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CMS muon alignment: System description and first results

Mar Sobron *, P. Martinez Ruiz del Arbol

Instituto de Fisica de Cantabria, CSIC-University of Cantabria, Avd. De los Castros s/n, 39005 Santander, Spain

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ABSTRACT

The CMS detector has been instrumented with a precise and complex opto-mechanical alignment subsystem that provides a common reference frame between tracker and muon detection systems by means of a net of laser beams. The system allows a continuous and accurate monitoring of the muon chambers positions with respect to the tracker body. Preliminary results of operation during the test of the CMS 4 T solenoid magnet, performed in 2006, are presented. These measurements complement the information provided by the use of survey techniques and the results of alignment algorithms based on muon tracks crossing the detector.

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1. Introduction

For optimal performance of the CMS muon spectrometer [1] over the entire momentum range up to the TeV range, the different muon chambers must be aligned with respect to each other and to the central tracking system to within a few hundred microns in $r\phi$. The required alignment precision for the endcap chambers is 75–200 μm, while for the barrel the precision varies from 150 μm for the inner station to 350 μm 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 (both from cosmic rays and from pp collisions) crossing the spectrometer.

During the Magnet Test and Cosmic Challenge (MTCC) [2] a third of the optical alignment system was implemented allowing preliminary studies of the detector behavior under the effect of magnetic forces.

In what follows we describe the alignment strategy, a brief description of the optical alignment system, and the results from the different measurements sources.

2. Alignment strategy

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 parts. The relative positioning of the different internal components of a chamber was measured during construction to be within the required tolerances [3].

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 4 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: (a) quality control data recorded during the construction of the chambers, (b) survey and photogrammetry measurements done at the different stages of chamber construction and detector assembly, (c) optical data provided by the optical muon alignment system, and finally (d) the information provided by the tracks (cosmic rays, beam halo, or collision tracks) crossing the detector.

3. Optical alignment system description

The muon alignment system [1] was designed to provide continuous and accurate monitoring of the barrel and endcap muon detectors among themselves as well as alignment between them and the inner tracker detector.

* Corresponding author. Tel.: +34 22 767 1657; fax: +34 22 767 8940.
E-mail address: sobron@ifca.unican.es (M. Sobron).

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The system must generate alignment information for the detector geometry with or without collisions in the accelerator. Its goal is to provide independent monitoring of the CMS tracking detector geometry with respect to an internal light-based reference system. This will help to disentangle geometrical errors from sources of uncertainty present in the track-based alignment approach, e.g., knowledge of the magnetic field, material description, and drift velocity.

The basic geometrical segmentation consists of 3 r–z alignment planes with 60° staggering in ϕ. This segmentation is based on the 12-fold geometry of the barrel muon detector. Within each plane, the 3 tracking sub-detectors of CMS (central tracker, barrel and endcap muon detectors) are linked together. Fig. 1 shows the schematic longitudinal and transverse views of CMS, with the light paths indicated.

The layout of the optical paths allows the monitoring of each of the 250 DT chambers, while only one-sixth of selected CSCs in the 4 endcap stations is directly monitored to reconstruct the plane geometry.

The optical network uses two types of light sources, with precise measuring devices and positioning sensors (distance sensors and inclinometers), complemented by temperature, humidity and Hall probes. It is divided into 3 basic subsystems, the main features of them are described below.

The barrel alignment subsystem monitors the positions of the barrel muon chambers with respect to each other. Each barrel muon chamber is equipped with light sources (LEDs, more than 900 in total). The LEDs are observed by small video-cameras (600 in total) mounted on rigid carbon-fiber structures called Module for the Alignment of the Barrel (MAB). The MABs (36 altogether) are fixed to the return yoke in the gaps between wheels. There is a direct optical connection among them such that they form a closed optical network. The MABs on the two external ends contain extra devices used to connect the three alignment subsystems.

The endcap alignment system is designed to monitor the relative positions of the muon chambers. Each endcap station is monitored by three laser lines (straight-line monitors) that allows one to map the geometry of each layer of chambers. Six axial transfer lines, in the outer detector boundaries, connect the two endcaps set of disks (forward and backward) as well as the barrel wheels.

