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The alignment of the CMS Silicon Tracker

Benedetta Caponeri for the CMS Collaboration

Abstract

The complex system of the CMS all-silicon Tracker, with 15 148 silicon strip and 1440 silicon pixel modules, requires sophisticated alignment procedures. In order to achieve an optimal track-parameter resolution, the position and orientation of its modules need to be determined with a precision of few micrometers. We present results of the alignment of the full Tracker, in its final position, used for the reconstruction of the first collisions recorded by the CMS experiment. The aligned geometry is based on the analysis of several million reconstructed tracks recorded during the commissioning of the CMS experiment, both with cosmic rays and with the first proton-proton collisions. The geometry has been systematically monitored in the different periods of operation of the CMS detector. The results have been validated by several data-driven studies (laser beam cross-checks, track fit self-consistency, track residuals in overlapping module regions, and track parameter resolution) and compared with predictions obtained from a detailed detector simulation.

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The Alignment of CMS Silicon Tracker

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Abstract

The complex system of the CMS silicon tracker, which consists of 15148 silicon strip and 1440 silicon pixel modules, requires sophisticated alignment procedures. In order to achieve optimal track parameter resolution, the position and orientation of these modules need to be determined with a precision of a few micrometers. We present results for the alignment of the tracker, in its final position. The results of this alignment procedure were subsequently used for the reconstruction of the first collisions recorded by the CMS experiment. The aligned geometry is based on the analysis of several million reconstructed cosmic ray tracks recorded during the commissioning of the CMS experiment. The geometry has been systematically monitored in the different periods of operation of the CMS detector. The results have been validated by several different data-driven studies and compared with predictions obtained from a detailed detector simulation.

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1. Introduction

The Compact Muon Solenoid (CMS) [1] detector is one of the multi-purpose experiments developed for data taking at the Large Hadron Collider (LHC) [2]. The main goals of the experiment range from the measurement of Standard Model (SM) [3] parameters to the potential discovery of physics beyond the Standard Model, for which good particle detection performance is needed. The CMS detector consists of, from outside to inside, a precise muon spectrometer, a superconducting coil that provides a 3.8T magnetic field for momentum measurements, a sampling hadronic calorimeter, an electromagnetic lead-tungstate calorimeter, and a full silicon tracker.

The CMS silicon tracker [4] covers the region defined by $|\, z \,| \leq 275$ cm and $r \leq 110$ cm, where z and r are the longitudinal and radial direction in the CMS rest frame, respectively, and is divided into a pixel detector surrounded by a micro-strip detector (see Fig.1). The 1440 modules of the pixel detector are arranged in 3 cylindrical layers (PXB) and 2×2 forward disks, (PXF): each module has a size of $100(r\phi) \times 150(z)\mu m^2$, with an instrinsic nominal resolution of 10 μm along $r\phi$ and 20 μm along z. In the outer region, the 15148 strip modules are organized in 4 layers of tracker inner barrel (TIB), surrounded by 6 layers of tracker outer barrel (TOB), plus 3×2 sets of tracker inner disks (TID) and 9×2 disks of tracker endcaps (TEC). The resolution is in the range 20-60 μm depending on the sensor pitch (80-205 μm). Two layers each in TIB and TOB, two rings in TID and three rings in TEC, are double-sided, which means that are made up of pairs of single-sided strip modules glued back-to-back with a stereo angle of 100 *mrad*. This allows the measurements of a second (stereo) coordinate and means that for each track at least 4 two-dimensional point measurements are possible. For a 100 GeV/c momentum muon, the global p_T resolution is approximately 1.5% and the impact parameter resolution is $15\mu m$.

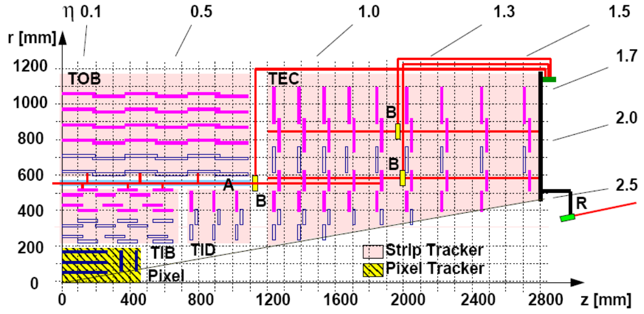

Figure 1: A quarter of the CMS silicon tracker in the rz view. Single-sided silicon strip module positions are indicated as solid lines, double-sided strip modules are shown with open lines.

