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Improving Magnet Aperture by Estimation of Errors due to the Influence of Temperature Gradients during Magnet Axis Measurements

E. Wildner, N. Emelianenko

Abstract

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Effects of temperature gradients in the cold bore tube of the magnet during measurements have been observed [6] and we show that this effect is the most probable explanation for our observations of the geometry measurements in the vertical plane. The aim of this work is to present an algorithmic approach to filter this effect and improve the measurement results. The effect is relatively small but for some magnets the displacement is up to -0.3 mm. The magnet positioning is controlled to 0.1 mm. Our analysis shows that by applying this correction we can insure the best positioning of the magnets (including the spool pieces) in the tunnel in the vertical plane.

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Improving magnet aperture by estimation of errors due to the influence of temperature gradients during magnet axis measurements

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Keywords: magnet geometry, magnet axis, magnet geometrical axis, saw tooth, aperture

Summary

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1. Introduction and observations

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 such 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 where the two measurements have been joined [3].

The evaluation of the limit of this unavoidable uncertainty is important to try to separate these measurement uncertainties from other error-sources. In Figure 1 we see an example of a measurement with a large "saw tooth". The difference between measurement points from the two sides is up to one mm. When we say this, we do not consider measurement points that are outliers, and we speak about cases where the entire measurement curves are displaced with respect to one another. In the figure we see the data from industry with a difference between a few consecutive measurement points less than 0.1 mm and the data from CERN, after cold test, where the difference is considerably larger. Due to the mean plane calculation using the best fit of the measurement points, we then observe that the position of the corrector magnet on the non connection 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. A change of the magnet shape cannot explain this observation of the position of the magnet ends. If we plot the two CERN measurements made from each side of the magnet separately (right plot in Figure 1) we clearly see that the difference in the two measurements is larger that the precision of the measurement procedure given in [2].

The "saw tooth" effect is present in both planes, the horizontal and the vertical, and has partly different origin. As we shall explain later, our algorithm is only valid for the vertical plane due to the origin of the error. The idea is valid for all our magnet measurements but a complete analysis is only made for the main dipole, due to the fact that the measurement effect is important in particular for long magnets (long tubes).

The effect is often referred to as the "saw tooth effect" and we will call it like this in the note.

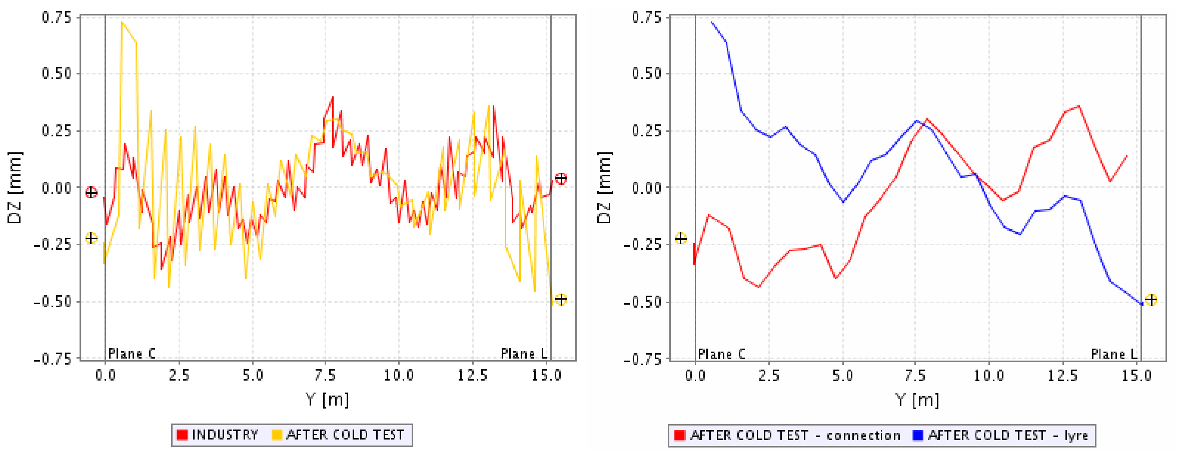


Figure 1 : The left plot shows the measurement of the main dipole 2248 in industry (red) and at CERN (yellow). In the plot to the right the measurements from the two sides of the measurement at CERN have been plotted separately.

A first glance of all final geometry measurements from industry and from CERN shows an interesting feature (see Figure 2)

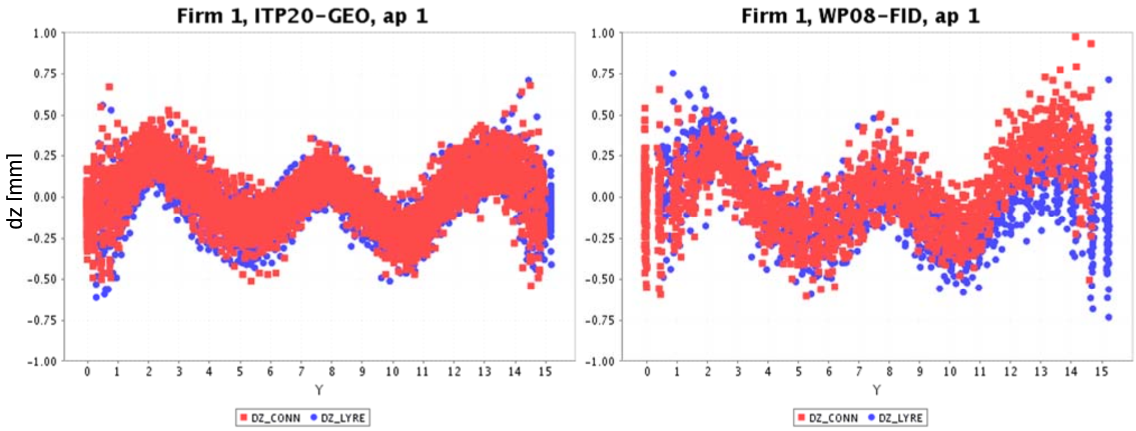


Figure 2 : Dipoles of firm 1 tested during last 5 months of 2005, aperture 1: in red we see the measurements from the connection side and in blue the measurements from the non-connection side. To the left we see data from industry and to the right we see data from CERN measurements. The horizontal axis length along the magnet [m] and the vertical axis is the deviation of he cold bore tube center w.r.t. the theoretical magnet center [mm].

The red points represent measurements from the connection side and the blue points from the non connection side. Looking at the final measurement in industry, Inspection and Test Plan 20, ITP20 [12] we cannot, from this plot, see any significant difference between points measured from either side. From the plot of the CERN measurements (corresponding to the Work-Package 8, WP08, measurement after the cold test) we see a clear tendency of a separation (horizontally in the plot) of the measurement values for measurements made from the two sides, in particular at the non connection side of the magnet (right part of the plot). In the plot we show firm 1 only, but the tendency is similar for all firms and for both apertures. There is, at the beginning of each measurement from either side, one point added, which is the measurement of the flange. This can be observed on the plot; there is no corresponding point from the measurement from the other side.

2. Sensitivity of the magnet classification to geometrical deviations

Aperture classes [4] are defined by applying limits for the allowed excursion of the Cold Bore Tube (CBT) centre from the nominal value. The limits are different in the horizontal and the vertical plane. The different limits of the tube centre excursion, that can be allowed, depend on where in the machine the magnet can be installed: a specific position in the lattice has its specific constraints. In this way magnets are classified in “Golden”, “Silver” and “Mid Cell” magnets according to if the CBT excursion is within the limits for these classes. “Golden” magnets have the best shapes and are needed in critical positions. “Golden” magnets can be placed (what geometry is concerned) in any position in the lattice.

