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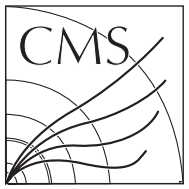

**The Compact Muon Solenoid Experiment**

**Conference Report**

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# Aligning the CMS Muon Endcap Detector with a System of Optical Sensors

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**Abstract**

The positions and orientations of one sixth of 468 large cathode strip chambers in the endcaps of the CMS muon detector are directly monitored by several hundred sensors including 2-D optical sensors with linear CCDs illuminated by cross-hair lasers. Position measurements obtained by photogrammetry and survey under field-off conditions show that chambers in the +Z endcap have been placed on the yoke disks with an average accuracy of $\approx 1$ mm in all 3 dimensions. We reconstruct absolute $Z_{CMS}$ positions and orientations of chambers at B=0T and B=4T using data from the optical alignment system. The measured position resolution and sensitivity to relative motion is about 60 $\mu m$. The precision for measuring chamber positions taking into account mechanical tolerances is $\approx 270 \mu m$. Comparing reconstruction of optical alignment data and photogrammetry measurements at B=0T indicates an accuracy of $\approx$ 680 $\mu m$ currently achieved with the hardware alignment system. Optical position measurements at B=4T show significant chamber displacements of up to 13 mm due to yoke disk deformation.

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***Abstract* – The positions and orientations of one sixth of 468 large cathode strip chambers in the endcaps of the CMS muon detector are directly monitored by several hundred sensors including 2-D optical sensors with linear CCDs illuminated by cross-hair lasers. Position measurements obtained by photogrammetry and survey under field-off conditions show that chambers in the +Z endcap have been placed on the yoke disks with an average accuracy of about ±1 mm in all 3 dimensions. We reconstruct absolute $Z_{CMS}$-positions and orientations of chambers at B=0T and B=4T using data from the optical alignment system. The measured position resolution and sensitivity to relative motion is ~60 μm. The precision for measuring chamber positions taking into account mechanical tolerances is ~270 μm. Comparing reconstruction of optical alignment data and photogrammetry measurements at B=0T indicates an accuracy of ~ 680 μm currently achieved with the hardware alignment system. Optical position measurements at B=4T show significant chamber displacements of up to 13 mm due to yoke disk deformation.**

## I. Introduction

The two muon endcaps [1] of the CMS experiment at the Large Hadron Collider at CERN comprise 468 large cathode strip chambers (CSCs) with sizes up to 3.4 m × 1.5 m. These chambers are mounted in 8 stations on large steel yoke disks [2]. The Muon Endcap (ME) hardware alignment system is designed to continuously monitor the actual absolute positions of the CSCs using optical and mechanical sensors with accuracies of ~0.15 mm in the Rφ-plane and ~1.0 mm in the Z-plane. This is necessary because switching the large solenoidal magnetic field of the CMS detector on and off causes the yoke steel and the CSCs mounted on it to undergo substantial motion and deformation on the order of a centimeter.

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The muon endcap alignment requirements, design of the alignment system, and first results on yoke disk deformation based on mechanical sensors during the first magnet test at full B=4T field in 2006 can be found elsewhere [3]. In these proceedings we focus on the alignment performance for the $Z_{CMS}$-coordinate in terms of resolution and precision achieved with a subset of the full optical sensor system shown in Fig.1. We also check the accuracy of the optical alignment measurements against independent measurements of the optical sensor and chamber positions at B=0T from an analysis of photogrammetry data supplied by the CERN survey group.

## II. Photogrammetry and Survey Results

The CERN survey group had performed dedicated surveys and photogrammetry (PG) measurements of all ME stations on the +Z side above ground during the magnet test period in summer 2006 [4]. In 2007 they completed survey and PG of the stations on the –Z side underground [5]. All surveys and PG measurements were performed with ME stations opened up and with magnetic field off.