The link alignment system [4] measures the relative positions of the muon spectrometer and the tracker in a common CMS coordinate system. It is designed to work in a challenging environment of very high radiation and magnetic fields, meet tight space constrains, and provide high precision measurements over long distances. A distributed network of opto-electronic position sensors, 2D Amorphous Silicon Position Detector (ASPD) sensors [5], placed around the muon spectrometer and tracker

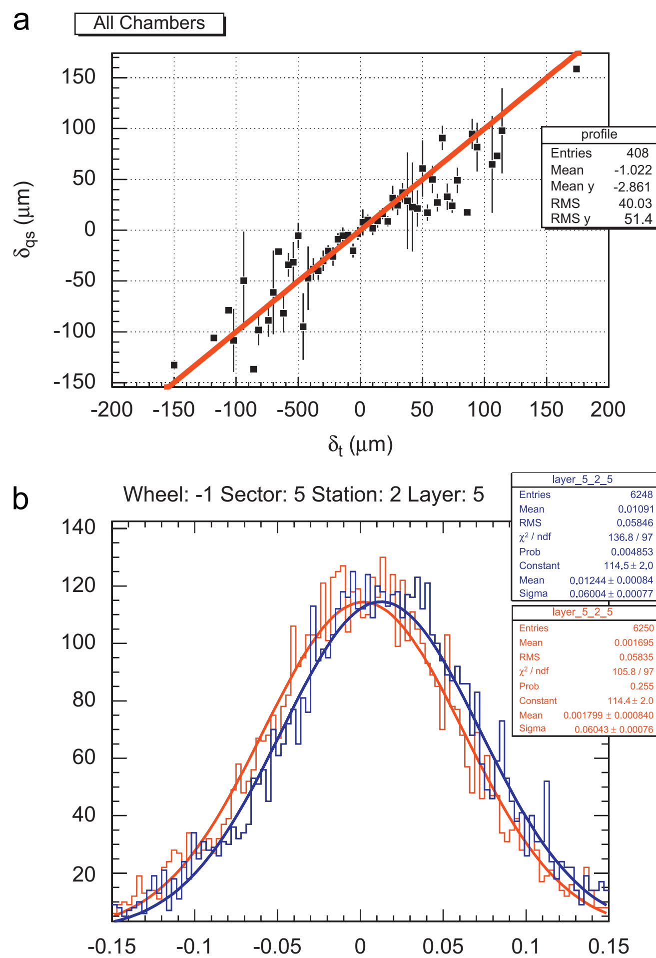

Fig. 2. Top: Good correlation between the displacements from nominal using quality control and survey techniques vs. the displacements from track alignment methods, for the barrel chambers. Bottom: Centering (in red) of the layers residual distribution in $r\phi$ after applying alignment correction to the barrel chambers.

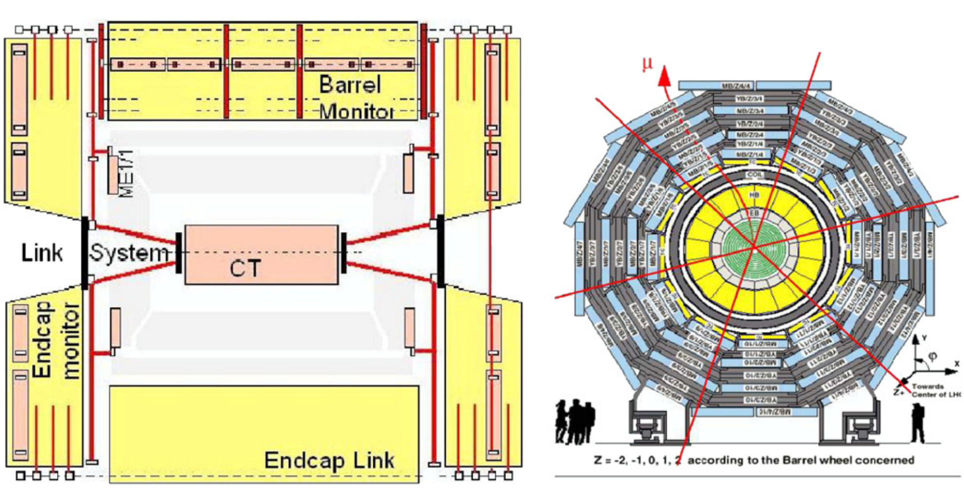

Fig. 1. Schematic view of the alignment system. Left: longitudinal view of CMS. The continuous and dotted lines show different optical light paths. Right: transverse view of the barrel muon detector. The crossing lines indicate the r–z alignment planes with 60° staggering in ϕ.

volumes are connected by laser lines. The entire system is divided into 12 laser paths, or lines: 6 on each side (positive or negative z) of the CMS detector. Rigid carbon-fiber annular structures are placed at both ends of the tracker (alignment rings) and at the first endcap disks of the muon spectrometer (link disks). The MABs attached to both ends of the barrel wheels also contain alignment components to complete the global optical network.

