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Mailing address: CMS CERN, CH-1211 GENEVA 23, Switzerland

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Alignment of the upgraded CMS pixel detector

Matthias Schröder on behalf of the CMS Collaboration

Abstract

The all-silicon tracking system of the CMS experiment provides excellent resolution for charged-particle tracks and an efficient tagging of heavy-flavour jets. After a new pixel detector has been installed during the LHC technical stop at the beginning of 2017, the positions, orientations, and surface curvatures of the sensors needed to be determined with a precision at the order of a few micrometres to ensure the required physics performance. This is far beyond the mechanical mounting precision but can be achieved using a track-based alignment procedure that minimises the track-hit residuals of reconstructed tracks. The results are carefully validated with data-driven methods.

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Alignment of the Upgraded CMS Pixel Detector

Matthias Schröder on behalf of the CMS Collaboration

Institute of Experimental Particle Physics at the Karlsruhe Institute of Technology (KIT)

Abstract

The all-silicon tracking system of the CMS experiment provides excellent resolution for charged-particle tracks and an efficient tagging of heavy-flavour jets. After a new pixel detector has been installed during the LHC technical stop at the beginning of 2017, the positions, orientations, and surface curvatures of the sensors needed to be determined with a precision at the order of a few micrometres to ensure the required physics performance. This is far beyond the mechanical mounting precision but can be achieved using a track-based alignment procedure that minimises the track-hit residuals of reconstructed tracks. The results are carefully validated with data-driven methods.

In this article, results of the CMS tracker alignment in 2017 from the early detector-commissioning phase and the later operation are presented, that were derived using several million reconstructed tracks in pp-collision and cosmic-ray data. Special emphasis is put on the alignment of the new pixel detector.

Keywords: Alignment, Tracker, Silicon Sensors, CMS

1. Introduction

A precise measurement of the trajectories of charged particles (*tracks*) is crucial to the physics performance of the whole CMS experiment [1] and ensures for example efficient identification of heavy-flavour jets and mitigation of the impact of pile-up collisions. The track-parameter resolution is limited by multiple-scattering effects and the precision of the hit-position measurement, which is determined by the intrinsic position-resolution of the sensors and by the uncertainty on the position, rotation, and surface shape of the sensors. Tracker alignment takes care of reducing this latter component to a level well below the intrinsic resolution of 10–30 μm .

During the LHC technical stop in winter 2016/17, the inner component (*pixel detector*) of the CMS tracking detector was replaced by an upgraded version in order to maintain and improve the tracking performance at higher luminosities. In particular, the new pixel detector includes one additional layer in the central barrel part and one additional disk in each of the endcaps [2].

The upgrade of the pixel detector posed a particular challenge to the tracker-alignment operation. The mounting precision of the modules at installation can be several orders of magnitude worse than the required alignment precision. At the same time, in order not to delay the physics programme of the CMS experiment,

a good-quality alignment had to be obtained within few days after start of the collision-data taking.

In this article, the tracker-alignment strategy adopted during the early detector-commissioning period and later operation in 2017 is described and the achieved performance is presented.

2. The CMS Tracking Detector

The CMS right-handed coordinate system [1] is used throughout this article and referred to as “global” coordinates. The origin lies at the centre of the detector, the x axis pointing to the centre of the LHC ring, the y axis pointing up (perpendicular to the plane of the LHC ring), and with the z axis along the anticlockwise-beam direction. The polar angle θ is defined relative to the positive z axis and the azimuthal angle ϕ is defined relative to the x axis in the x - y plane. Particle pseudorapidity η is defined as $-\ln[\tan(\theta/2)]$.

The CMS tracking detector [1, 2] covers a cylindrical volume of 5.8 m in length and 2.5 m in diameter, with its axis parallel to the LHC beam pipe. It consists of an outer part (*strip detector*), which comprises 15 148 silicon strip-sensor modules, and an inner part (the upgraded *pixel detector*), which comprises 1856 silicon pixel-sensor modules. The pixel detector itself is subdivided into a barrel part (*BPIX*), which consists of four

cylindrical layers hosting the modules, and two endcaps (*FPIX*) in the forward regions at large $|\eta|$, which consist of three disks each. The intrinsic hit-position resolution of the pixel detector is approximately $10\text{ }\mu\text{m}$ in the transverse plane and $20\text{--}40\text{ }\mu\text{m}$ in the z direction.