These aperture classes defined for the magnets are very sensitive in the vertical plane. If, for example, we constrain the limit for the golden class by slightly more than 0.1 mm, all magnets classified as belonging to the “Golden” class, measured up to December 2005 (~ 500 magnets), degrade to “Silver”. We need a certain number of “Golden” magnets. In Figure 3 we show the fraction of golden magnets that degrade as a function of more constraining limitation of the “Golden” class limit for the horizontal plane and the vertical plane separately. On the abscissa we have the increase in tolerance constraint. We see that the fraction of degraded magnets reach 1 (all magnets) if the vertical limit is smaller by slightly more than 0.1 mm, keeping the horizontal limit for the class constant (blue curve). For the horizontal plane (red curve) we see that fewer magnets are at the limit of the class bound. In Figure 3 we also see that after 0.25 mm of more severe limitation, only applied to the horizontal plane, we still have half of the golden magnets. This demonstration aims at showing how small errors in the measurements, and in particular errors that change the mean plane and consequently the vertical position of the magnet in the tunnel, have to be carefully looked after.

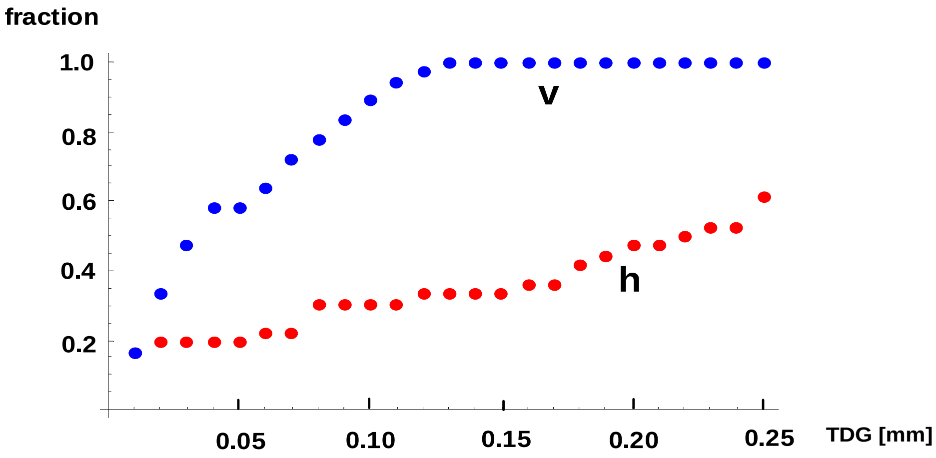


Figure 3 : Fraction of golden magnets that degrade versus Tolerance Decrease for the Golden class (TDG). We see that, for the vertical plane, if we constrain the class limit slightly more than 0.1 mm, all golden magnets degrade into the silver class, blue curve (the fraction of degraded magnets, golden to silver, reach 1, which means 100% of degraded magnets). For the horizontal plane the rate of degraded magnets when we constrain the tolerances is considerably slower.

The corrector magnet position follows the magnet position and if the mean plane is not optimally established, the corrector magnets will not have the best possible position. Corrector magnet position is not important for one single magnet, contrary to the individual main magnet position due to aperture consideration; however a bias in the position of all corrector magnets has an impact on the machine tune and the standard deviation should be kept within the specification (0.3 mm).

To put into context the need for vertical positioning accuracy for the dipole, we mention that positioning of 0.1 mm is significant in the Magnet Evaluation Board work.

3. Sources of uncertainties in the geometric 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 by the laser tracker given by the manufacturer to 5 ppm at one standard deviation.

3) Centring error *ce* of the measurement device (the mole) inside the CBT is measured as 0.07 mm at one standard deviation.

Therefore the 3 standard deviation difference between the two measurements from either side is 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, measuring from one side, and d2 is the distance of the same point to the laser tracker in position 2, measuring from the other side.

This gives a limit of 0.47 mm, at 3 standard deviations. In [2] it is stated that if the measurement exceeds this value it has to be redone.

From observing the measurements, we see that this limit is not respected, see for example the measurement in Figure 1. The explanation is, that even if the measurement is repeated and control of linkage error and calibration errors have been performed, the difference of the measurement from the two sides is larger than 0.47 mm probably due to additional effects of different origin not mentioned above and which we will discuss further.

We have made analysis of the measurement uncertainty for a single measurement, see annex 1. It confirms the specifications.

3.1 The mole centring

Both planes are concerned by the contributions from 1), 2), and 3). For the horizontal plane, the centring error 3) is cancelled out at the best fit of the measurements from the two sides, so the mean plane will not be affected by this error, but the saw tooth effect will still be present. However, for the vertical plane a total displacement of the magnet will be the result if the centring of the mole positioning is not correctly calibrated (0.07mm at one standard deviation). In Figure 4 we demonstrate this by showing possible mole positions when the measurement is made from the connection and the non connection side respectively. The top part of the figure shows the effect of a horizontal calibration (centring) error, the lower part shows the vertical plane. We will not detect any difference in the Cold Bore Tube (CBT) position between the measurements from either side in the vertical plane (we will see no saw tooth for this error). So in the vertical plane the mean plane position will contain the calibration error, with constrained aperture distance.

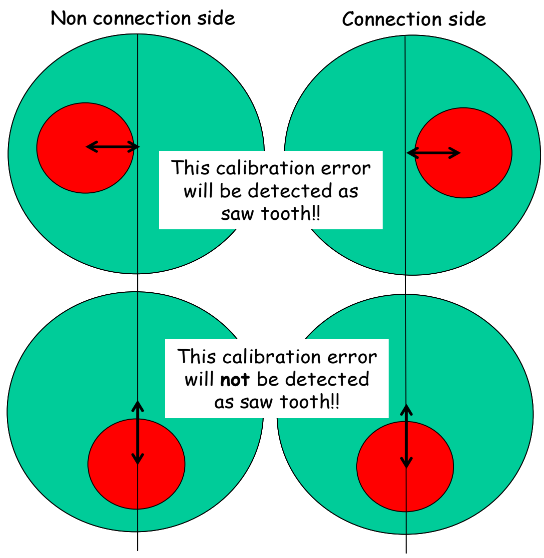


Figure 4 : Illustration of the contribution of a calibration (centring) error to the difference in CBT centre position values, measured from different sides, horizontal top, vertical bottom.

The conclusion for what follows is that we do not have any contribution to the “saw tooth” in the vertical plane from mole centring errors (it will only contribute to the net vertical displacement of the magnet, corresponding to the calibration error).

3.2 The bundle error

The two measurements, from either side, require moving the laser tracker and hence measuring several times the network of reference points to establish the reference frame. The resulting uncertainties in the reference frame were studied in [3].

