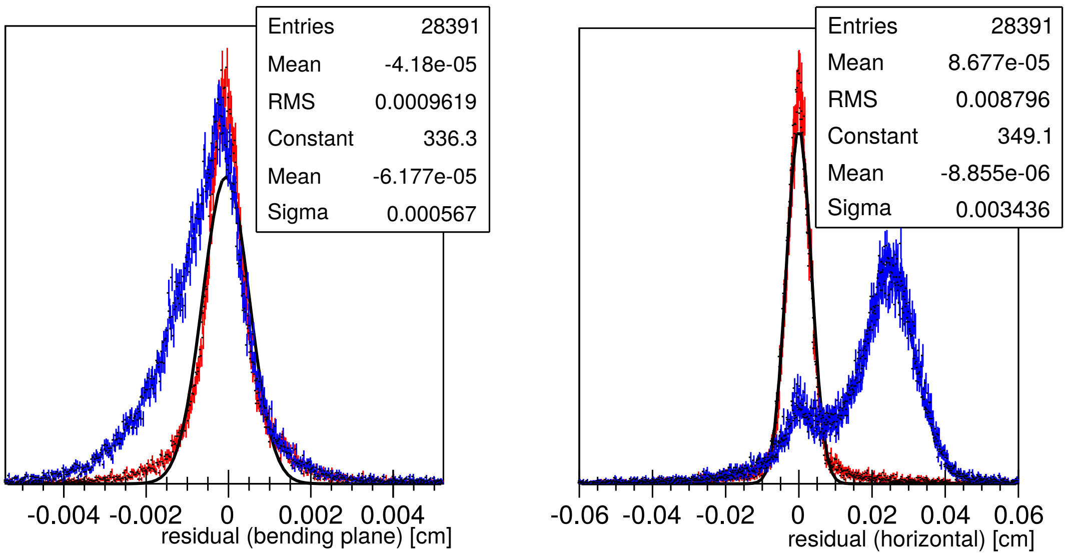

Figure 4: DESY beam test data: GBL track fit residuals in V (left) and U (right) directions of the second SVD sensor using nominal (blue) and aligned (red) geometry. Parameters of a Gaussian fit (black curve) to the red histogram are presented.

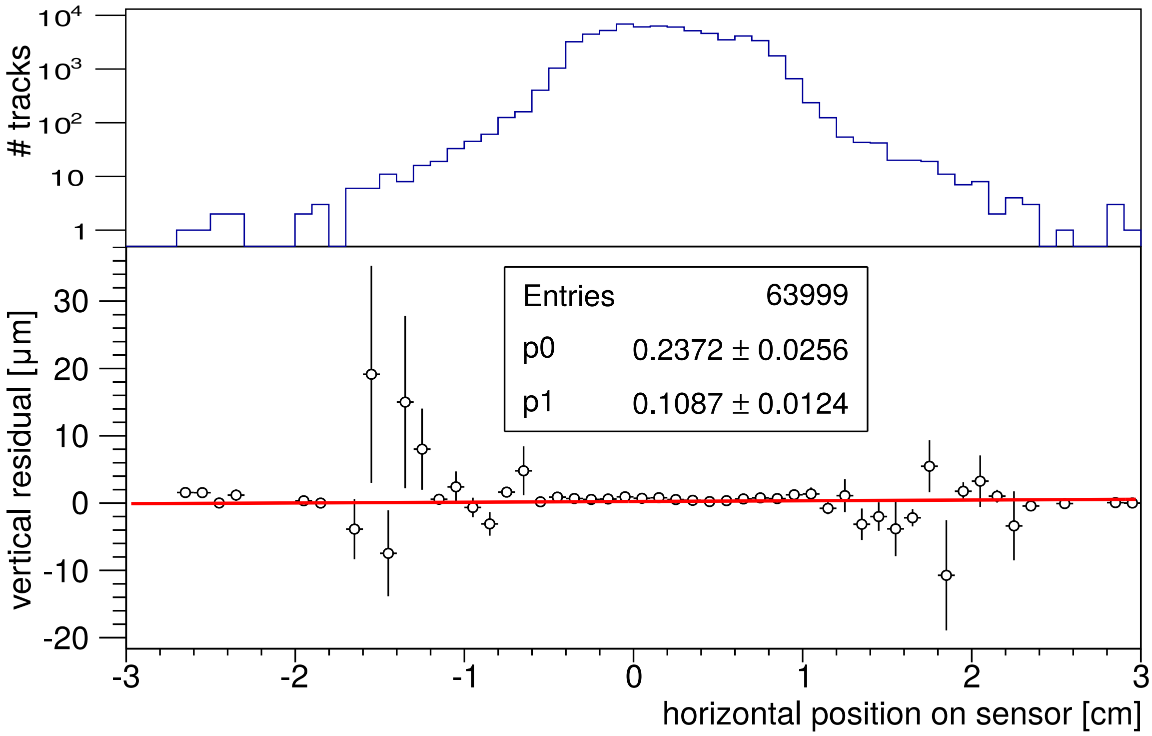

Figure 5: DESY beam test data: Correlation of residual mean value in vertical coordinate and the fitted horizontal position of the track on the last SVD sensor after alignment (bottom plot). Linear fit is shown (red). The slope parameter p1 corresponds to the residual rotation in the sensor plane. Large fluctuations are caused by low statistics at the periphery of the beam spot (limited by trigger scintilator size) and noise in the device. The upper plot shows the number of tracks contributing to each bin of the bottom plot. The units of fit parameters are μm for p0 and mrad$\times 10^{-1}$ for p1.

runs, due to the larger spread of incident angles of the tracks. However, the observed deviations in sensor positions of up to 40 μm among runs with and without magnet prevent us from combining the data samples to reach better alignment precision and reduce weak modes. The corrections to the nominal geometry were typically less than 1 mm / 10 mrad. The only exception was the PXD sensor shifted by about 5mm. As an example, in Fig. 4, changes of residual distributions of the second SVD sensor after alignment in the magnetic field are shown. Clear improvements of residuals after the alignment procedure are observed. The precision of the alignment of rotation of the last SVD sensor is demonstrated in Fig. 5, where the largest residual rotation is observed after alignment (rotation of the first sensor is fixed as an reference).