3. Track-Based Alignment

In order to achieve the best possible track-parameter resolution, and thus e.g. momentum resolution, the spatial position of the detector modules has to be known to at least the same precision as the intrinsic hit resolution, i.e. to better than approximately $10\text{ }\mu\text{m}$ in the pixel detector. At CMS, this is achieved using a track-based alignment procedure. The method is based on a least-squares fit of the track-hit residuals of many tracks, which are sensitive to local deviations of the module positions from the positions assumed in the track reconstruction. Global systematic distortions of the module positions are controlled by mixing tracks from cosmic-rays and collision events and by imposing additional constraints during the minimisation procedure, for example on the reconstructed invariant mass of the two muons in $Z \rightarrow \mu\mu$ events. In this way, the optimal values of the $O(10^5)$ alignment parameters are derived, which describe the position, rotation, and surface deformations of the approximately 17 000 modules relative to the initially assumed geometry.

Two independent algorithms are employed for the minimisation: a global approach (MILLEPEDE II) [3–5], which fits simultaneously all alignment and track parameters taking into account their correlations, and a local approach (HIPHY) [5], which fits alignment and track parameters separately taking into account the correlations in an iterative procedure.

The final alignment precision, which also takes into account time-dependent changes of the geometry, is typically achieved using up to $O(10^8)$ tracks from cosmic-rays and collision events in the fit. Here and in the following, the number of tracks refers to tracks fulfilling high quality criteria.

4. Alignment of the Upgraded Pixel Detector

After installation of the upgraded pixel detector, the modules had to be expected to be severely misaligned w.r.t. the assumed geometry, potentially orders of magnitude worse than the required alignment precision. Hence, the alignment fit would have to determine large corrections using severely mis-reconstructed tracks. This is difficult to achieve within a short time.

Thus, in order not to delay the physics programme of CMS, cosmic-ray tracks have been recorded at a magnetic field of both 0 T and 3.8 T prior to the pp collision-data taking and used to obtain an improved initial alignment. Then, the early collision data could be used to quickly converge at an alignment precision adequate for good-quality data taking.

4.1. Alignment with cosmic-ray data

Cosmic-ray tracks have been recorded at 0 T, of which approximately 40 000 traverse the pixel detector. These have been used in a first step to determine the positions and rotations of the higher-level mechanical structures of the pixel detector, such as ladders and blades [2], and to correct large-scale mis-alignments. Furthermore, minor corrections to the strip-detector alignment have been performed, which has been very stable during the winter shut-down period. In a second step, starting from the improved high-level structure alignment, the alignment of the individual pixel-detector modules has been determined.

The determined pixel-module positions are compared to the positions assumed initially before any alignment in Figs. 1 and 2. Differences of up to several millimetres are observed.

Figure 1: Comparison of the BPIX module positions before and after performing the alignment at module level with 0 T cosmic-ray tracks. Each dot corresponds to one module. Shown is the position difference Δ (after - before) in global- x direction as a function of global radius r in the transverse plane before alignment. [6]

The four groups of dots at increasing radii in Fig. 1 correspond to the four layers composing the BPIX. It is found to be displaced by 2 mm in the global- x direction w.r.t. the position assumed before the alignment. Since the detector is also rotated w.r.t. the geometry before alignment, there is an increasing spread of Δx with the

Figure 2: Comparison of the FPIX module positions before and after performing the alignment at module level with 0 T cosmic-ray tracks. Each dot corresponds to one module. Shown is the position difference Δ (after - before) in global- z direction as a function of global- z position before alignment. [6]

radial distance r from the beam pipe. The two groups of dots at negative and positive z values in Fig. 2 correspond to the two FPIX endcaps, each of which is composed of three disks. The FPIX $-z$ side is found to be displaced by -3 mm in the global- z direction w.r.t. the position assumed before the alignment, while the displacement of the $+z$ side is -0.4 mm.