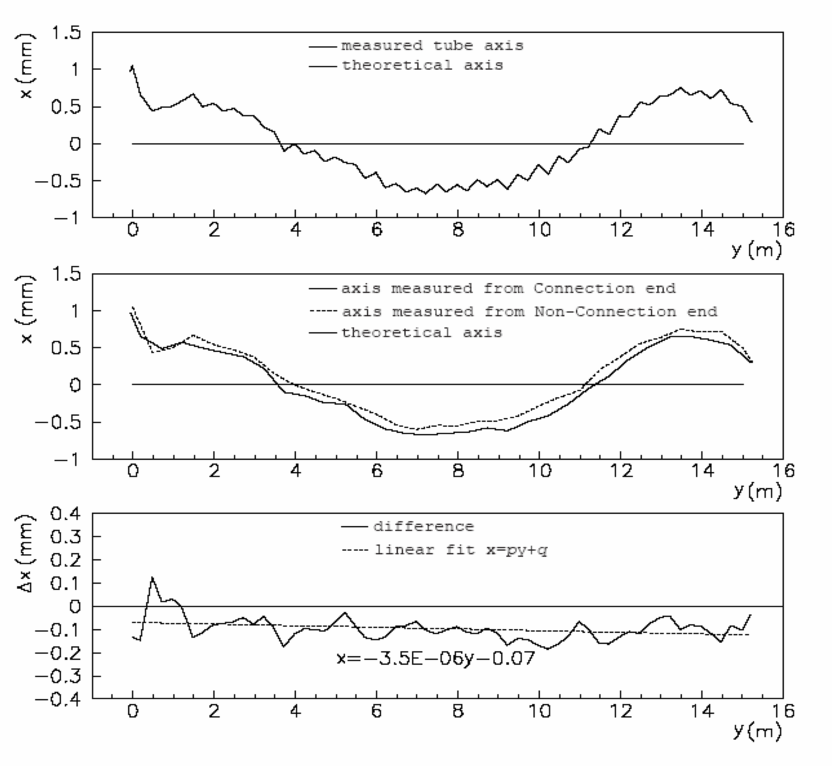


Figure 5 : Saw-tooth effect (top) due to the mismatching between measurements from opposite stations (middle) whose difference shows linear trend (bottom). Taken from [3].

The difference between the same dipole axis obtained from two different stations has been evaluated and best-fitted by a 1*st* order polynomial (see Figure 5, bottom). Then the coefficients of the 1*st* and 0*th* degree terms represent respectively the rotation p and shift q between the two station's reference systems. The statistical values of p and q in terms of average (Avg) and standard deviation (Std) from the simulation are reported in Table 1 along with the saw-tooth height h (see next chapter for definition) averaged over the length of each aperture. In the not steady simulation some effect of the sinking of the Leica device into the ground is taken into account [3]. This effect is included in our statistical evaluations of the measurements (the effect, if present, is measured together with all other effects).

Table 1 : Results from the numerical simulation after 100 iterations. Roto-translation: *p* is slope, *q* is shift, *h* is saw tooth height (will be defined below). Values are in rad for *p* and in mm for *q* and *h*. The table is taken from [3].

	Steady		Not steady	
	Avg	Std	Avg	Std
p [rad]	-2.98E-07	4.59E–06	-2.36E-07	3.79E-06
q [mm]	0.004	0.04	-0.015	0.16
h [mm]	0.065	0.01	0.125	0.095

We will need to compare these simulated errors, aiming at estimating the intrinsic measurement error, with what we find from a statistical analysis of the collected measurement data. We will show that an additional measurement effect is present and needs to be understood.

4. The saw tooth, definition and observations

4.1 Definition

We measure the importance of the "saw tooth" feature by the saw tooth height. It is defined by, for each measured point from one side, finding the corresponding value (same abscissa) for the measurement from the other side by linear interpolation. See Figure 6.

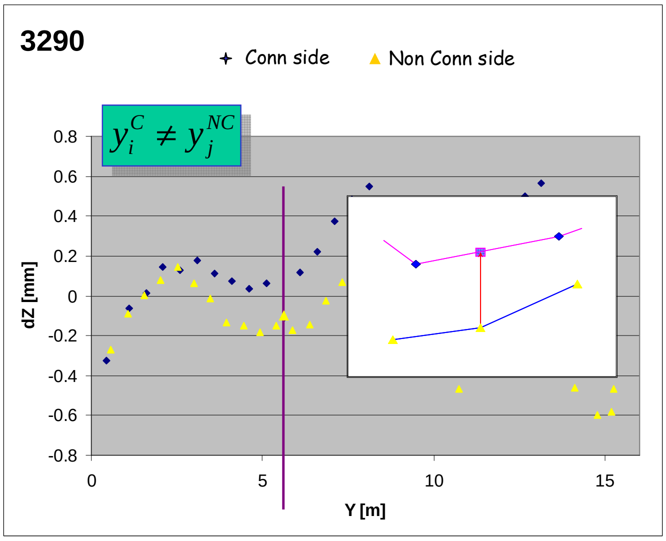


Figure 6 : The saw tooth height is calculated from the distance, red arrow, between the two measurements at a certain value along the length of the magnet (y coordinate). Linear interpolation is used.

The estimated saw tooth effect over the whole measurement is calculated from

$$\bar{h} = \frac{S_{diff}}{y_{\max} - y_{\min}} \qquad (2)$$

where S_{diff} is the sum area between the two curves. See Figure 7. Since the points are evenly spread this differs from simple average by max 0.02 mm. If the connection side curve lies below the non connection side curve, the area is negative. We can sum up with sign, "signed" or without sign, "absolute". The signed saw tooth gives an indication of the crossover point of the two curves, which gives us information on which measurement is most affected (see below for explanation of the direction of the deflection of the measurement curves).

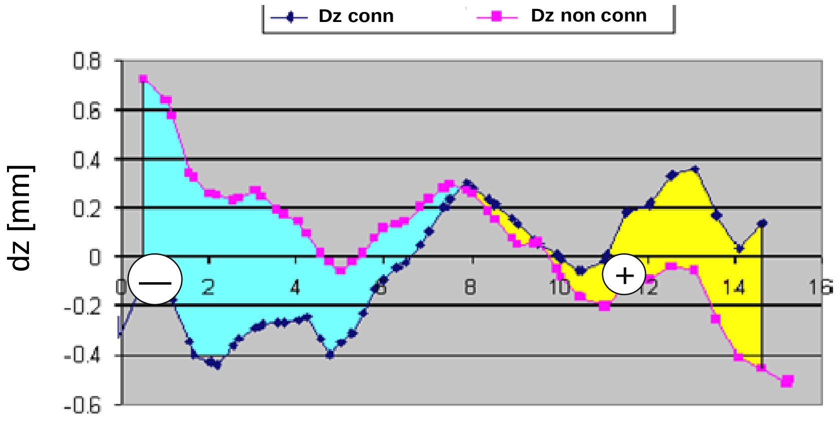


Figure 7 : The average saw tooth height is calculated as the area between the measurement curves (connection and non connection), with sign, "signed" or without, "absolute".

4.2 Observations in the vertical plane

With these definitions of the saw tooth value we look at the measured magnets. Figure 8 shows that the saw tooth is larger from February 2005 for the CERN measurements. We also see for the CERN measurements a larger contribution at the non connection side since the signed saw tooth value is positive. If we refer to Figure 7 we see that for a large positive saw tooth we have measurements showing a large difference at the non connection side with the measurements from the connection side deviating more in the positive direction than the measurements from the non connection side. This seems also to be enhanced from February 2005.

