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The Compact Muon Solenoid Experiment

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The CMS Muon System Alignment

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Abstract

The alignment of the muon system of CMS is performed using different techniques: photogrammetry measurements, optical alignment and alignment with tracks. For track-based alignment, several methods are employed, ranging from a hit and impact point (HIP) algorithm and a procedure exploiting chamber overlaps to a global fit method based on the Millepede approach. For start-up alignment as long as available integrated luminosity is still significantly limiting the size of the muon sample from collisions, cosmic muon and beam halo signatures play a very strong role. During the last commissioning runs in 2008 the first aligned geometries have been produced and validated with data. The CMS offline computing infrastructure has been used in order to perform improved reconstructions. We present the computational aspects related to the calculation of alignment constants at the CERN Analysis Facility (CAF), the production and population of databases and the validation and performance in the official reconstruction. Also the integration of track-based and other sources of alignment is discussed.

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1. Introduction

The CMS experiment [1] is a multi-purpose detector installed at the Large Hadron Collider [2] in the proximity of the city of Geneva, Switzerland. In order to provide very good lepton identification and momentum resolution the experiment was equipped with a very precise central-sillicon tracker [3] and a powerful muon spectrometer [4].

For optimal performance of the CMS muon spectrometer over the entire momentum range up to the TeV range, different muon chambers must be aligned with respect to each other and to the central tracking system to within a few hundred microns in the $r\phi$ plane.

The required alignment precision for the endcap chambers is $75 - 200\,\mu m$, while for the barrel the precision varies from $150\,\mu m$ for the inner station to $350\,\mu m$ for the outer station. To this end, after following strict chamber construction specifications, CMS combines precise survey and photogrammetry measurements, measurements from an opto-mechanical system, and the results of alignment algorithms based on muon tracks (from cosmic rays, beam halo and from pp collisions) crossing the spectrometer.

There are several potential sources of misalignment in the muon spectrometer, from chamber production to final detector operating conditions, including:

- Chamber construction tolerances: These are unavoidable geometrical tolerances in the production of the chamber components. The relative positioning of the different internal components of a chamber was measured during construction to be within the required tolerances.
- Detector assembly, closing tolerances: Gravitational distortions of the return yoke lead to static deformations of the steel support. This effect, together with the installation tolerances, results in displacements of the chambers in the different barrel wheels and endcap disks of up to several millimeters with respect to their nominal detector positions.
- Solenoid effects: Magnetic forces generated by the $3.8\,T$ solenoid field lead to displacements and deformations of the return yoke which is at the same time the support structure of the muon chambers. This results in further displacements of the chambers with respect to their nominal positions.
- Time-dependent effects: During operation, thermal instabilities and other time-dependent factors can cause dynamic misalignments at the sub-millimeter level.

The strategy for the alignment of the CMS muon spectrometer is to combine different sources of information: from the production phase of the muon chambers to the final monitoring during operation. The set of data comes from:

- Quality control data recorded during the construction of the chambers.
- Survey and photogrammetry measurements done at the different stages of chamber construction and detector assembly.
- Optical data provided by the optical muon alignment system.
- The information provided by the tracks (cosmic rays, beam halo, or collision tracks) crossing the detector.

2. The Muon Optical Alignment System

The muon system of CMS comprises an optical alignment system which allows a fast and independent measurement of the misalignments. A network of laser lines, light detectors, distance meters and tiltmeters are extended over CMS in a redundant scheme able to determine movements of the different structures. Figure 1 illustrates the laser net intercalated between the barrel wheels.

The muon optical alignment system is divided into three subsystems:

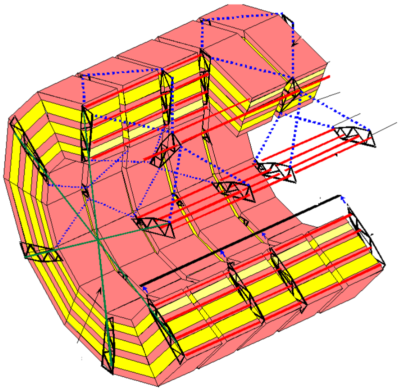


Figure 1. The muon chamber position is monitored with the help of a net of laser lines. Light measurements are complemented using distancemeters and tiltmeters.