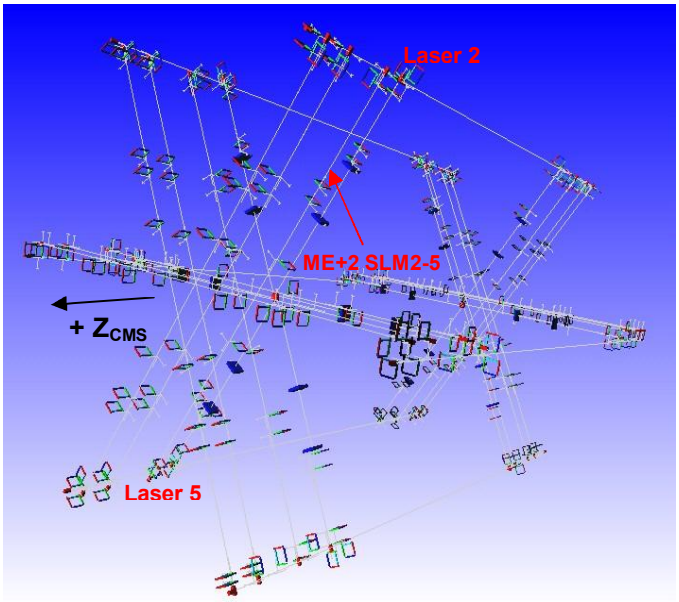


Fig. 1. Optical components of the entire CMS Muon Endcap Alignment system. The square objects represent digital optical alignment sensors (DCOPS) for monitoring three straight laser lines across each muon endcap station. The particular Straight Line Monitor (SLM) 2-5 for station ME+2 that is analyzed here is indicated.

Various circular reflective targets of ~1cm diameter were attached to Digital CCD Optical Position Sensors (DCOPS), Rφ-Z transfer plates, and CSC alignment pins that in turn locate the cathode planes inside the chambers. In addition, larger coded targets were affixed to the outside skins of the CSC main bodies. By photographing the targets and conducting surveys the target positions relative to each yoke disk center could be determined in all 3 coordinates X, Y, and Z with an uncertainty of $\delta X_{PG} = \delta Y_{PG} = \delta Z_{PG} = 300$ μm.

We compare the actual positions of chambers measured by PG with the nominal chamber positions in Figs. 2-4. The rms widths of the obtained distributions for the deviations $\Delta X = X_{PG} - X_{nominal}$, $\Delta Y = Y_{PG} - Y_{nominal}$, $\Delta Z = Z_{PG} - Z_{nominal}$

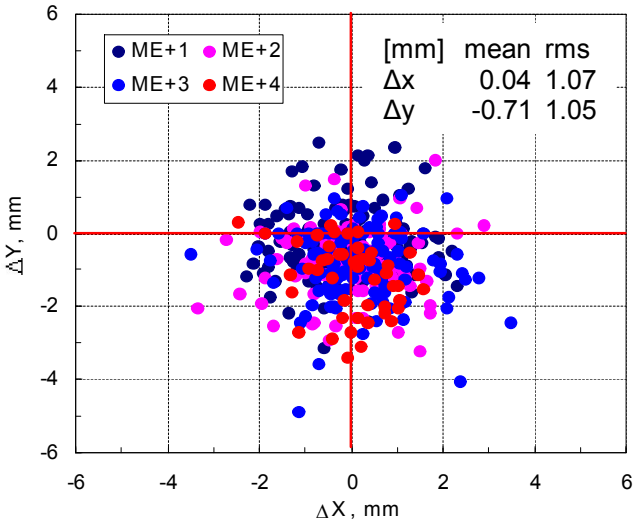


Fig. 2. Deviations $\Delta Y = Y_{PG} - Y_{nominal}$ vs. deviations $\Delta X = X_{PG} - X_{nominal}$ of the actual CSC alignment pin positions ($X_{PG}$, $Y_{PG}$) on the yoke disks as measured by photogrammetry (PG) from the nominal CSC positions ($X_{nominal}$, $Y_{nominal}$) for all CSCs in the +Z muon endcap. The PG resolution is estimated to be $\delta X_{PG} = \delta Y_{PG} = \pm 300$ μm [4].

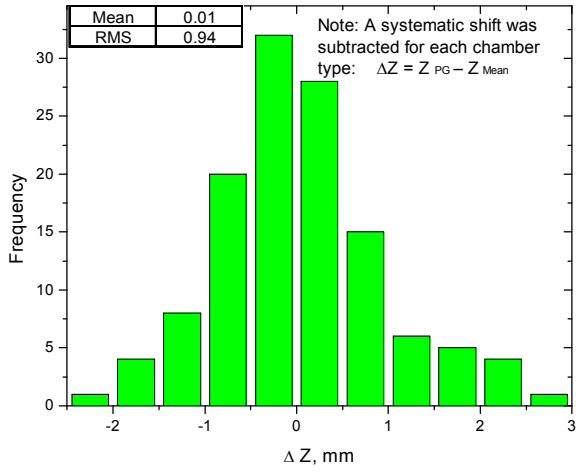


Fig. 3. Deviations $\Delta Z = Z_{PG} - Z_{nominal}$ of the actual positions $Z_{PG}$ of the CSC outer PCB skins as measured by photogrammetry (PG) from the nominal CSC skin positions $Z_{nominal}$ on the yoke disks for all CSCs in the +Z muon endcap. The PG resolution in Z is estimated at $\delta Z_{PG} = \pm 300$ μm [4].