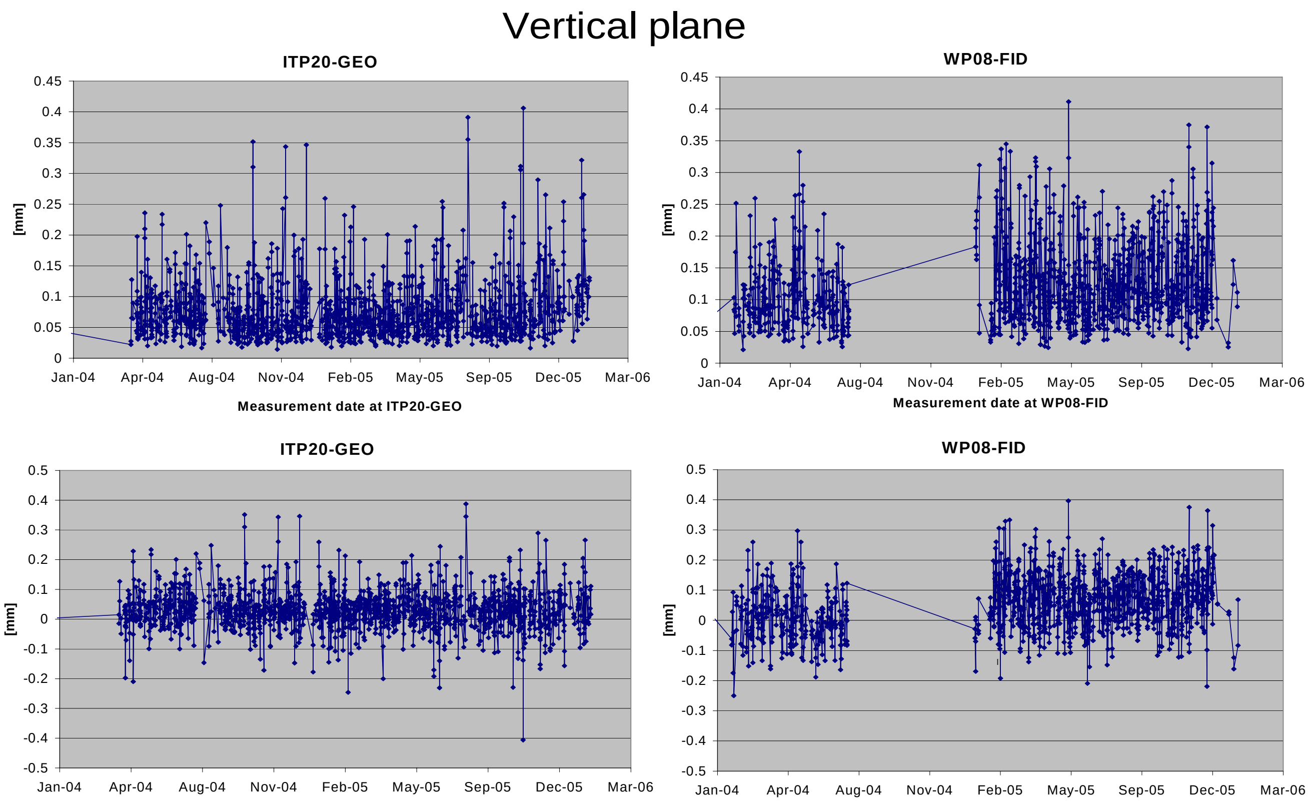
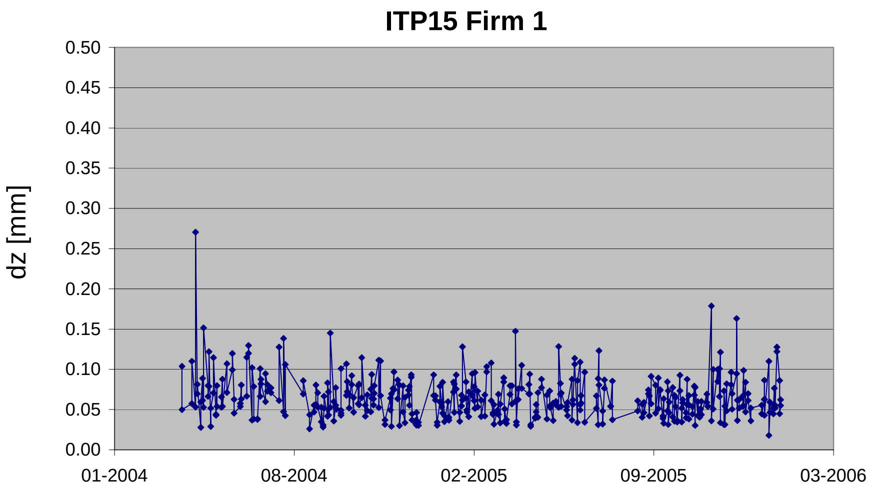


Figure 8 : The average saw tooth height applied to the measured dipoles up to Mars 2005, the average saw tooth, "absolute", in the top of the figure and the average saw tooth with sign in the bottom, industry (ITP20) left and CERN (WP08) right

In Figure 9 we see the saw tooth "absolute" height of the ITP15 measurement (measurement made in industry before closure of the magnet) for firm 1 and firm 2. Firm 3 data are similar to firm 1 data. We see that for firm 1 that saw tooth behaviour is less important. All industrial measurements seem better than at CERN. The correct mean plane calculation using the measurements from both sides in production is essential for the positioning of the spool piece corrector. At later measurements we have no access (end cover closed) and we have to indirectly estimate the position by comparing the measurements at ITP15 and ITP20 with the measurements made with closed end-cover. The ITP15 and ITP20 measurements are normally very similar and the spool piece position at ITP20 is the same as for ITP15 (ITP15 measurements are used to quantify the spool piece position). If the saw tooth is too large in either measurement step we will not be able to calculate correctly the position of the spool piece relative to the mean plane (the theoretical machine plane) since the mean plane is calculated as a best fit of the measurement points.



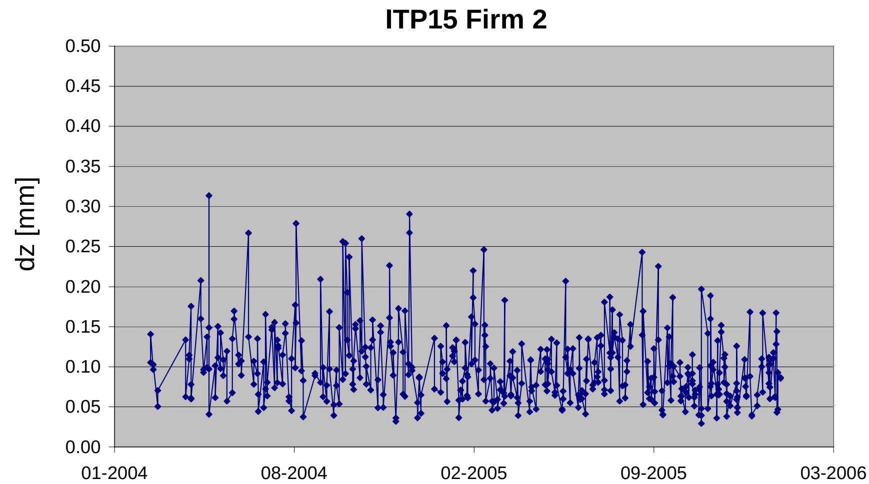


Figure 9 : ITP15 is the measurement done immediately before the positioning of the spool piece corrector mounting. We see the saw tooth height calculated from measurements from firm 1 and 2. Firm 3 data are similar to firm 1 data.

The saw tooth height at CERN seems to change with the measurement date. This, may be related to the cold mass temperature. It may also be related to production speed up since magnets are measured closely after cold test. In Figure 10 we see the evolution of the saw tooth height from May 2002 to March 2006.