4. Results from alignment studies

In this section, we present selected results from different alignment studies, from the reconstruction of the internal chamber geometry to the measurements of the muon chamber support structures under 4 T field operation conditions. We also give a preliminary estimation of the reached performance.

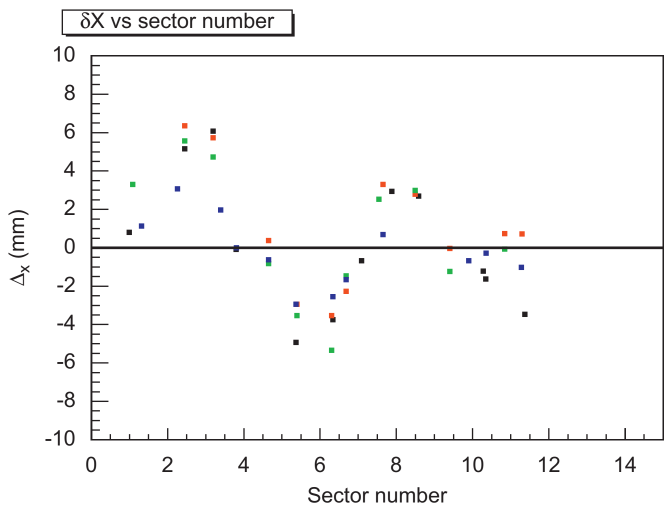

Fig. 3. Deviations from nominal in the x coordinate of the chambers in the second positive barrel wheel with respect to the sector number. Results showed the gravitational effect.

4.1. Internal alignment of the muon chambers

The aim of the internal alignment is to provide the internal geometry of the barrel and endcap chambers using all available data: from the quality control measurements during construction and assembly, from photogrammetry and survey measurements of the assembled chamber, and from cosmic tracks collected during the commissioning of the chambers at CERN. Although neither of these different measurements provides by itself full information of the internal geometry, there are some redundant parameters that allow to check the consistency (see Fig. 2) of all of these measurements.

The alignment correction, extracted from the above source, shows a centering of the residual distribution of ~80 μm and ~20 μrad (see Fig. 2), the results are stables in time, and independent of the chamber location in the detector. This data is compared with construction drawings and cosmic data to provide corrections to the nominal chamber geometry.

4.2. Survey measurements of installed chambers

After the chamber installation, survey and photogrammetry measurements were performed for each wheel and disk [6]. These measurements provide an initial geometry (position and orientation of each muon chamber in the different yoke structures) which absorbs installation tolerances and static steel deformations. The position of each chamber was measured with respect to the wheel and compared to its nominal position.

Results show a global accuracy and precision on the installation of about 1 mm in all three coordinates and the effect of CMS