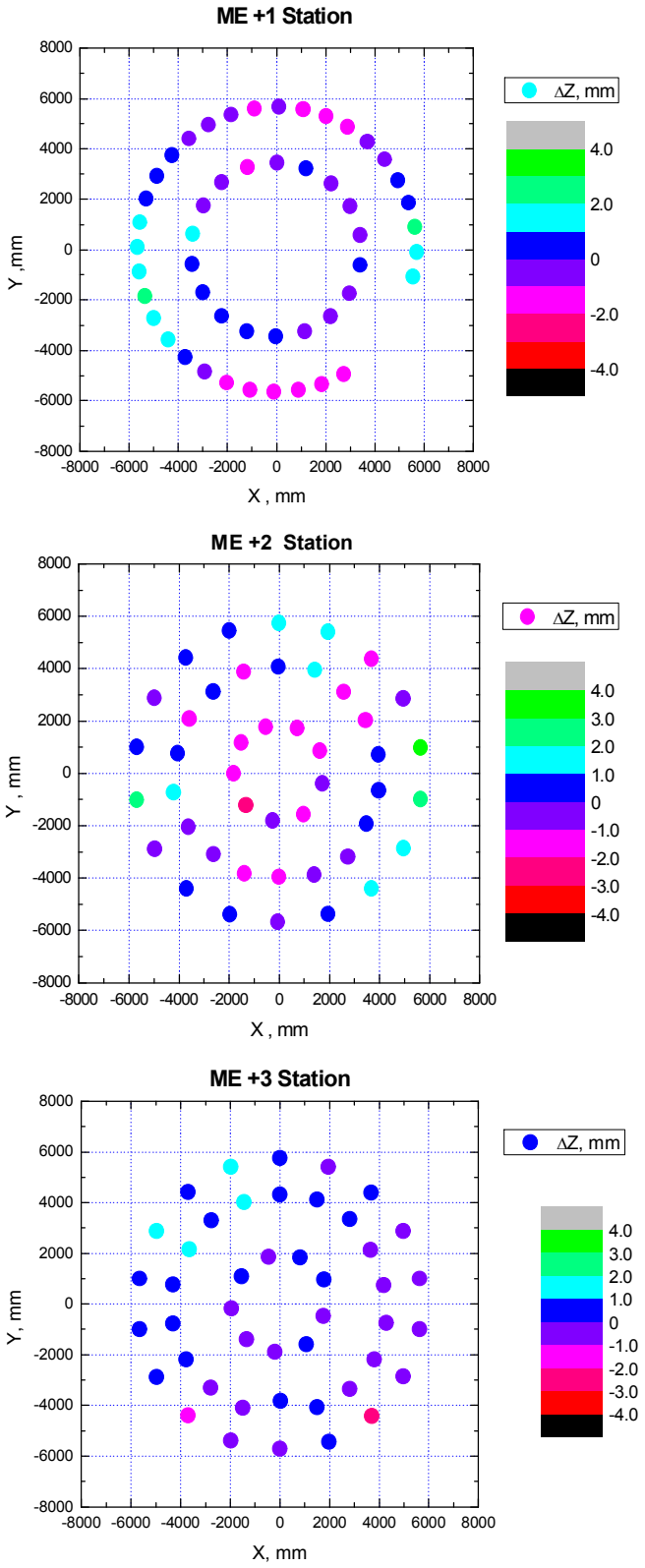


Fig. 4. Deviations $\Delta Z = Z_{PG} - Z_{nominal}$ of the actual positions $Z_{PG}$ of the CSCs measured by photogrammetry (PG) of coded targets on the outer PCB skins from the nominal CSC positions $Z_{nominal}$ as a function of their X,Y positions on the yoke disks. Note that the larger outer chambers in stations ME+2 and ME+3 each have two targets whereas the smaller inner chambers on those two stations and the ME+1 chambers have only one target each.

show that the chambers on the +Z endcap have been placed on the 15m diameter yoke disks with an average accuracy of about ± 1mm in all 3 dimensions.