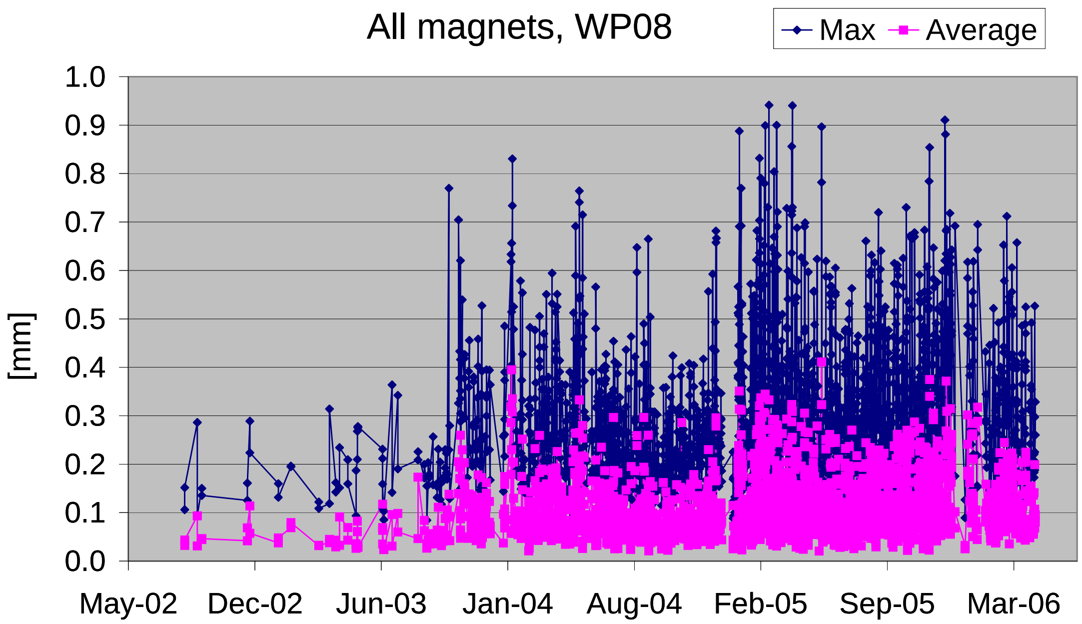


Figure 10 : Saw tooth "absolute" height and the maximum height for the measurement plotted against measurement date, all magnets, for the measurements after cold test. Vertical plane.

4.3 Observations in the horizontal plane for comparison

We have checked the statistics of the saw tooth in the horizontal plane and compared it to the study documented in reference [3]. We see in Table 2 that in the horizontal plane the measurement data are somewhere in between steady and non steady simulations. The shift (q) of the measurement is the 0^{th} coefficient of the linear fit of the difference between the two measurement curves. The slope (p) is the first coefficient and corresponds to the rotation between the two measurements station´s reference systems. In the horizontal plane we also have the calibration (mole centring) included in the real measurement data. No saw tooth contribution from mole centring can be detected in the vertical plane since it has the same sign when the measurement mole changes side. For the horizontal plane the sign changes and the contribution from calibration is visible as two times the calibration error. The conclusion is that the simulation and the real data are close and that the inherent effects from the measurement procedure and from the instrumentation (as simulated) are larger than what is measured, for the horizontal plane.

Monte Carlo simulations for the vertical plane are very close to those for the horizontal plane and do not strongly depend on the network points configuration [3].

Table 2 : Simulated and measured saw tooth data at the different production stages. Horizontal plane.

STEP	Height avg [mm]	Height std [mm]	Slope avg [mm]	Slope std [mm]	Shift avg [mm]	Shift std [mm]
Simulation (steady)	0.065	0.010	-3.0E-07	4.6E-06	0.040	0.040
Simulation (non steady)	0.125	0.095	-2.4E-07	4.0E-06	-0.015	0.160
Firm, ITP15	0.083	0.050	-9.5E-08	7.0E-06	0.016	0.110
Firm, ITP20	0.085	0.048	9.3E-07	8.4E-06	0.011	0.112
CERN, WP08	0.091	0.053	3.2E-06	6.9E-06	-0.016	0.112

In Figure 11 we see a comparison between measurements in the vertical and the horizontal planes for the difference production stages ITP15, ITP20 and WP08. We see that we have a significant increase in the average values of the slope and the shift for the measurements at CERN for the vertical plane. We see that for the horizontal plane the measurements are very similar for the different production stages ITP15, ITP20 and WP08 which we consider an indication that the measurement method applied is consistent. It has been argued that what we see in the vertical plane could be due to movements of different kinds of the instrument between the two measurements. The stability in the horizontal plane is a counter indication of this idea.

Laser tracker errors of 5 ppm cannot explain the roto-translation between the two measurement curves in the vertical plane.

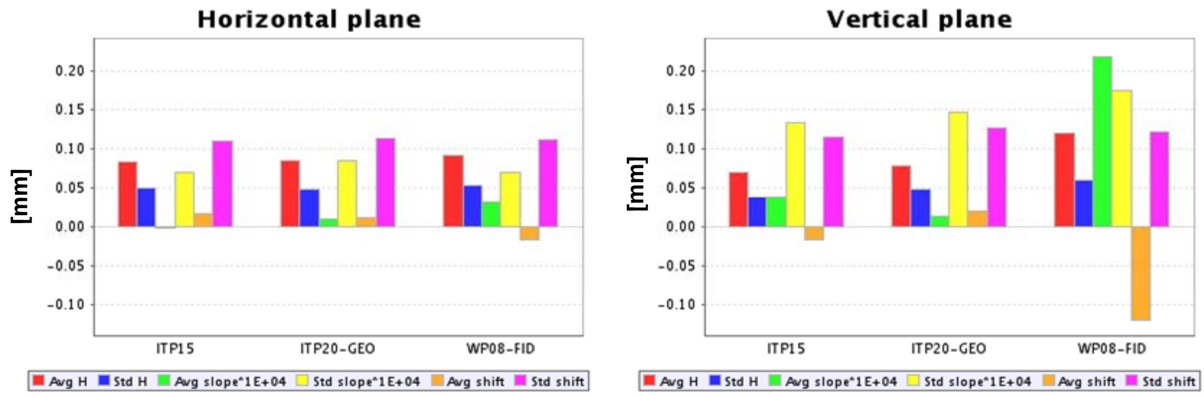


Figure 11 : Some saw tooth criteria applied to measurements in industry and at CERN. We see a significant change in the data for the CERN measurements in the vertical plane only.

In Table 3 we see the amount of magnets falling outside the criterion for re-measurement (max saw tooth > 0.47) and we also show the number of magnets falling outside a few other increasingly constraining bounds. It is important to say here that a re-measurement very seldom gives an improvement of the result, which has led to a relaxation of the criterion for re-measurement [1].

Table 3 : Number of magnets with large saw tooth (μ - the average saw tooth height, "absolute", along the aperture, σ – its standard deviation)

Industry			CERN		
Criterion	Amount	Percentage	Criterion	Amount	Percentage
$\mu + 1\sigma > 0.47$	12	0.2	$\mu + 1\sigma > 0.47$	32	1.3
$\mu + 2\sigma > 0.47$	47	1.0	$\mu + 2\sigma > 0.47$	209	8.3
$\mu + 3\sigma > 0.47$	144	3.0	$\mu + 3\sigma > 0.47$	474	18.9
Max > 0.47	83	**1.7**	Max > 0.47	291	**11.6**

Figure 12 shows saw tooth height, slope and shift over all production stages, where we have distinguished the different measurements at WP08 with the idea to see if the effect disappears with the warm-up of the magnet. Apart the very sparsely populated step WP08D, we cannot detect a significant improvement of the measurement with the warm-up of the magnet except for the average slope, which for all firms get smaller by 0.1 mm.