- **Endcap System.** The endcap hardware alignment provides an internal alignment of each of the endcaps individually, and a relative alignment of the two endcaps with respect to each other.
- **Barrel System.** The barrel system aligns internally the muon barrel.
- **Link System.** This system connects the endcap system, the barrel system, and the central silicon-strip tracker.

The technologies for each subsystem vary depending on the specific needs and configurations. The distribution of the detectors is also characteristic of each subsystem. Nevertheless the three subsystems share the same reconstruction software named COCOA [5], integrated in the standard software of CMS (CMSSW [6]).

COCOA builds a geometrical model of the optical system. A χ^2 minimization is performed to find the alignment parameters that best fit the observed deviations between the measurements and the base model, taking into account all the correlations. The base model assumed by COCOA as starting point is calculated from the ideal positions in the drawings and updated using photogrammetry results.

Lasers and sensors are connected in a discrete sequence synchronized with the readout electronics. Each complete readout cycle is called an “event”. The time needed to acquire an event ranges from several minutes for the Link System, to a couple of hours for the Barrel System. The size is also different for different subsystems, from some tenths of KB in the link, up to 2 MB in the barrel.

Figure 2 shows the workflow associated to the optical alignment system. Alignment events are recorded through the standard DAQ of CMS, based on PVSS [7]. The information is then stored in an online ORACLE [8] database. A subset of this information is translated into ROOT [9] format and given to the Tier0 injector, which sends the information from the online environment to the Tier0 [10]. Events are then written to tape, and through an automatic subscription sent to the CAF (Cern Analysis Facility), a computer farm dedicated to critical latency activities. In the CAF, the reconstruction software is run producing updated geometries.

During normal operation several events are collected along the day. The transfer to the offline environment takes place once a day, providing more than one event for all the subsystems.

The optical alignment system is able to provide a very fast alignment. Reconstruction of the geometry is performed on a day-by-day basis. On top of this, large misalignments can be spotted

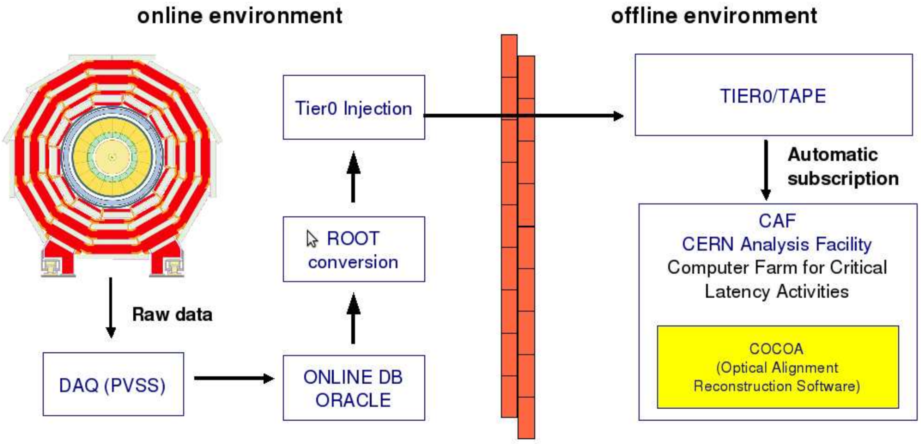


Figure 2. Alignment events are collected and filtered in the online environment and then injected into the offline environment (separated physically and logically), transfered to the CAF, where the reconstruction software is run.

in a quasi-online time scale, through the observation of direct measurements in the PVSS control panel.

3. Track Based Alignment

To complement the optical system, tracks from physics-run collisions, cosmic-ray data and beam halo will be used to measure the position and orientation of the muon chambers. This technique requires the accumulation of a high number of tracks which are processed offline to convert the redundancy in the track determination into information about the alignment. The latency and systematic errors associated to this procedure are rather different from the optical alignment system.