Fig.2 also shows that the ME+ chambers exhibit an average systematic shift of about 1mm in the downward (-y) direction – presumably due to a gravitational sagging effect. In X direction the distribution is well centered. Plotting the deviations of the chamber Z coordinates from nominal as a function of the X,Y positions of the chambers on the disks in Fig.4 indicates small systematic Z-shifts at the top and bottom of the ME+1 station and at the center of the ME+2 station.

## III. RECONSTRUCTION OF CHAMBER POSITIONS IN $Z_{CMS}$

We reconstruct chamber positions in $Z_{CMS}$ based on an optical alignment event recorded for the ME+2 Straight Line Monitor (SLM) 2-5 on Nov 3, 2006 at B=0T. An SLM locates four CSCs with two DCOP sensors mounted on each CSC. Two more DCOP sensors are mounted on transfer plates located at the edge of the yoke disk. Fig. 5 shows sets of laser profiles for this event recorded by CCDs 2 and 4, which measure the $Z_{CMS}$ coordinate, for all 10 DCOP sensors in this SLM. The CCDs were illuminated separately by lasers at each end of the SLM.

The seven CCD laser profiles closest to each laser (red boxes in Fig. 5) have well-defined peaks and are used for reconstruction. To compensate for anticipated laser rotation due to yoke disk deformation at full magnetic field, the laser beams were intentionally pointed towards the chambers at B=0T instead of going straight across the SLM. This causes the beams to entirely or partially miss the three DCOP sensors at the respective far ends from the lasers. Consequently, the data from the CCDs at the far ends are bad and are not used in the reconstruction analysis. Widening of the laser beam profiles with increasing distance from a laser source due to beam divergence is clearly observed in the raw laser profiles.

We fit the beam profiles to a Gaussian on top of a quadratic to determine the beam centroid. We currently define the larger of the following two quantities as the error of this centroid: error on the Gaussian mean as returned by the fit or our estimate of 17 μm for the reproducibility of DCOPS positions based on mounting-dismounting tests on a lab bench. We simultaneously fit all laser hits to two lines and reconstruct the SLM (Fig. 6).

SLM fitting and all position reconstruction is done with the COCOA program [6] for optical alignment. The program employs non-linear least-squares fitting. Derivatives of positions and angles of optical and other objects with respect to sensor measurements are obtained with a numerical method and used to reconstruct the path of light rays through the system elements. Errors based on scatter in the input data and uncertainties of object positions due to mechanical tolerances are fully propagated to obtain the best estimate of the uncertainties on the positions and angles of all objects to

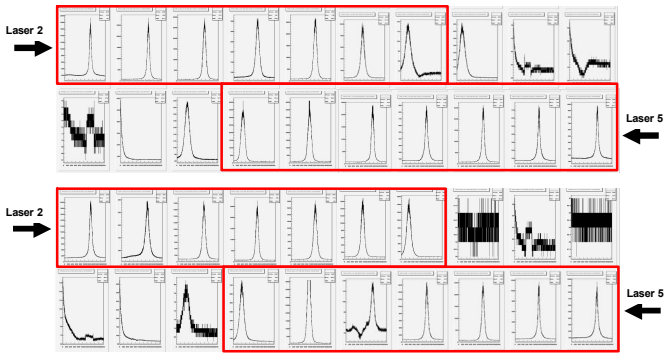


Fig. 5. Laser profiles measured with CCDs #2 (top two rows) and CCDs #4 (bottom two rows) of the 10 DCOPS's in SLM 2-5 on the ME+2 station. All CCDs were illuminated separately by lasers #2 and #5 located at the two ends of the SLM. This particular alignment event was recorded on Nov 3, 2006 at 00:01:48. Only good laser profiles indicated by the red boxes are used in the event reconstruction.