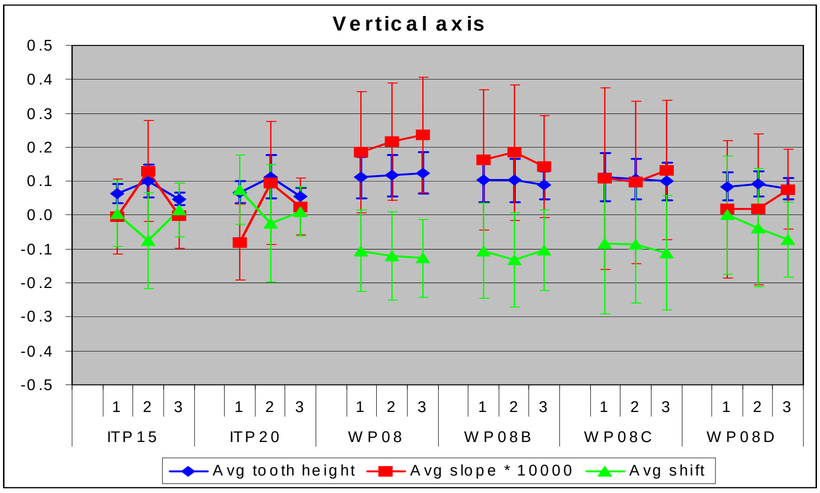


Figure 12 : Saw tooth height, slope and shift over all production stages, distinguishing steps made at work package 8 at CERN. The idea is to see if there is a trend with the warm up of the magnet. At WP08-D the population is very small. Values in mm.

4.4 A systematic thermal effect

References [6],[7] and [8] describe the evidence of a vertical deflection of the laser beam used in the measurement system. The reason, according to these studies, is a convection zone at some 20 cm from the end of the tube. This convection cell only deflects the beam in the vertical direction. We use these results in our study without entering into the physics of this phenomenon. The phenomenon appears confirmed by our geometry analysis.

5. Corrective algorithm

We have developed a measurement correction mechanism based on the of a convection cell at the ends of the tubes. We have made a sensitivity analysis of the distance of this convection cell from the end of the magnet. We also look at the linearity of the difference between the two measurements which is an indication that only one significant convection cell perturbs the measurement and creates the effect of a mirage. The behaviour is shown in Figure 13.

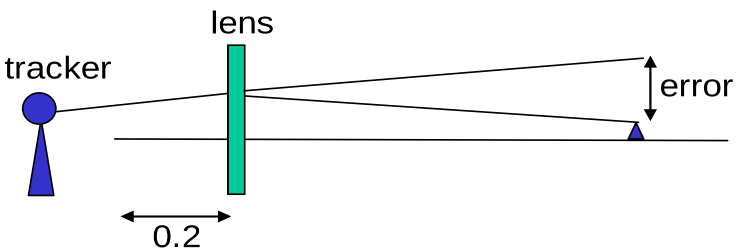


Figure 13 : A convection cell at 0.2 m from the CBT end acts as a lens and bends the laser tracker beam used in the measurement. The convection cell is acting as a lens (the green rectangle in the figure)

The measurements cannot be improved by re-measurement for most cases, it is a systematic effect so we assume that the effect originates from the described phenomenon. This hypothesis is tested. If we can accept this hypothesis, that the convection cell deflects the beam at the beam the cold bore tube ends, as proposed in [6], we can improve the measurement result significantly.

5.1 Basic assumptions and checks for the correction procedure

In Figure 14 we show a MB dipole measurement where we have separated the two measurements. We have also marked the points close to and far from the Leica laser tracker. In the figure we also see the position of the spool piece corrector magnets, which in industry are monted at zero nominal position within 0.1 mm rms.

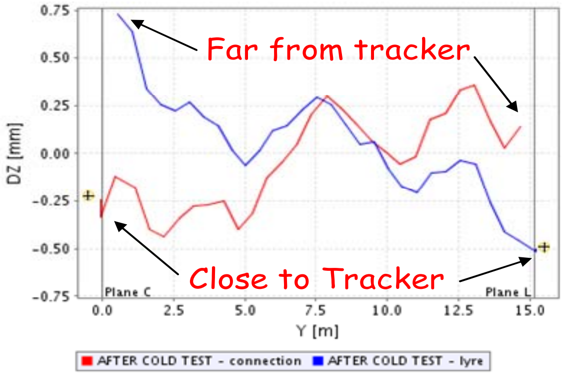


Figure 14 : The two measurements of a dipole separated. Points close/far to/from have been marked.

The basic assumptions for the algorithmic approach are the following:

- Points close to the laser tracker are more correct than points far from the tracker.
- We assume that there is deflection of the measurement beam at one point at the entrance of the CBT [6].
- The deflections at the two ends are not related.
- No change in the reference system is made at the correction, which means that all installation parameters used by TS/SU are unchanged after the correction.
- We assume that the points close to the tracker are the most accurate points. So we superpose the two measurements on those points (those points have very high weight, the corresponding points from the other measurement have the lowest accuracy)
- It may happen that there is a convection cell at only one side

There are points measured outside the CBT hence not affected by the convection cell in the CBT (end cover position). Those points are valuable checkpoints.

Our criteria of success is that, after the CERN measurements, we can recover the shape from industry and find the end cover positions at the same place as in industry, within measurement errors and shape changes. The vertical shape may indeed be changed by errors in the adjustment of the central support and this makes the check more difficult.

5.2 Correction procedure

The correction scheme is based on the assumption that the laser beam, used for the measurement, gets a significant deflection only at one point situated at a small distance from the cold bore tube ends [6]. Under this assumption we can say that measurements should overlap (within some norm) and that the good points are the points close to the tracker: those points should be kept without correction. The points affected by the lens effect of the convection cell are interpolated linearly (similarity to mean plane calculation). This interpolation line of measurement points should overlap with interpolated points at the ends. Linear interpolation is close to the method used by TS-SU to calculate the magnet mean plane.

In Figure 15 we see the two measurements from the two sides, the two convections cells at 0.2 m from the ends of the CBT (sometimes there is only one, at one side) and the linear interpolations of the two measurements. We see also the "reference line" which is a linear interpolation of the points not affected by the deviation of the beam, both sides. The idea is to say that the interpolated lines of the two measurements should coincide with the reference line. The good accuracy of the measurements of these points is important for the mean plane estimation and achievable with good care during the measurement. The points we take into account to establish the reference line contain the measurement of the flange centre which is a measurement made with a more accurate device, outside the CBT.