2. Motivations and Strategy for Full Tracker Alignment

During the assembly phase every effort was made to ensure the alignment was as precise as it could possibly be, but it is clearly impossible to do it perfectly. Therefore, in order to achieve the optimum track parameters resolution, the position and orientation of each module has to be determined to within a precision of leighter than 10 μm. As there are six degrees of freedom for each module (3 translational and 3 rotational around the local right-handed coordinate system shown in Fig.2), the alignment of the full tracker therefore requires the optimization of $O(10^5)$ parameters. The alignment strategy is therefore performed using a number of different methods:

- Optical survey that consists of a set of data used to measure the desired positioning accuracy for all the components from a vast number of measurements made by coordinate measurement machines and photogrammetry.

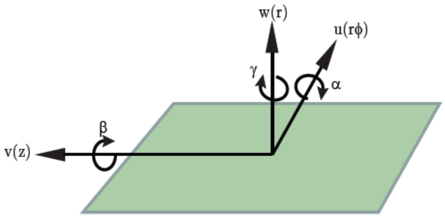

Figure 2: Illustration of the module local coordinates u, v, w and the corresponding rotations α, β, γ for a single-sided strip module. The u-axis is defined along the more precisely measured coordinate of the module (typically along the azimuthal direction in the global system), the v-axis is orthogonal to the u-axis and in the module plane, pointing away from the redout electronics, and the w-axis is normal to the module plane.

- Laser Alignment System (LAS) that is used to monitor the alignment continously, providing knowledge of the positioning of the different tracker substructures at the level of 100 μm.

- Track Based Algorithms, which are devoted to determine the module positions from a large sample of reconstructed particle trajectories. Each trajectory is built from charge depositions ("hits") on individual detectors, incorporating the effects from multiple scattering and energy loss. The module position corrections ("alignment parameters"), **p**, are determined by minimizing the following function:

$$\chi^2(\mathbf{p},\mathbf{q}) = \sum_j \sum_i \mathbf{r}_{ij}^T(\mathbf{p},\mathbf{q_j}) V_{ij}^{-1} \mathbf{r}_{ij}(\mathbf{p},\mathbf{q_j}) \qquad (1)$$

  where j, i are the track and hit iterators, respectively. The variables $\mathbf{q}_j$ are the track parameters, which $\mathbf{r}_{ij}$ represent the residuals, defined as the difference between the hit position measured on the module and the predicted hit from the track model. The variable V_{ij} represents the corrisponding covariance matrix.

Two statistical approaches were employed to solve the problem: the global alignment algorithm ("Millepede II") [5] which minimizes the Eq. 1 by taking into account track and alignment parameters simultaneously, and the local iterative method (" Hits and Impact Points - HIP") [6] which minimizes Eq. 1 by assuming no track parameter dependence and therefore ignores correlations between alignment parameters for different modules in any given iteration. Even though the global method takes into account module correlations and finds the solution with small computing resources, in the version used for this analysis assumed a simple helical trajectory model for charged particle tracks and paritially considered the effects of the material in the tracker. The local method, on the other hand, uses the full implementation of the Kalman filter track reconstruction algorithm adopted in CMS [7], therefore requiring a large number of iterations and large computing resources to refit the tracks at each iteration.

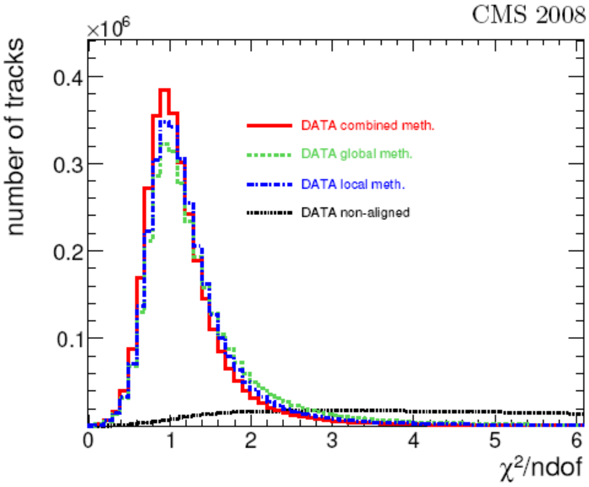

Figure 3: The $\chi^2/ndof$ distribution of thracs for the pre-alignment (black-dotted), local method (blue-dashed-dotted), global method (green-dashed) and combined method (red-solid) geometries. The three alignment procedures improve the χ^2 distribution as expected, with the combined method outperforming the others.