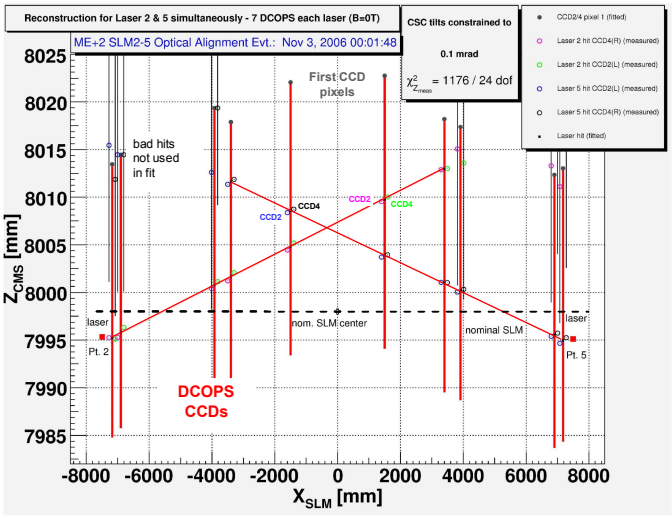


Fig. 6. Best line fits and reconstruction of the absolute $Z_{CMS}$-positions of the DCOPS CCDs 2 & 4 vs. the $X_{SLM}$–coordinate along SLM 2-5 in ME+2 for the B=0T alignment event shown in Fig.5. Hits on different CCDs and from different lasers are distinguished by different colors. Error bars on hits used in the fit are smaller than the marker symbols. Note that the lasers were intentionally tilted towards the chambers, i.e. towards higher $Z_{CMS}$, to compensate for anticipated disk bending and laser rotation at B = 4T.

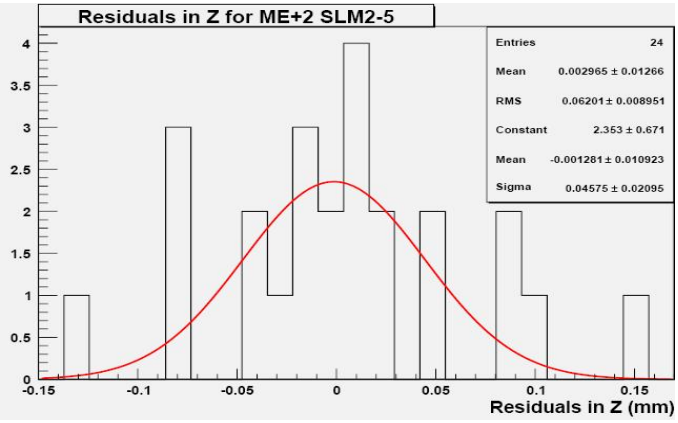


Fig. 7. Residuals of the line fits shown in Fig. 6 indicating a ~ 60 μm resolution (rms).

be aligned. The program reconstructs the absolute positions and orientations of known and unknown system objects by adjusting the reconstructed positions and orientations to minimize a $\chi^2$ variable.

We find that both laser lines can be accommodated simultaneously by shifting the CCDs to their reconstructed positions shown in Fig. 6. The overlap of the lines for the inner four DCOPS's on the inner two chambers is important for referencing one laser line relative to the other. It allows reconstruction of the entire SLM even though neither line traverses the entire length of the SLM.

Fig. 7 shows the residuals for both line fits together in a single plot. The distribution is well centered and its rms indicates that this optical system achieves a spatial resolution of about 60 μm. This resolution reflects the sensitivity of the system towards any relative changes in positions.

The precision for locating chambers in absolute $Z_{CMS}$ also must take into account mechanical tolerances of the alignment objects. Tab. 1 lists the relevant object tolerances used as input to the reconstruction model and the uncertainties of the same objects returned by the fitting procedure. The propagated uncertainties of ± 272 μm returned by the fit for the chambers reflect the experimental precision with which the chambers are currently located from real data. This result indicates that the precision is dominated by mechanical tolerances rather than by the scatter of the laser hits characterized by the resolution

## IV. RECONSTRUCTION VS. PHOTOGRAMMETRY AT B=0T

Using the geometric model of the DCOP sensors implemented in the SLM reconstruction we can relate the first pixel of each CCD to a precision dowel pin with which a DCOPS is located on a chamber or transfer plate. Using the reference chain: laser beam centroid → first CCD pixel → DCOPS dowel pin → chamber skin we can reconstruct the absolute cathode strip chamber positions in $Z_{CMS}$. The only additional external input needed for this reconstruction besides the laser data and the geometry model are the PG measurements of the $Z_{CMS}$ coordinates for the two transfer plates at the ends of the SLM. These are needed to set the global $Z_{CMS}$ position of the entire SLM.