A data-driven measurement of the achieved alignment quality can be obtained from the reconstructed tracks themselves by studying the difference between the measured hit position and the position expected from the corresponding track (*track-hit residuals*), where the hit under scrutiny is not used in the track fit to avoid biases. The width of the track-hit residuals distribution is a measure of the alignment resolution, but also has contributions due to the uncertainty of the local hit-position reconstruction (*calibration*) and statistical fluctuations of the hit position around the track. Systematic mis-alignments can cause the mean value of the distribution to be different from zero.

In Fig. 3, the distribution of track-hit residuals measured with the modules of the BPIX is shown. The residuals are computed in local- x' direction, which corresponds to global r - ϕ direction, i.e. the direction of the highest resolution of the modules. The tracks have been collected at 0 T and have been fitted using different alignments. Already after the first alignment of the high-level structures, both the bias and the width of the distributions are strongly reduced with respect to the geometry assumed initially before any alignment. After alignment at module level, the width of the distributions is further improved. Similar improvement is observed

Figure 3: Track-hit residuals measured with 0 T cosmic-ray tracks in local- x' direction for the modules in the BPIX. The tracks have been fitted using the pixel-detector geometry assumed before any alignment (black circles), after the alignment of the high-level structures (cyan triangles), and after the subsequent alignment at module level (red squares) derived with 0 T cosmic-ray tracks. [6]

in the FPIX.

The achieved alignment precision is limited by the worse track resolution at 0 T caused by the poor description of multiple-scattering effects at 0 T. Due to the limited time after the ramp of the CMS magnet and before the start of the LHC operation, only a small number of cosmic-ray tracks has been collected at 3.8 T, of which approximately 1500 traverse the pixel detector. This is not sufficient to perform alignment at module-level, but the data has been used to correct the high-level structure positions of the pixel detector for movements of up to $200 \mu\text{m}$ in global- z direction due to the change of the magnetic field.

Due to the predominant direction of the cosmic-ray tracks, some modules are traversed under very shallow angles, and the corresponding hits cannot be used in alignment. Still, approximately 5 % of all pixel modules received enough hits and have been successfully aligned using the cosmic-ray tracks, and the remaining modules are subject at least to the alignment of the high-level structures they are attached to.

4.2. Alignment with collision data

Starting from the alignment derived with cosmic-ray tracks, the module-level alignment of the pixel detector is further improved using collision data at 3.8 T. Several million tracks suffice to achieve a good-quality alignment of the pixel detector, in particular also of those

modules not well-illuminated by the cosmic rays.

The medians of the track-hit residual distributions of many modules enter the *distribution of median residuals (DMR)*, which provides a further data-driven measurement of the local alignment precision. In case of perfect alignment, the distribution of track-hit residuals of a single modules is expected to be centred around zero within the statistical accuracy of the hit-position reconstruction. Hence, the width of the DMR reflects residual random mis-alignment of the modules, e.g. due to the statistical uncertainty of the alignment fit. An additional intrinsic component of the width is due to the number of tracks used to construct the DMR, which is why the same number of tracks has been used when comparing the DMR of two different alignments. Deviations of the DMR mean from zero indicate possible systematic mis-alignments.

The DMR of all modules in the BPIX are depicted in Figs. 4 and 5 for collision-data tracks collected at 3.8 T. Three different alignments have been used to fit the tracks: the geometry assumed before any alignment, after the alignment derived with cosmic-ray tracks, and after the subsequent alignment derived with collision data. A large improvement towards a narrower DMR is observed after each alignment step.