3. Alignment with cosmic rays

The CMS Collaboration has performed the commissioning of the tracker in its final position at the end of 2008 [8]. During the Cosmic Run at Four Tesla (CRAFT) data-taking period, 300 million cosmic ray events were recorded with the solenoid at the nominal field strength. The tracks used for alignment were required to consist of at least eight hits with signal-to-noise ratio higher than 12. Hits were also rejected during refitting if the track angle relative to the detector plane was less than 20°. In addition two hits were required to be on either pixel modules or double-sided strip modules, allowing precise measurement of the polar angle, θ. The particle momentum had to be greather than 4 GeV/c and outlying hits (those that like several sigma away from the predicted position) were removed from the track. Only 3.2 million cosmic ray events were suitable for use in the tracker alignment after application of these selection criteria: 3% of these tracks had hits in PXB and 1.5% had hits in PXF. Both the global and local algorithms were used in a multi-step approach aligning first the highest level structures (half-barrels, endcaps) and then proceeding in order of increasing granularity down to the individual module level. After verifying that the two methods yielded consistent results, the two algorithms have been applied in sequence in order to take advantage of their complementary strength. The global method is used first to identify the global correlations, then the local method is used to adjust the individual module positions. Optical survey data were used in the local method to apply additional constraints on module position along the directions not precisely measured by the sensors. As shown in Fig.3 , the best performance was obtained using the sequential combination of the two alignment algorithms.

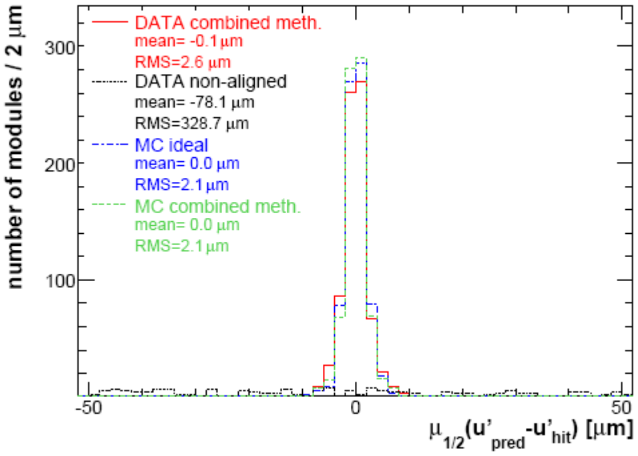

Figure 4: The distribution of the median $\mu_{1/2}$ of the residuals for modules with more than 30 hits in PXB (local-u) before alignment (black-dotted), after alignment with the combined method (red-solid), combined method MC (green-dashed) and ideal MC (blue-dashed-dotted).

4. Validation of the alignment results

Several approaches were employed to validate the alignment results, starting from the monitoring of low level quantities, that are minimized by the alignment algorithms, such as the residuals distribution, up to the validation of higher level quantities, such as the track parameters. The distribution of hit residuals is dominated by the track extrapolation uncertainties (such as the impact of multiple scattering) and by the hit position reconstruction uncertainties, which give the residuals non-gaussian tails. Since these are random effects while the alignment procedure identifies systematic shifts, the distribution of the median of the residuals (DMR) is taken as the most appropriate measure of the success of the alignment procedure. The DMR for PXB is shown in Fig.4 . To determine the statistical precision of track-based alignment, Monte Carlo (MC) simulations were used, in which module positions from the combined method obtained with data were used as the starting geometry in the MC alignment procedure. This approach in MC effectively models the situation in data prior to and during the alignment. The resulting DMR values are listed in Table1. Even the poorer results in PXF agree with the MC expectations; they are caused by the relative small number of cosmics tracks that traverse the forward pixel detectors, compared to the barrel region.