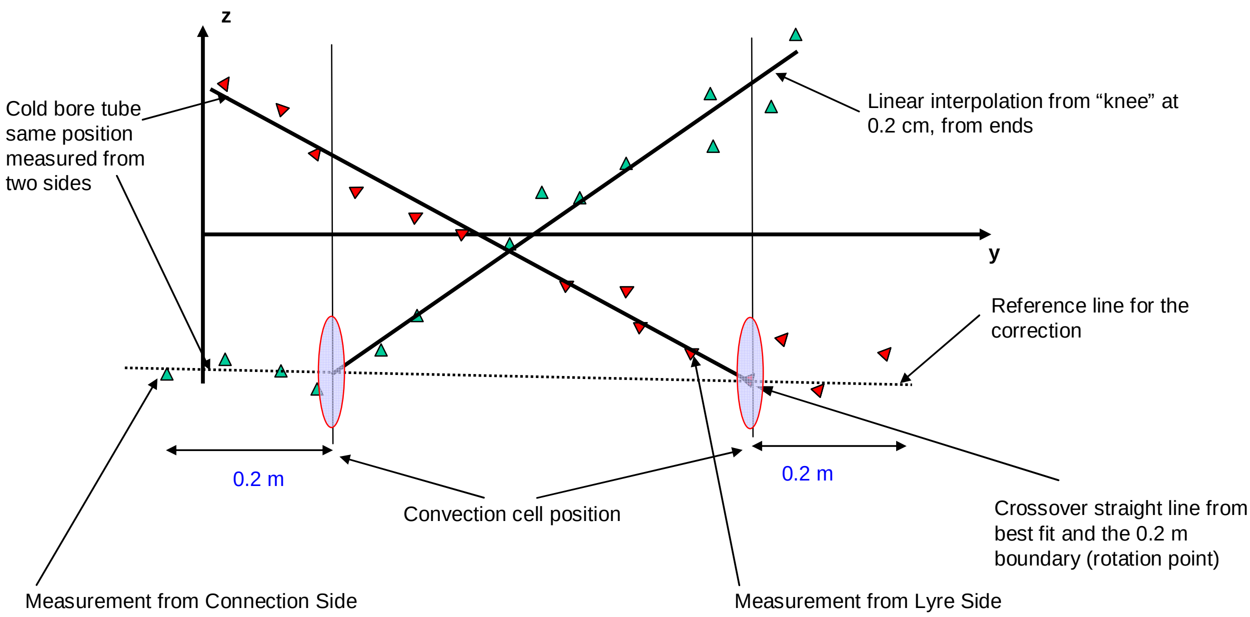


Figure 15 : Illustration of the correction method, see text.

Equation (3) below describes how the points are superposed for the measurement from the connection side:

$$z_{corr,i} = z_i - (z_{connectionfit}(y_i) - z_{ref}(y_i)) \qquad (3)$$

where the variables are described in Figure 16. The measured point z_i should be corrected by the difference between the two interpolated curves at the corresponding longitudinal coordinate

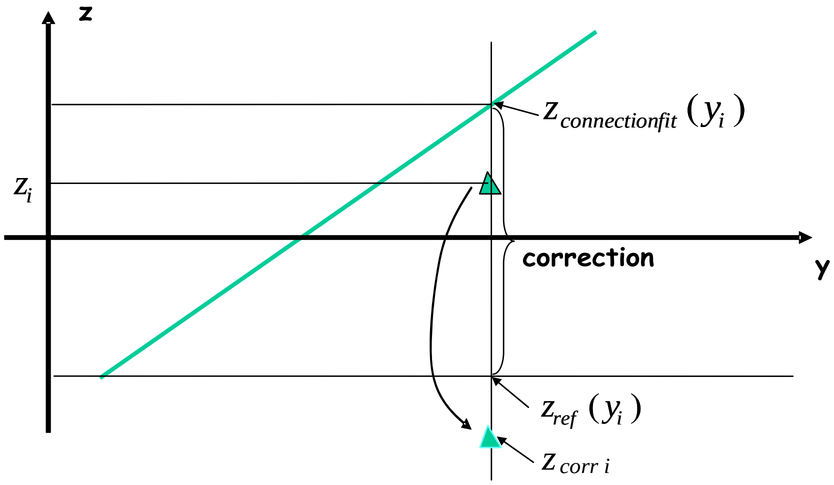


Figure 16 : Correction of measurements point for the measurement from the connection side.

After correction of each tube we can calculate a new mean plane (3 dimensions, both tubes) to evaluate the "misplacement" of the magnet due to the saw tooth effect and make statistics. This calculation can also be used to evaluate the best correcting shifts for the magnet installation.

5.3 Worked out examples.

First example:

1. The measurements

The magnet 2248 was measured in industry, ITP20 and at CERN after cold test. The measurement is shown in Figure 17.

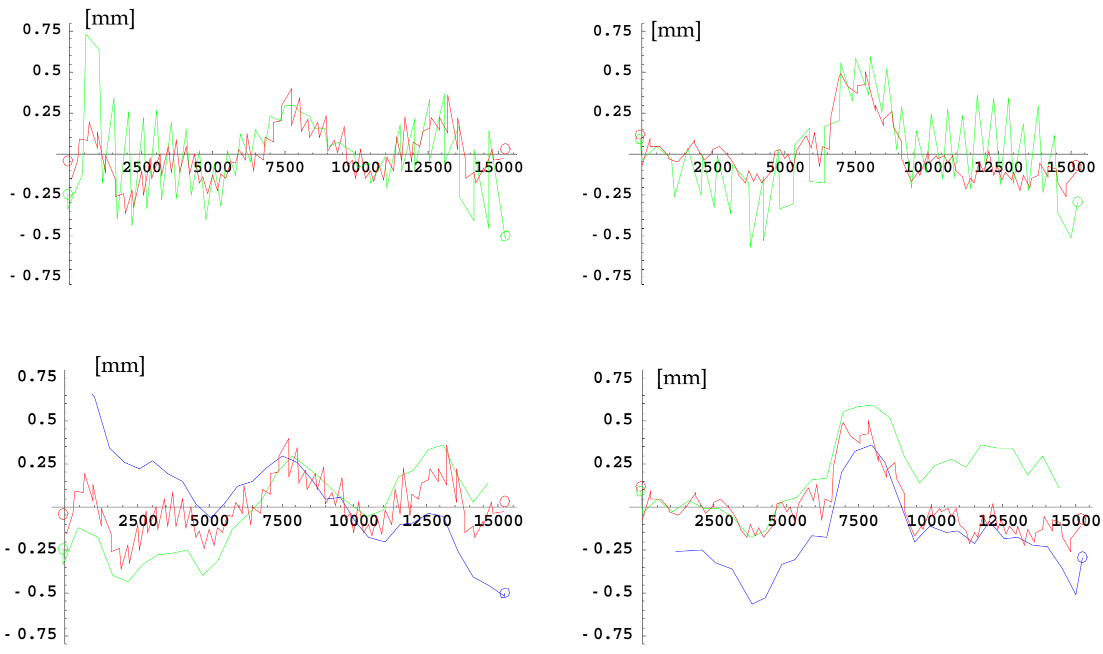


Figure 17 : Magnet 2248: Top: Original measurements of the vertical shape along the magnet the 18th of October 2005 industry (ITP20), red, and the 11th of Novemember 2005 at CERN, green. The magnet is statistically adjusted to ITP20 shape. We see the position of the flanges (the first point in each measurement) which are points with higher measurement accuracy. Bottom: the two partial measurements at CERN are shown separately, the measurement from the connection side is green and from the non connection side blue. Red is industry measurement.

2. The correction

The common reference line for the two measurements from either side is calculated by a linear interpolation of the points for each measurement excluding the first 20 cm for each measurement. Then we construct the reference line by linearly fitting the points we believe not affected by the convection cell including the flange measurements. See Figure 18.