Figure 4: Distribution of median track-hit residuals in local- x' direction for BPIX modules measured with collision-data tracks. The tracks have been fitted using the pixel-detector geometry assumed before any alignment (black histogram) and after the alignment derived with cosmic-ray tracks (blue histogram). The mean values μ and standard deviations σ are the parameters of Gaussian fits. [7]

The alignment quality is also measured by its effect on the physics-object performance. The pixel-detector

Figure 5: Distribution of median track-hit residuals in local- x' direction for BPIX modules measured with collision-data tracks. The tracks have been fitted using the alignment derived with cosmic-ray tracks (blue histogram, same as in Fig. 4) and after the alignment derived with collision data (red histogram). The mean values μ and standard deviations σ are the parameters of Gaussian fits. [7]

alignment in particular impacts the resolution of the reconstructed primary-vertex position, since the pixel detector is closest to the interaction point and has the best intrinsic hit-position resolution. In order to assess the performance of the vertex reconstruction, the unbiased track-vertex residuals (impact parameters) are measured: the vertex position is recalculated excluding the track under scrutiny and the distance of this track to the vertex is computed; then the procedure is repeated for all other tracks. A deterministic annealing clustering algorithm is used for the vertex fit to mitigate the impact of pile-up vertices [8].

The mean values of the distributions of unbiased track-vertex residuals in the transverse plane are shown in Figs. 6 and 7 as a function of the track η and ϕ , respectively. In case of perfect alignment and calibrations, mean values of zero are expected, while systematic mis-alignments can result in deviations from zero. The mean values obtained when using the initial cosmic-ray based alignment in the track fit are compared to those obtained with the subsequent collision-data based alignment. A clear improvement is observed with close-to-ideal performance in η direction. The residual six-fold structure in ϕ direction is an imprint of the inner layer structure of the pixel detector. The bias is at the level of the intrinsic hit resolution and possibly also includes Lorentz-drift effects not fully described yet by the pixel calibrations.

Figure 6: Mean values of the distributions of track-vertex residuals in the transverse plane as a function of track η in collision events. Tracks have been fitted using the alignment derived with cosmic-ray tracks (blue) and the alignment derived with collision data (red). [7]

Figure 7: Mean values of the distributions of track-vertex residuals in the transverse plane as a function of track ϕ in collision events. Tracks have been fitted using the alignment derived with cosmic-ray tracks (blue) and the alignment derived with collision data (red). [7]

5. Alignment of the Entire Tracker

After collecting a larger amount of collision data, a first module-level alignment of the entire tracker, both pixel and strip detectors, has been performed, completing the commissioning phase. The used data, corresponding to in total approximately 35 million tracks, include in particular also several million $Z \rightarrow \mu\mu$ events and a few hundred thousand cosmic-ray tracks, which are crucial to control systematic deformations of the detector [4]. These deformations can lead to biases of the reconstructed track curvature and thus the reconstructed momentum of the track.

This effect can be monitored by investigating the reconstructed invariant mass of the two muons in $Z \rightarrow \mu\mu$ events. The invariant-mass distribution is fitted with a Voigtian function to model the reconstructed Z-boson lineshape and an exponential function to model the background, and the mean of the Voigtian is used as estimate of the Z-boson mass. The reconstructed mass obtained when using the initial alignment derived with cosmic-ray tracks in the track fit shows a clear dependence on the azimuthal direction of the positively charged muon with differences up to 1.5 GeV, cf. Fig. 8. The effect is corrected after the alignment of the entire detector.

Figure 8: Reconstructed mass of the $Z \rightarrow \mu^+\mu^-$ candidates as a function of ϕ of the positively charged muon. Tracks have been fitted using the alignment derived with cosmic-ray tracks only (blue) and the alignment of the entire tracker derived with both cosmic-ray and collision data (red). The plot does not show the performance of the CMS muon reconstruction and calibration since there is no additional calibration of the muon momenta applied. [7]

6. Conclusions

In order to ensure the physics performance of the CMS experiment, an alignment of the tracking detector at a precision of a few μm is required. This is achieved using a track-based alignment procedure.

The alignment strategy and results of the early operation period in 2017 have been presented. Initial mis-alignments of the upgraded pixel detector at the level of several millimetres have been identified and corrected using cosmic-ray tracks prior to the start of the pp-collision data taking. Subsequent alignments derived using different amounts of collision data and cosmic-ray tracks further improve the alignment quality and conclude the commissioning phase of the upgraded pixel detector.

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