5.2 Full Belle II Vertex Detector Alignment

An initial Monte Carlo study was performed with the complete Belle II VXD alignment using single track events. The total number of parameters to be determined is 1266, six per each sensor. The sensors were aligned all independently in their local coordinate systems. To test the procedure, a set of data samples was generated with various conditions and particle sources in an ideal geometry:

- 500 k muons with uniform angular coverage and momentum generation from 0.05 to 4 GeV/c in the magnetic field,
- 76 k cosmic ray muons without magnetic field,
- 55 k cosmic ray tracks in the magnetic field,
- 100 k muons coming from interaction point and continuing from VXD to the central drift chamber of Belle II with momentum in the range 3 to 4 GeV/c. [3]

The data sample is then fitted using a different, displaced geometry, where the sensors' positions are shifted from those in the ideal case. The displacement is applied randomly to each sensor individually in range of 50 μm in all three translations axes and 1 mrad in rotation in the sensor planes. The alignment procedure was applied to the output of the GBL fit stored in binary files and the procedure was iterated to check for its stability. A comparison of some quantities showing the quality of the alignment procedure is shown in Fig. 6. The vertex reconstruction residuals in the z-coordinate show a small bias in the order of micrometers and both distributions are wider after alignment than in the ideal case. Nevertheless, the procedure clearly shows radical improvements compared to the displaced geometry. Some intended extensions and improvements of the procedure are discussed in the next section.

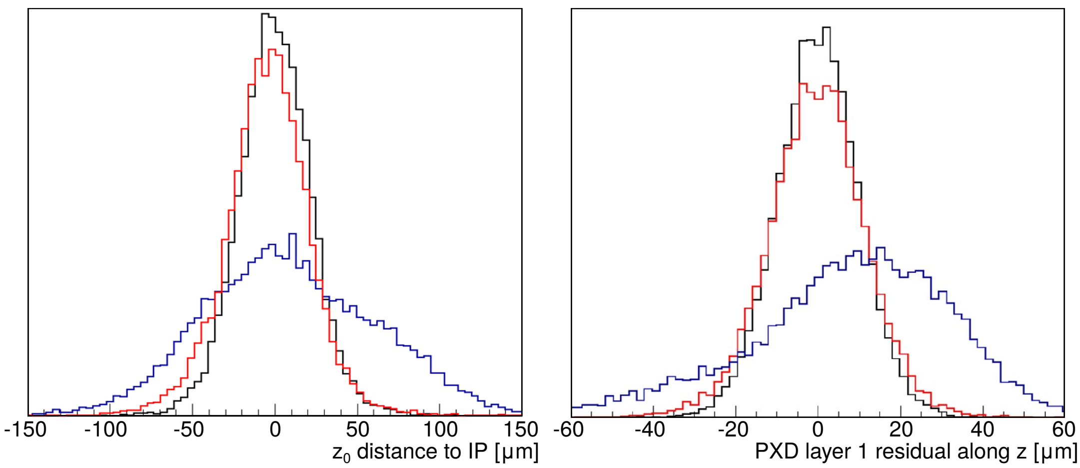

Figure 6: Simulation study of full Belle II VXD alignment: Residual of generated (true) and reconstructed vertex position in z-coordinate along the beam axis in the vertex detector (left) and GBL track fit residual distribution in the first layer of the pixel detector (right). Black - ideal geometry, blue - with applied displacement, red - after Millepede II alignment. Both plots are produced for a control sample of muons originating exactly from the interaction point (IP) with momentum of 2 GeV/c, distributed uniformly in the detector acceptance.

[3] In this study, GBL was used to fit the entire trajectory including the drift chamber of Belle II, which was however not a subject of the alignment procedure and also it was not displaced. In this demonstration, it works as an absolute reference, which removed unconstrained degrees of freedom in the alignment procedure.

6. Outlook

The developed procedure provides solid ground for application of the Millepede method in the alignment of the Belle II vertex detector. One of the key ingredients, the interface between GENFIT and GBL, brings the potential of this alignment procedure to the experiment-independent toolkit and thus might be used also in other experiments.

The alignment was successfuly tested in experimental conditions of the beam test. Also, initial Monte Carlo studies on the alignment of complete VXD show promising results, but require additional efforts to fully understand the specifics of the detector and the data sample needed for reliable alignment procedure, namely, the study of weak modes and methods to control them.

The next step is to focus on the extension of the alignment procedure, namely, introduction of hierarchy constraints and combined track objects with mass and/or vertex constraints. The fitting procedure was also successfully applied in Monte Carlo simulations of the Belle II drift chamber and extension of the procedure to alignment and calibration of the drift chamber is planned.

As the Belle II experiment is approaching to the start of its physics program, a reliable alignment procedure will be of the highest importance. Further developments will also focus on development of a complete calibration infrastructure in order to deliver data at analysis-level quality as soon as possible after the first collisions.

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