PROCESSING MAGNET GEOMETRY MEASUREMENTS FOR BETTER CONTROL OF LHC APERTURE

E. Wildner, CERN, Geneva, Switzerland

N. Emelianenko, CERN, Geneva, Switzerland

Abstract

The Large Hadron Collider superconducting axes of the magnet are measured from both ends. These two redundant measurements are combined to get a reliable measurement result. When the two measurements are put together, we observe a "saw tooth" effect due to the fact that the two measurements are, in general, not identical. This is expected from the accuracy of the two measurements. However the effect observed, in the vertical plane, is considerably larger than expected. Effects of temperature gradients in the cold bore tube during measurements have been observed and we show that this effect is the most probable explanation for the observations of the large differences in the measurements between the two sides. This work proposes an algorithmic approach to filter this effect to improve measurement results. Magnets are positioned with an accuracy of 0.1 mm, and the error in positioning coming from measurement errors due to the temperature effects can be up to 0.3 mm. Our analysis shows that by applying this correction we can assure the best positioning of the magnets in the tunnel in the vertical plane. Analysis is done for the 15 m long main dipoles, for which the effect is most visible.

INTRODUCTION

The LHC magnet axes are measured from both ends of the magnet. The measurements are represented in a coordinate system defined by the 3-dimensional ideal beam trajectories in the magnet by doing a best fit of the measurement points (both sides, both apertures) on the ideal beam trajectories [1,2]. The xy-plane in this coordinate system is the magnet mean-plane and the magnet will be installed so that this plane corresponds to the machine plane. The mean plane calculation, resulting from correct interpretation of the value of the measured points and the best fit, is important for corrector magnet position and maximized beam aperture. Due to limitations in the precision of the measurement procedure we can always observe some "saw tooth" in the final measurement, after the two measurements have been joined [3]. However, we have observed that the measurement uncertainties are larger than specifications. By combined statistical and analytical analysis of measurement data, we separate the different kinds of measurement uncertainties to single out a specific effect contributing to the measurement uncertainty. This is the effect we correct algorithmically. Figure 1 shows a measurement with a large "saw tooth". The difference between measurement points from the two sides is up to one mm. To put this in context, magnets are positioned

within 0.1 mm precision. Figure 1 (bottom) displays both the data from industry, where the difference between consecutive measurement points less than 0.1 mm and the data from CERN, after cold test, where the difference is considerably larger. After the calculation of the magnet mean-plane, which defines the reference coordinate system, we observe that the position of the corrector magnet on the non connection side (right side) is -0.5 mm for the CERN measurement. In industry the corrector magnet is positioned at less than 0.1 mm from the axis for this magnet. This change can not be explained by changes in the shape of the magnet. If we plot the two CERN measurements, made from each side of the magnet, separately (Figure 1, top) we observe that the difference in the two measurements is larger that the precision of the measurement procedure given in [2]. The effect is considerably less important in industry than at CERN.
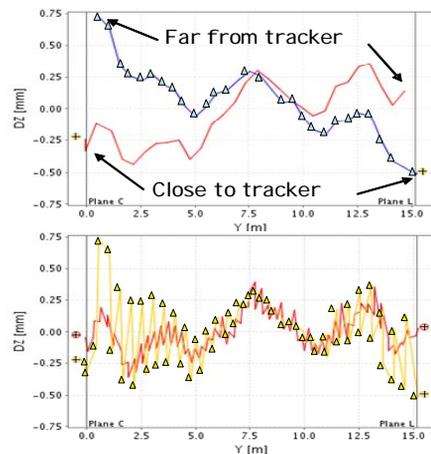

Figure 1: Top: the two vertical measurements, curve with markers from the non connection side. Bottom: the final result, points measured from both sides joined together, curve with markers represent the CERN measurements. The joined measurements in industry are also displayed, curve without markers. The crosses in circles at the ends of the measurements represent the position of the corrector magnets.

SOURCES OF UNCERTAINTIES

We define the "saw tooth" height as the difference between the two measurements of the cold bore tube centre at the same longitudinal position of the magnet. The saw tooth may be larger at one side of the magnet. The *difference* between the measurements has been fit to a 1st order polynomial. The coefficients of the 1st and 0th degree terms represent, respectively, the slope and shift between the two measurements.

The specifications for measurement accuracy and recommendations listed below are taken from [2].

1. Linkage of the laser tracker positions characterized by the bundle adjustment, *ba,* limited to 0.08 mm at one standard deviation.
2. Measurement error *me* of a point measured by the laser tracker is given by the manufacturer as 5 parts per million at one standard deviation.
3. The centring error *ce* of the measurement device (the mole) inside the cold bore tube is measured as 0.07 mm at one standard deviation.