A CMS alignment framework has been developed specifically to the needs of tracking devices. This framework has the following functionalities:

- **Management of Alignment Constants.** The framework allows to deal transparently with different database formats. The application of the alignment constants to the geometry is also managed by the framework. There is a hierarchical model of the geometry which allows the propagation of corrections in large structures to their child-contained substructures. Tools for the generation of misalignment scenarios for Monte-Carlo studies are also provided.
- **Generic interface to Alignment Algorithms.** A common interface is defined by the framework. Different alignment algorithms are configured as alignment plugins. The format of the input and output information related to the algorithms is standarized.

For the muon spectrometer exist three track-based alignment algorithms:

- HIP (Hit Impact Point) [11] alignment algorithm.
- Millepede [12] similar approach.
- CSC Overlap Alignment Algorithm

The HIP and the Millepede approach algorithms have a general scope: they are adapted to perform an alignment of the muon chambers with respect to the tracker. On the contrary, the

CSC Overlap Alignment Algorithm is more specific, focusing in the alignment of the endcap rings using the existing overlap between chambers. A further explanation will be provided in the following chapters.

4. Stream production for Alignment and Calibration purposes

In order to improve the latency of the alignment and calibration workflow, dedicated data sets are designed and produced centrally at the Tier0. These data sets are usually referred to as AlCaReco samples, and only contain information relevant for the particular alignment and calibration task they are intented for.

AlCaReco samples are produced on the basis of an event selection using High Level Trigger [13] bits, cuts on track parameters, and selection of the event content. The kept fraction of the muon alignment AlCaRecos ranges from 2% to 10% of the full sample.

The production of AlCaReco samples takes place centrally at the Tier0 from where they are automatically transfered to the CAF. In order to ensure the quality of the samples a Data Quality Monitoring tool is run as soon as the data arrive to the CAF. Several control plots with basic quantities such as residual and momentum distributions, geometrical occupancies etc are performed.

The muon alignment workflow is fully integrated in the general alignment and calibration workflow of CMS (see [14] for more information). Dedicated data streams containing both track and optical alignment system based information arrive to the Tier0 where the AlCaReco samples are produced. The data are then transferred to the CAF and feed the different alignment and calibration workflows resulting in a new set of alignment and calibration constants. Only after validation, alignment constants are stored in databases.

5. Results From The Muon Alignment System

In the following sections a variety of results regarding the alignment of the muon system will be presented. Results from early commissioning without magnetic field as well as from a large data sample recorded at nominal field are described.

5.1. Alignment of Barrel Chambers inside the wheels

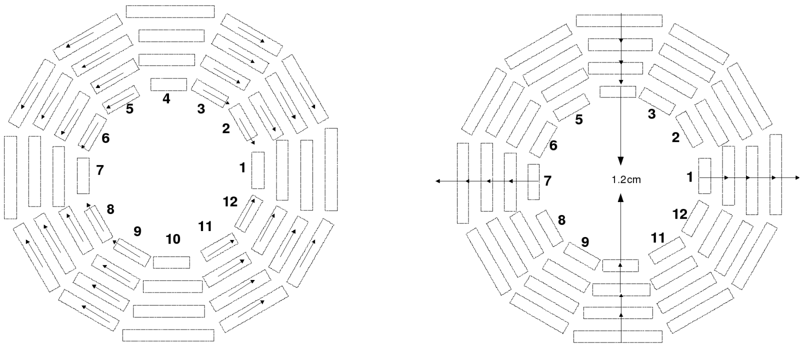
The position of muon chambers was determined from photogrammetry. These measurements provide a first real measurement of the position of the chambers with respect to the wheel center. Afterwards, refinements over this geometry were computed using tracks reconstructed only in the muon system, recorded without magnetic field.

Results of this analysis are shown in figure 3. A gravitational sag of about $1.2\,cm$ is observed in the wheels. The shape of the radial displacements is very illustrative: chambers in the top and bottom are getting closer to each other, while the distance between the chambers on the left and right sides increases.