Fig. 8 shows the result for the reconstructed absolute $Z_{CMS}$ positions (solid marker symbols) for DCOPS dowel pins and sensor frames, CSC centers and alignment pins, as well as the CSC angles relative to the $X_{CMS}$-$Y_{CMS}$ plane at B=0T. We also reconstruct special shimming that was introduced under the DCOP sensors – again in anticipation of disk bending at B=4T. The same figure also shows the corresponding results from photogrammetry measurements for DCOPS frames, CSC centers, and CSC alignment pins with open marker symbols. The error bars for the alignment pins are larger than the standard 300 μm errors quoted for PG measurements above because there was a technical problem with inserting

| All tolerances and uncertainties in μm | Input Tolerance specified in COCOA Reconstruction model | Uncertainties returned by fit | | |
|---|---|---|---|---|
| | | Ideal Case | B = 0 T | B = 4 T |
| **Transfer plate** | 300 | 0 (kept fixed) | 290 | 290 |
| **Laser** | 200 | 48 | 50 | 50 |
| **Reference DCOPS** | 20 | 20 | 20 | 20 |
| **Chamber DCOPS** | 100 | 95 | 95 | 95 |
| **Total tolerance by simply adding all in quadrature** | 388 | 108 | 310 | 310 |
| **Tolerance by adding in quad. & using 1/sqrt(2) for 2 DCOPS** | **371** | **95** | **306** | **306** |
| **CSC uncertainties actually returned by fit** | | **90** | **272** | **272** |

Tab. 1. Mechanical tolerances of Z-positions of physical alignment objects, which are used as inputs to the reconstruction, and propagated object uncertainties returned by the fit including the resulting precision of reconstructed CSC positions.

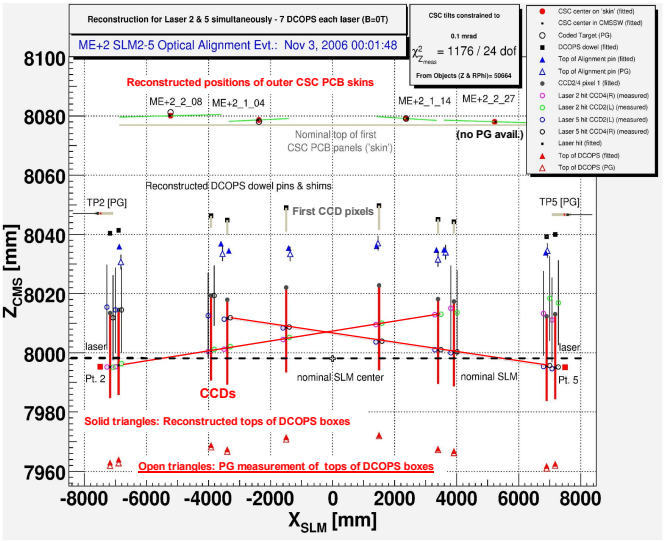


Fig. 8. Reconstruction at B = 0T of the absolute $Z_{CMS}$-positions for the four CSCs monitored by SLM 2-5 in ME+2, for the two alignment pins on each CSC, and for the 10 DCOP Sensors (solid markers). Also shown are the corresponding measurements from photogrammetry (open markers). The two independent position measurements are in good agreement.

those particular targets fully into the target holders. We estimate the error for these particular targets to be $\delta Z_{PG} = \pm 2$ mm. Note that the errors for photogrammetry measurement of the alignment pin targets in X and Y are unaffected by this issue.

Comparing our reconstruction results and the PG results shows close agreement between these two independent position measurements. This gives us confidence in the accuracy of the reconstruction results. To quantify the average accuracy of our reconstruction, we plot the discrepancies $\Delta Z = Z_{PG} - Z_{reconstructed}$ between PG and reconstruction results in Fig. 9. We take the 683 μm offset of the mean of the ΔZ distribution from zero as our current estimate for the average

accuracy of the reconstruction of the $Z_{CMS}$ coordinates from optical measurements. Note that there is a 405 μm intrinsic uncertainty on ΔZ obtained from adding PG error and reconstruction precision in quadrature.

## V. RECONSTRUCTION AT B=4T

We also reconstruct the absolute $Z_{CMS}$ positions of the DCOP sensors and CSCs in the same ME+2 SLM 2-5 for an event that was taken at full 4T solenoid field on Oct 31, 2006. The reconstruction result shown in Fig. 10 clearly indicates significant shifts for the chambers of up to 13 mm from their B=0T positions and a bending of the CSC plane (green lines) toward the central detector. The uncertainties on chamber positions returned by the fit for this field-on measurement are the same as for the field-off case as expected (see Tab.1).