The difference (3 standard deviations limit) between the two measurements from either side is then given by

$$dev = 3 \cdot \sqrt{ba^2 + (d1 \cdot me)^2 + (d2 \cdot me)^2 + 2 \cdot ce^2} \qquad (1)$$

where *d1* is the distance from a point to the laser tracker in position 1, measured from one side, and *d2* is the distance of the same point to the tracker in position 2, measured from the other side. This gives 0.47 mm.

In spite control of known errors, observations show that this limit is exceeded (see Figure 1). The larger difference between the measurements from the two sides is probably due to additional effects of different origin than from those mentioned in points 1 to 3, above.

The bundle error and the laser tracker distance errors (point 1 in the list above) have been analysed [3] by simulating errors using Monte Carlo methods. We have compared these results and the measured data for the *horizontal* plane. Table 1 shows two simulations, with and without estimated floor movements, two independent measurements on the same magnet (Firm a, and Firm b) and the measurement after cold test at CERN. We see that the saw tooth height, slope and shift for both the average value and the variation are between the steady and the floor movement simulations.

Table 1: Simulations and measurements, hor. plane.

	Height avg [mm]	Height std [mm]	Slope avg [rad]	Slope std [rad]	Shift avg [mm]	Shift std [mm]
Sim. (steady)	0.065	0.010	-3.0E-07	4.6E-06	0.040	0.040
Sim. (+floor)	0.125	0.095	-2.4E-07	4.0E-06	-0.015	0.160
Firm a	0.083	0.050	-9.5E-08	7.0E-06	0.016	0.110
Firm b	0.085	0.048	9.3E-07	8.4E-06	0.011	0.112
CERN	0.091	0.053	3.2E-06	6.9E-06	-0.016	0.112

In addition, the mole centring errors do not contribute to the "saw tooth" in the vertical plane contrary to the horizontal plane where the mole is turned and the error is seen as a difference between the two measurements. See Figure 2.
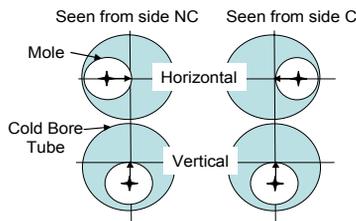

Figure 2: Mole centring errors in the two measurement planes: errors in the vertical plane not detectable.
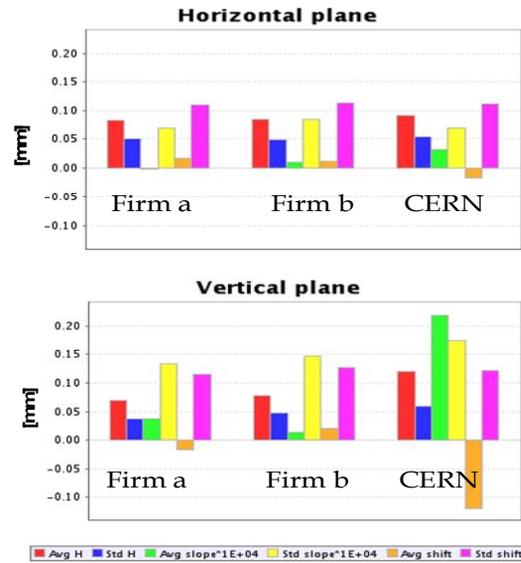
Figure 3: Saw tooth criteria, height (H) and slope applied to measurements in industry and at CERN. We see a significant change in the data for the CERN data, in the vertical plane only.

Reference [4] describes evidence of vertical deflection of the laser beam used in the measurements. The reason, according to these studies, is a convection zone at around 20 cm from the end of the tube. This convection zone only deflects the beam in the vertical direction. We use these results without entering into the physics of this phenomenon. See Figure 4.
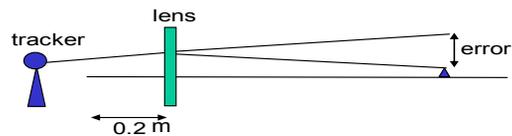

Figure 4: A convection zone at 0.2 m from the cold bore tube end acts as a lens and bends the laser beam used in the measurement. The convection zone is acting as a lens.

We make the following assumptions for this possible bias:
- There may be a parasitic deflection of the measurement beam at each entrance of the cold bore tube.
- The deflections at the two ends are not related in magnitude.
- There may be a convection cell at only one side
- We assume that the points close to the laser tracker are the most accurate points.