5.2. CSC Overlap Alignment Using Beam Halo Muons

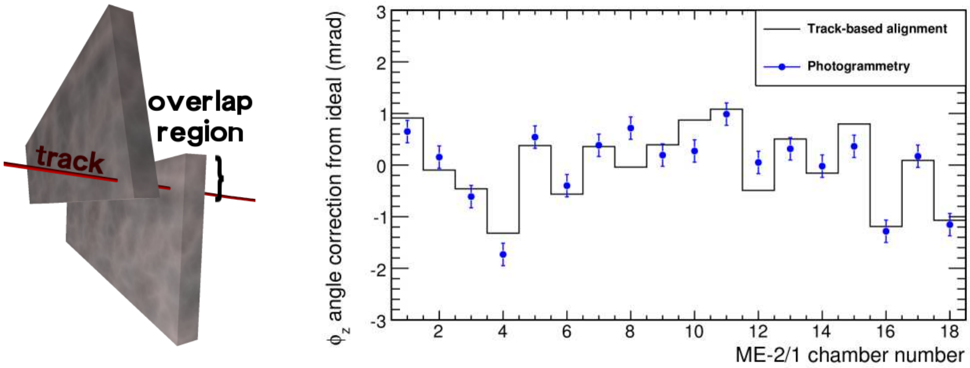
In September 2008 the Large Hadron Collider was operated for the first time. During one week bunches of protons circulated in both senses of the ring, producing a large amount of beam halo muons in the direction parallel to the beam line. Because of their topology, beam halo muons illuminate efficiently the two endcaps of CMS which are perpendicular to the beam pipe.

In the endcaps, Cathode Strip Chambers attached to the yoke form rings of 18 or 36 chambers. In order to properly cover the full ϕ range, rings are composed of two layers of chambers equally distributed in phi along the circumference. The two layers overlap to guarantee hermeticity. This geometry configuration allows a region of overlap close to the edges of chambers in different layers, as shown in figure 4(a).



(a) (b)

Figure 3. Gravitational sag observed in the barrel wheels. The yoke compresses in the vertical direction and expands horizontally.



(a) (b)

Figure 4. Overlap between two CSC chambers 4(a). Comparison between photogrammetry and track measurements for a complete ring of the endcap 4(b).

The relative alignment between chambers is calculated imposing coherency between the track segments in each chamber in the overlap region. Provided that every chamber overlaps with the previous and next chamber in ϕ, it is possible to perform a complete alignment of the ring requiring ring closure.

In figure 4(b) a comparison between the results obtained by photogrammetry measurements and the results obtained with this procedure is shown. The achieved alignment precision of the order of $200 - 300\,\mu m$, with a total of 33000 events.

5.3. The Cosmic Run At Four Tesla (CRAFT)

Between 13 October and 11 November 2008, CMS was fully operated at a magnetic field of $3.8\,T$ during 19 days. All subdetectors were operational. The total number of collected muon events, including those recorded at zero magnetic field, is 390 million, whereas 194 million events were recorded at $3.8\,T$. The fraction of cosmic muons reconstructed in both the muon system and the tracker was 3%. During this period the optical alignment system collected more than 200 Alignment Events.

5.4. Results from the optical alignment system

In order to understand and measure the impact of magnetic forces in the structures of CMS, the events were recorded before and after every ramp up and down of the magnet.