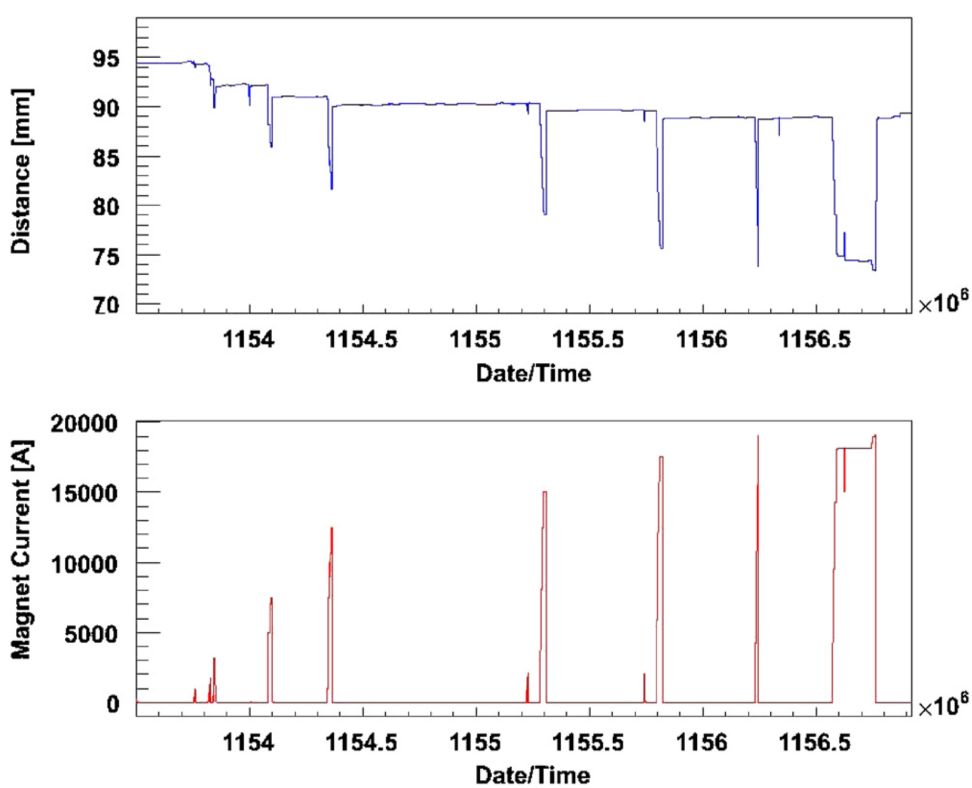

Fig. 4. Deformations of endcap disks vs. magnet current cycling. The bottom plot shows the magnet powering cycle exercised during the first phase of the magnet test period. The top plot shows the measured central part of the first endcap disk and its compression towards the interaction point.

weight: gravitational deformation of the order of 1 mm in the endcap disk and ~6 mm in the barrel wheels (see Fig. 3).

4.3. Magnetic effects on the muon chambers supporting structures

A test of the CMS magnet (MTCC) took place in two different phases during summer and autumn 2006 in the CMS assembly area. Approximately 5% of the muon spectrometer was operational and about a third of the alignment system was commissioned during this test. This allowed the first full-scale dynamic test of the system. The performances of the system as well as the main features of the yoke displacements and deformation were studied.

Thermal effects (day–night variations) for DT and CSC chambers were recorded for the conditions present during the