CORRECTION PROCEDURE

The procedure assumes that the best magnet mean-plane is calculated using the points not affected by the convection cell including one point measured outside the cold bore tube (Figure 5). Those points are close to the measurements device and have highest accuracy. This best fit defines the magnet mean-plane and the reference coordinate system. The deviated points, measured after

the convection cell, are then also best fit to a line. These lines, if rotated around the points where the perturbing deflection takes place, represent the measurement of the rest of the magnet. In our implementation, the rotation is calculated as the angle between the line defined by the best fit of the non affected points and the linear best fit of the deviated points. The rotation is indicated by arrows in Figure 5. This procedure is here demonstrated in two dimensions for simplicity, i.e. for one aperture). The complete procedure is three-dimensional, using measurements from both cold bore tubes of the two-bore magnet. The three dimensional analysis also gives the corrected angle around the longitudinal axis of the magnet, which indicates the corrected direction of the magnetic field.
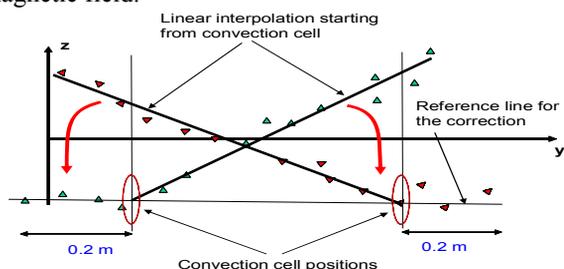

Figure 5: The correction procedure, see text.

RESULTS AND CONCLUSION

The goal of the procedure is to decrease the "saw tooth". To rule out cases where the "saw tooth" effect may come from other sources than the convection cell (like for example movements of the measurement tracker) we have also checked the preservation of the position of more accurately measured points outside the cold bore tube, therefore not affected by a possible convection cell. If these points are preserved between several independent corrected measurements with large and small saw tooth, we pretend that the correction procedure is a good approach to minimizing the errors. For 33 magnets with saw tooth height > 0.47 mm (arbitrarily taken as equal to the limit for re-measurement) we see the preservation of these accurate points in Table 2. The average of the difference is close to zero and the variation is also reduced. The negative bias of the original measurements is due to the fact that the convection cell generally deviates the measurement beam downwards.

Table 2: Correction applied to 33 magnets. C stands for connection side and NC for non connection side. Orig. stand for original measurement, corr. for corrected.

Difference CERN-industry for original and corrected measurements				
	Orig C	Orig NC	Corr C	Corr NC
Avg [mm]	-0.10	-0.17	*0.02*	*0.01*
Stdev [mm]	0.21	0.19	0.17	0.16

The magnet shape preservation between measurements in industry and measurements at CERN is also checked. The natural shape change is very small, therefore this comparison gives a good check of the procedure including correction of the mean plane. The magnet shape

is classified according to the maximum difference in the excursion of the cold bore tube centre with respect to the nominal centre position, along the axis [5]. Figure 6 shows this classification for 54 magnets measured after accurate mechanical adjustment of the shape to the shape in industry. This process is a delicate adjustment and may also introduce errors. The left bar shows the classification of industry measurements, the middle bar CERN, and the rightmost bar the corrected CERN measurements. Corrected data are closer to industry for most classes except the silver class but we have to take into account that the classification also includes the horizontal plane mechanical adjustments which are included in the CERN data. For the precious golden class the vertical plane limit is very tight (0.5 mm over the magnet length including the flexion from gravity) and gives the highest probability of a change in classification.
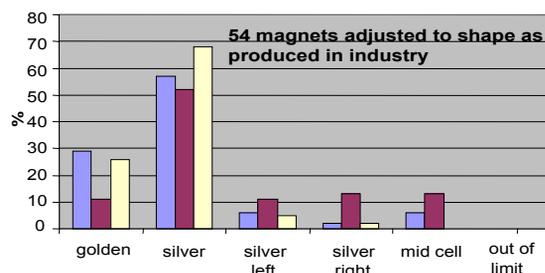

Figure 6: Comparison of magnets shape, industry, CERN and after the correction has been applied.

Final Result for LHC, Installed Magnets

For the complete set of 1232 magnets installed, we have, according to our analysis, 40 magnets with a mean plane of more than 0.2 mm below the machine plane and 176 magnets with mean planes between 0.1 and 0.2 mm below. The inclination around the axis of the magnet (affecting the field direction) has a zero mean value (equally probable to have the effect in either aperture) and the spread is 0.2 mrad rms.

REFERENCES

[1] D. Missiaen, M. Plusquellec, M. Dupont, Measuring The Mechanical Axis Of Lhc Dipoles Using A Laser Tracker. Installation Procedure. LHC-G-IP-0015 rev 1.0. CERN EDMS 334686. 2002-01-17.

[2] D. Missiaen, M. Dupont, P. Winkes, The Laser Tracker: a major tool for the metrology of the LHC, IWAA2004, CERN, Geneva, 4-7 October 2004

[3] G. Gubello, M. La China, W. Scandale, Instrumental Uncertainty In Measuring The Geometry Of The LHC Main Dipoles.LHC, EPAC04, 5-9 July 2004, Lucerne, Switzerland

[4] N. Smirnov et al., The methods of the LHC Magnets' Magnetic Axis Location Measurement, IWAA 1999.

[4] S. Fartoukh, Classification of the LHC main dipoles and installation strategy, 1st LHC Workshop, Chamonix XIII, Chamonix, France , 19 - 23 Jan 2004.

06 Instrumentation, Controls, Feedback & Operational Aspects

T17 Alignment and Survey