An additional method for validating the results of the alignment procedure is to use the hits from tracks passing through the region where modules overlap within a tracker layer. The difference between the residuals for the two measurements in the overlapping modules is compared, once the hits in the layer under consideration are both removed from the track fit. The proximity of the hits reduces the amount of material between the two hits and minimizes the uncertainties on the predicted positions, allowing an assessment of the relative alignment between two adjacent modules to be made, as shown in Fig.5.

Table 1: RMS observed values of DMR for all subdetectors.

Subdetectors (coordinates)	Data not aligned (μm)	Data combined method (μm)	MC combined method (μm)	MC ideal (μm)
PXB (u')	328.7	2.6	2.1	2.1
PXB (v')	274.1	4.0	2.5	2.4
PXF (u')	389.0	13.1	12.0	9.4
PXF (v')	385.8	13.9	11.6	9.3
TIB (u')	712.2	2.5	1.2	1.1
TID (u')	168.6	2.6	1.4	1.1
TOB (u')	295.0	3.3	2.4	1.6
TEC (u')	216.9	7.4	4.6	2.5

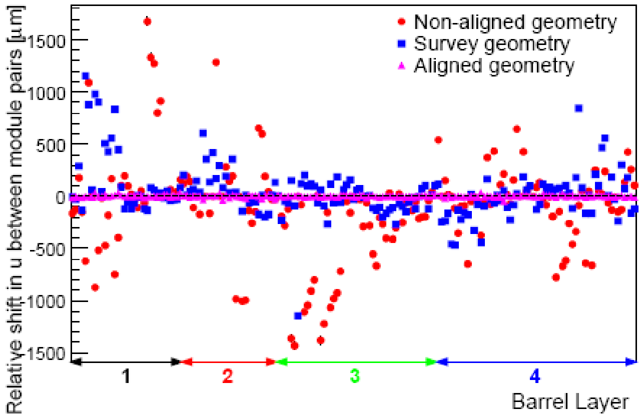

Figure 5: Relative shift between module pairs in the local u-coordinate in the TIB. Only modules in the slice $80^\circ < \phi < 100^\circ$ are shown before alignment (red-dots), including survey measurement (blue-squares) and after alignment (purple-triangles). The survey data improve the starting geometry, but applying the alignment results gives a greater improvement.

To validate track parameter resolutions, an independent reconstruction of the upper and the lower parts of cosmic ray tracks can be used to compare the two sets of resulting track parameters at the point of closest approach to the nominal beam line. Both the upper and lower track segments were required to have at least three hits in the pixel detector to mimic the topology of collision tracks. Fig.6 shows the distributions of the difference in the curvature parameter: there is a significant improvement due to the tracker alignment, with good agreement between data and MC simulations.

5. Conclusions

The alignment performed using 3.2 million cosmic ray events recorded with the 3.8T magnetic field has been very successful: all the validation studies show that the tracker is performing very well. The precision with which the detector positions are

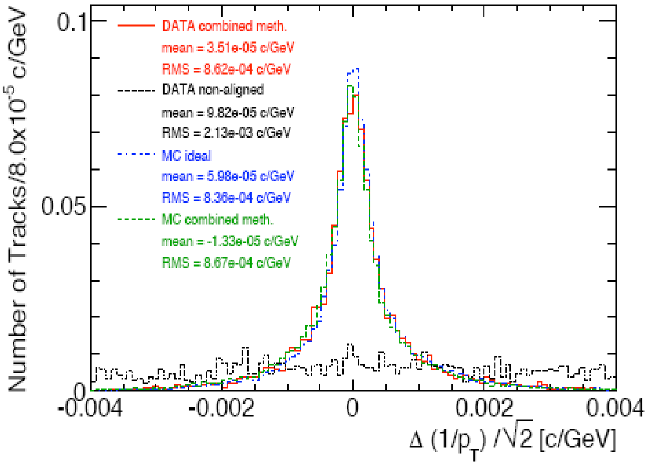

Figure 6: Residuals for the curvature parameter measured at the point closest to beamline for not-aligned data (black-dotted), data with combined method alignment(red-solid), combined method MC (green-dashed), and ideal MC (blue-dashed-dotted).

known using particle trajectories, derived from the RMS of the DMR, is 3-4 μm in the barrel and 3-14 μm in the endcaps for the most sensitive coordinate. Alignment with cosmics has been repeated several times since Autumn 2008, showing that the tracker was already well aligned before first collisions.

6. Aknowledgements

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