Strong magnetic forces that pull the muon endcap yoke disks towards the central detector deform the disks. The magnitude of this effect that we measure with the optical system is consistent with our previous measurements using mechanical sensors [3]. The disk bending also rotates the lasers mounted on the disks via transfer plates, which causes the laser hits to move to the other end of the CCDs compared to the B=0T event in Fig. 8.

Since the detector is closed at B=4T, it is not possible to perform photogrammetry at full field. The CMS experiment will have to rely on this type of position reconstruction for aligning the CMS muon endcaps at full field with the hardware alignment system.

## VI. SUMMARY

Photogrammetry measurements show that chambers on the +Z muon endcap of CMS have been placed on the 15m diameter yoke disks with an average accuracy of about ± 1 mm in all 3 dimensions. We have successfully reconstructed absolute $Z_{CMS}$-positions and orientations of four cathode strip chambers using data from laser beams and optical sensors in one of the Straight Line Monitors of the hardware alignment system. The measured position resolution and sensitivity to relative motion is ~ 60 μm and the precision for chamber positions including mechanical tolerances is measured to be ~ 270 μm.

Reconstruction and photogrammetry measurements at B=0T agree well and indicate an accuracy on the order of 680 μm currently achieved by the hardware alignment system. This satisfies the alignment requirement of 1 mm or better for this coordinate. Comparing optical position measurements at B=4T with those at B=0T shows significant chamber displacements of up to 13 mm and rotations of laser beams due to the strong magnetic forces on the endcap yokes, which confirms our previous measurements with mechanical sensors.

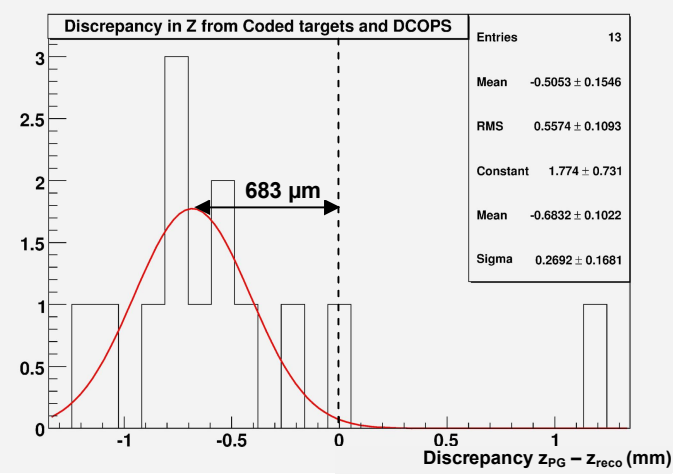


Fig. 9. Differences between absolute $Z_{CMS}$ positions of CSCs and DCOP Sensors measured independently by reconstruction and by photogrammetry at B=0T.

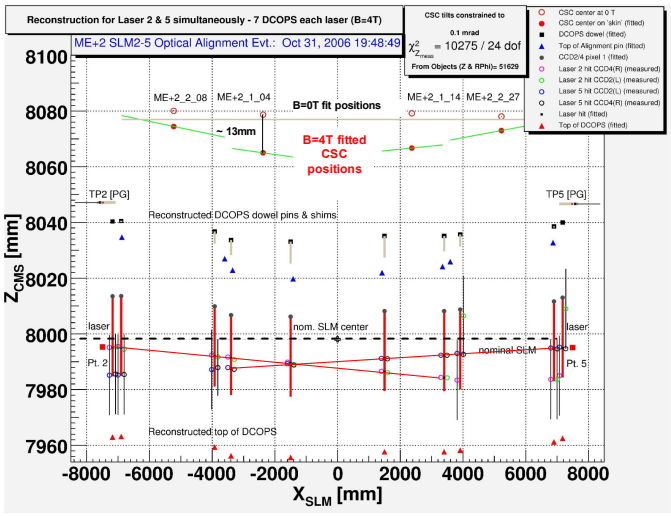


Fig. 10. Reconstruction at B = 4T of the absolute $Z_{CMS}$-positions for the four CSCs monitored by SLM 2-5 in ME+2, for the two alignment pins on each CSC, and for the 10 DCOP Sensors. Significant deviations of the CSC position from the B = 0T positions are observed.

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