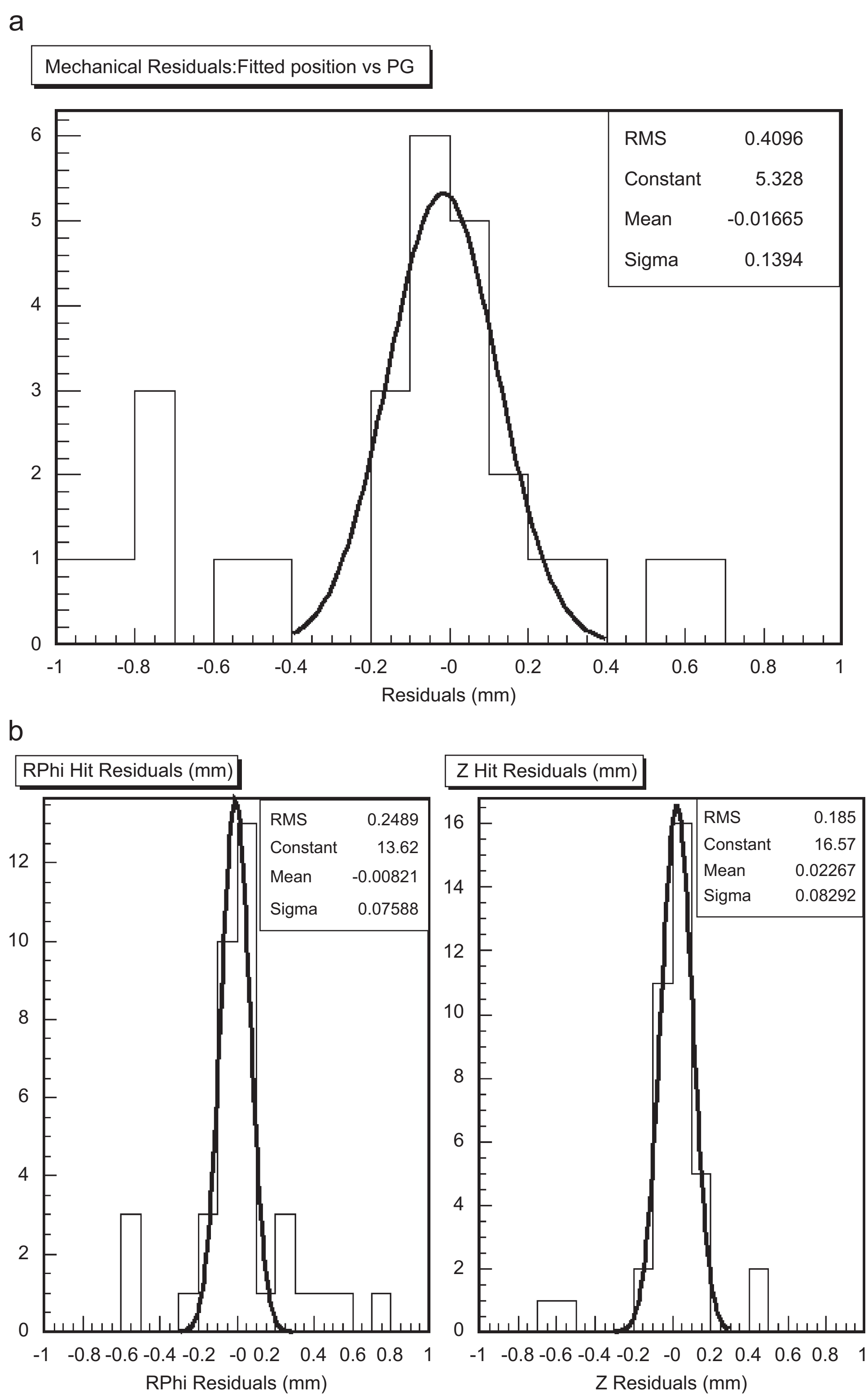

Fig. 5. Top: System accuracy, defined as the difference between photogrammetry and fitted position from optical data. Bottom: System resolution, defined as the difference between measured and fitted coordinates, in $r\phi$ (left) and z (right) coordinates.

test. The measured relative movement did not exceed 50 μm over the entire test period, with changes in position showing a good correlation with temperature. Although a movement of this magnitude is not relevant from the physics analysis point of view, the measurement illustrates the good resolution of the optical alignment system. Two effects were observed when the magnet was powered on: the first was the change of the original closed positions of the structures (the positions before any magnet operation) after the first magnet cycles. A permanent compression towards the interaction point (IP), along the beam line axis, of several mm was measured and it was interpreted as the final closing of the structures due to the magnetic forces acting on the iron. This magnitude is understood as specific of the test conditions and cannot be extrapolated to other scenarios. The second effect is the almost perfectly elastic deformations of the iron structures between magnet-on and magnet-off states. Both effects can be seen in Fig. 4. The top figure shows for each measurement the distance between the tracker end and the first endcap muon disk, for the different field values, shown at the bottom part of the figure. The strong magnetic forces pull the central part of the endcap disks towards the IP. At 4 T it is pulled approximately 16 mm. This displacement follows, as expected, a quadratic behavior with the magnet intensity. The same compression effect, although of much smaller magnitude, was measured for the barrel wheels. Small deformations in the $r\phi$ plane were also observed.

The global reconstruction of the optical data is handled by a software package called COCOA [7]. It obtains positions and orientation angles of defined reference points or structures from a non-linear least-squares fit. In addition to the optical measurement recorded, the system description has to be provided, including the interconnection of elements and hierarchy of the components, together with an approximation of the geometry provided with previous measurements (calibrations or photogrammetry). Supplying a good estimation of the geometry speeds the convergence, ensures the goodness of the result and avoids falling in local minima.

The reconstruction method has been applied to the link system. The system was fully described with MTCC geometry and the first geometry of the detector (barrel and endcap with respect to the tracker) was reconstructed at 0 and 4 T. Comparing these two geometries, the movements and displacements of the structures, from 0 to 4 T, were obtained.

With data recorded during the whole period of the MTCC the reconstruction method was validated and the system performance was evaluated, showing a system accuracy of ~140 μm and a resolution of ~80 μm in both coordinates, as shown in Fig. 5.

5. Conclusion

The procedure to align the detectors in CMS makes use of different source of information. It includes survey and photogrammetry measurements, optical data and the results of the track-based alignment algorithms.

An analysis with tracks, taken during the commissioning, together with survey information, has allowed to build a first set of alignment corrections for the internal alignment of the muon chambers.

A complex optical muon alignment system has been successfully completed and a significant part of the system was, for the first time, tested with the full detector closed and with the 4 T solenoid field on, running in a continuous mode.

With the link system data the magnetic field effects on the detector geometry were measured. A good consistency of the results measured from different data source was obtained. A first CMS geometry of the barrel wheels and endcap disk with respect to the tracker detector, as in operation conditions, was established and the system accuracy and precision was validated with respect to the design values [1].

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