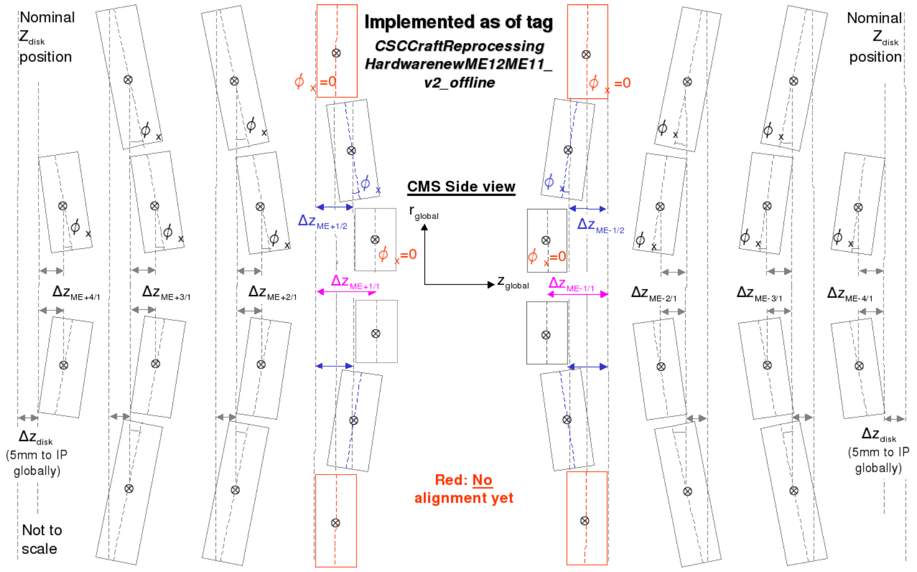


Figure 5. Longitudinal view of CMS. Vertical lines show the position of the chambers before the magnet is switched on. After its connection, the endcaps displace towards the interaction point and suffer a lens-shape deformation.

The results obtained after running the reconstruction software showed an axial deformation of the Endcaps at $3.8\,T$ as can be seen in Figure 5. There is a compression of the endcap disks towards the interaction point and a deformation of the disks of the form of a lens. The largest displacement is $1.5\,cm$ and the typical chamber rotation is about $4\,mrad$. The precision is always better than $1\,mm$.

5.5. Alignment With Tracks In The Barrel

During CRAFT an alignment of the Barrel Chambers with respect to the tracker was performed. Two different algorithms were used, HIP and a Millepede simmilar approach. Both algorithms used the same strategy: muons reconstructed in both the tracker and the muon system were considered for the analysis. Muon track parameters were determined using only the tracker information and then extrapolated into the muon system where a comparison between the measurement and the extrapolated value was performed.

Figure 5.5 shows a comparison between the track-based measurements and the photogrammetry results for one single wheel and for three of the stations. Both measurements show a similar compatible trend.Perfect agreement was not expected as photogrammetry measurements do not take into account global movements of the wheels. The precision achieved in the $r\phi$ coordinate is of about $1-2\,mm$.

6. Conclusions

The alignment of the CMS muon spectrometer is performed employing different techniques, each technique with different systematics and latencies. The muon alignment workflow is

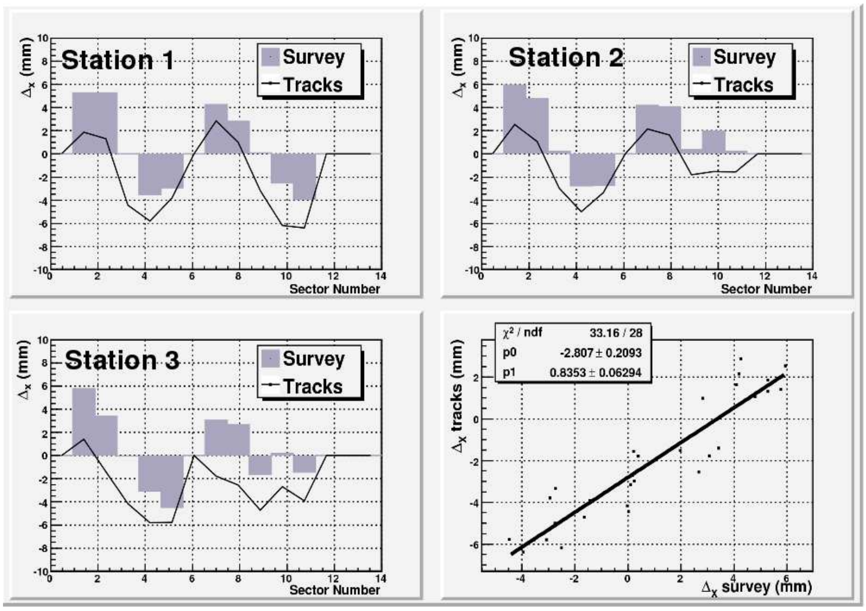


Figure 6. Grey blocks represent the measurements given by the photogrammetry techniques and the black line the results obtained using track-based algorithms. Both sets of measurements show a simmilar trend.

integrated into the general alignment and calibration workflow of CMS: data transfer from CMS to the Tier0, production of specific streams, calculation, validation and storage of constants in databases.

During the first commissioning of CMS in 2008 the workflow was tested and first results obtained. In particular, during the last large cosmic global run (CRAFT) the deformation of the endcaps due to the magnetic forces was measured and a first alignment of the barrel chambers with respect to the tracker achieved.

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