Alignment of the CMS Muon Endcap with Tracks in Overlapping Pairs of Chambers (CMS Note version)

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January 11, 2009

Abstract

We present a method for aligning the endcap muon chambers (and the layers within them) using tracks that pass through pairs of neighboring chambers in the same ring. A muons's trajectory within an endcap ring doesn't pass through any thick layers of iron, so the trajectories of these tracks are nearly free of multiple scattering effects and are therefore highly predictable. Included in this Note are results from Monte Carlo simulations and from real beam-halo data from the September 2008 run of the LHC, in which we demonstrate a 270 μm $r\phi$-alignment of chambers using tracks from 9 minutes of collected beam. This is roughly the intrinsic resolution of the chambers and within the scope of our "long-term" alignment goals.

1 Motivation, Geometry, and Coordinate Systems

The momentum resolution of any tracking system is determined by the intrinsic hit resolution its subdetectors and one's knowledge of the positions of those subdetectors in space. Since these two sources of uncertainty add in quadrature for any charged particle track, they tend to be dominated by the worst of the two. The 200–300 μm hit resolution of the Cathode Strip Chambers (CSCs) in the CMS endcap muon system has been well demonstrated by studies of the chambers in isolation [?]. Now that the whole CMS detector has been assembled and is taking data, it is important to learn the relative positions of all its elements (that is, "align the detector") with the same degree of accuracy.

1.1 Methods of Alignment and their Motivations

There are several independent approaches to alignment, and they can be used to verify one another. The first and most straight-forward is photogrammetry: hundreds of high-precision photographs were taken of the assembled system and fed into a computer to fit for the positions of all the chambers. Two alignment pins are built into each CSC; they are physically attached to all the layers that sense the passage of charged particles and are visible from the outside. Every pin was capped with a reflective disk and illuminated with a bright light, so that they glowed as easy-to-reconstruct circles in the photographs. Though the disks are about a centimeter in radius, their centers were reconstructed with a precision of about 300 μm [**?**].

Unfortunately, photogrammetry can only be performed while the muon system is "open," before the largest components are slid into place (leaving no room for cameras) and the magnetic field is turned on. The CMS magnetic field has a profound effect on the shape of the detector, applying forces on the thick iron disks of the endcap which are many times their weight, bending them by a centimeter in the middle. Under these forces, the individual chambers might shift unpredictably, invalidating the photogrammetry result. We must therefore be able to align the system again while it is in operation.

To achieve this, the detector is also instrumented with continuously-active alignment devices— lasers, digital sensors, inclinometers (like a carpenter's level), and mechanical calipers. All of this information is read out in a separate stream from the detector data and compiled into a global geometry description. The Muon Hardware Alignment System (MHAS) therefore has the following advantages:

- it measures positions using physical instruments, as a ruler would,
- it can observe the evolution of the system from the state measured by photogrammetry into a state where it can start taking data,
- and it can measure any component of displacement, including those that are parallel to the trajectories of charged particle tracks.

However, the MHAS only monitors the positions of 6 out of the 18 to 36 chambers in each endcap ring, and requires great care to translate device read-outs into global chamber positions. To derive a geometry which is useful for track reconstruction, the measurements must be propagated in two directions: outward to all the other tracking systems, through a diverse chain of devices, and inward from the devices mounted on the chamber frames to the sensitive layers which actually measure the passage of charged particles. These issues are being studied carefully, but for a complete understanding of the muon system alignment, we will need another independent method.

A standard technique is to use the tracks measured by the detector itself for alignment. Muon tracks from LHC collisions traverse the entire CMS detector in a continuous line, simplifying the alignment of distant subdetectors, such as the muon system and the central silicon tracker. Also, the local hit measurements that make up a track are automatically in the right coordinate systems for aligning the sensitive components, rather than their physical structures. Track-based alignment methods involve a cycle of fitting tracks with a trial detector alignment, observing systematic offsets in the hit residuals (difference between the best-fit track prediction and the hit measurement on a given detector element), and using these to correct the trial alignment. Sometimes the cycle is an explicit iterative loop, and sometimes it is a combined fit.

Track-based alignment also has its challenges, in that track-propagation errors limit the precision and accuracy of the detector alignment. Multiple scattering in the iron return yoke of the CMS solenoid introduces an independent error into each track, broadening the residuals distributions, making it harder to see the offset in the mean due to misalignment. This type of uncertainty can be cured with high statistics. More serious are systematic distortions to all tracks passing through a given region of the detector, such as an error in the magnetic field description or a misalignment in a part of the silicon tracker. In these cases, one might accidentally absorb non-misalignment errors into the detector geometry, making it harder to solve these problems. Fortunately, we can also identify them using a number of track-based techniques, including

- closed loops of relative alignment measurements (B relative to A and C relative to A compared to B relative to C) using a broad distribution of track entrance angles (cosmic rays),
- distinguishing magnetic field effects, which vary as a function of momentum ($\vec{B} \times \vec{p}$) and flip sign with charge, from misalignment effects which are independent of the set of tracks used in the study,
- identifying the smoking gun of a real misalignment by observing the discontinuity in residuals at the known boundaries between detectors,
- and averaging over localized errors by combining tracks from a large tracking volume in a single alignment measurement.

Most of these techniques are beyond the scope of this Note, and will be described in a follow-up document on track-based muon alignment in general. They are part of an ongoing, integrated project of aligning all the tracking systems and correcting errors in CMS's global track model.

In this Note, we will present one completed part of the project, the development of a procedure to align CSCs in the endcap rings using tracks that pass through overlapping chambers. This "CSC Overlaps" alignment procedure avoids all of the above issues because it depends only on the parts of the tracks that are between thick layers of iron, where multiple scattering is negligible and the magnetic field is parallel to the beamline (because it jumps across the air gap through the chambers, minimizing the lengths of its field lines). This procedure is both precise in a statistical sense because the minimal multiple scattering leads to narrow residuals distributions, and is proven to be accurate because it exactly reproduces the geometry known from photogrammetry. It demonstrates that we will be able to very quickly align the endcaps with LHC beam-halo or collisions, in that the so-called "long-term" (or "100 pb^{-1}") goal of 200–300 μm accuracy is achieved in 9 minutes of LHC beam from the short September 2008 run.

1.2 Geometry and Coordinates of the Muon Endcap System

2 Track-based Method in Detail

3 Simulation Results

4 Real-Data Results

5 Preliminary Results for Layer Alignment

6 Concluding Remarks