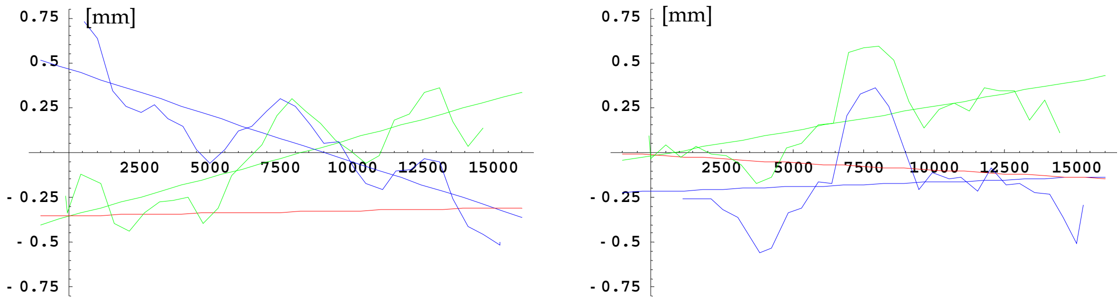


Figure 18 : The two measurements of the vertical shape along the magnet linearly interpolated, blue and green, and the reference line (interpolated not affected measurement points) in red.

Then we superpose the reference line (the good points close to the tracker, points not affected by the presence of the convection cells), and the two measurements, where we have excluded the points before the convection cells. The result is shown in Figure 19, top part. We see the good correspondence between the two partial measurements and the saw tooth is very small. We also see that the mean plane of the magnet is not correct, according to our assumptions. In the lower part of the Figure 19 we show the measurement of this magnet with the mean plane recalculated (shifted and rotated) and we have, after the mean plane correction, superimposed the measurement in industry. It is very important to have “good points” not affected by the convection cell to estimate the magnet mean plane.

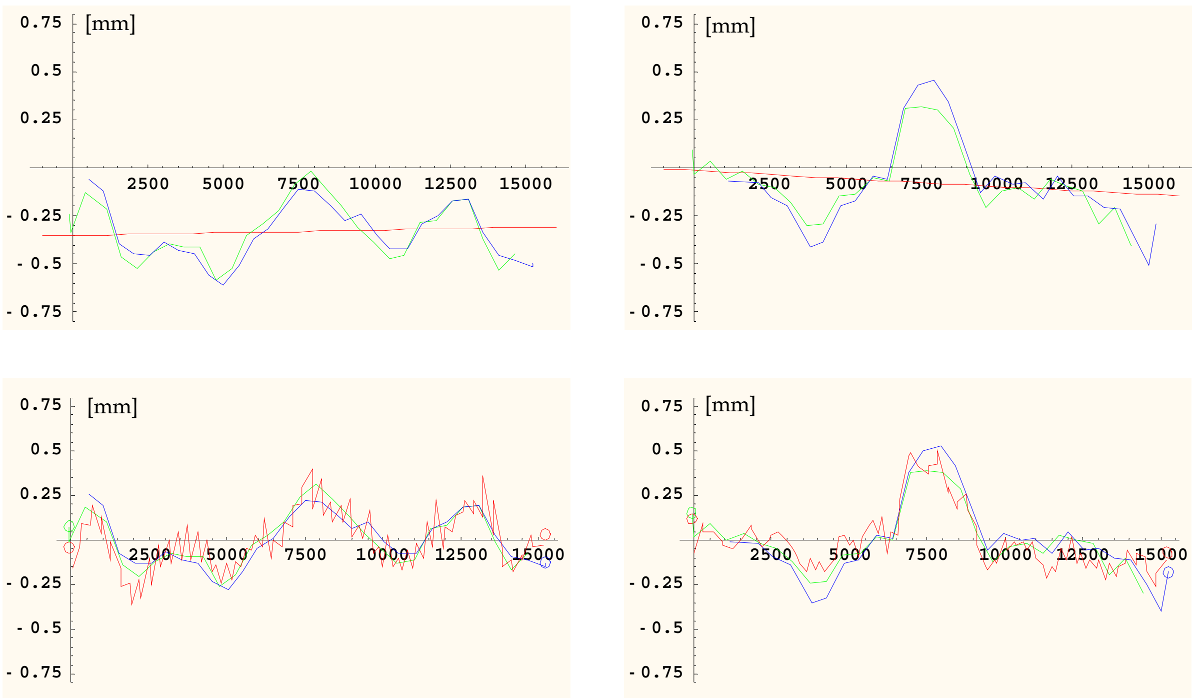


Figure 19 : Top: the two measurements after correction, aperture one to the left and aperture two to the right. We see that the mean plane (red line) does not any longer correspond to the reference system we use. Bottom: recalculation of mean plane for both apertures. The measurement from industry is also included for comparison, in red (untreated measurement with mean plane as calculated in industry).

We see that we recuperate the magnet shape from industry with good agreement. We also see that the endpoints correspond better after correction (accurate points). This operation decreases the maximum distance between the curves from 0.86 to 0.11mm for aperture1 and from 0.52 mm to 0.15 mm for aperture 2. In Table 4 we see that the end covers are closer to the industry measurements after correction.

Table 4 : End cover positions for magnet 2248 at firm, at CERN (original and corrected measurement respectively).

	Connection side [mm]	Non Connection side [mm]
Firm Data	-0.22	-0.20
Original CERN	-0.34	-0.54
Corrected CERN	-0.15	-0.30

3. The consequence

To have an idea of the shift and rotation we could give to a magnet to correct the mean plane calculation due to the temperature effect in the cold bore tube we can redo a mean plane calculation in the following way in 3 dimensions (see Figure 20).

For the 4 sets of data (two apertures horizontal and vertical data): Choose the orthogonal basis

with axis X (pointing into machine center) and Y (along the magnet) in the plane:

- new Z (vertical coordinate) is perpendicular to the plane.
- new Y-axis lays in the vertical plane with the old one.

The proposed shift is calculated as the mean change in vertical position of all four end cover centres. The rotation and tilt are calculated as the angle between the old and the new y-axis and the old and the new mean plane with respect to the old axis. For the magnet 2248 we get that the magnet is 0.15 mm too low and that the rotation angle (corresponding to a field angle change) is 1.30 mrad.

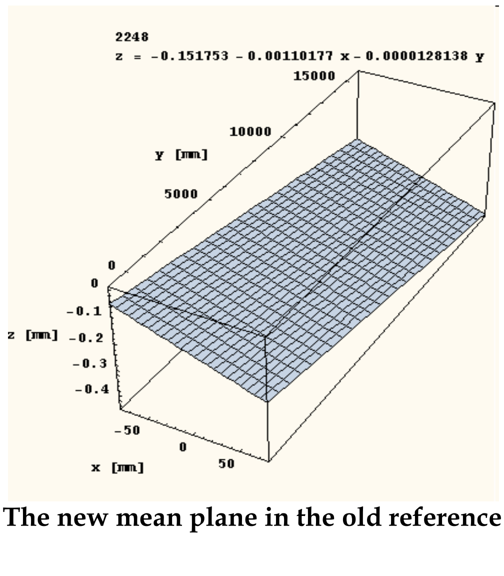


Figure 20 : The new mean plane in the old reference system.

A second example is shown in Figure 21, magnet 2086 where the mean plane positioned by around 0.3 mm lower than what we get if we correct for the effect of a convection cell.

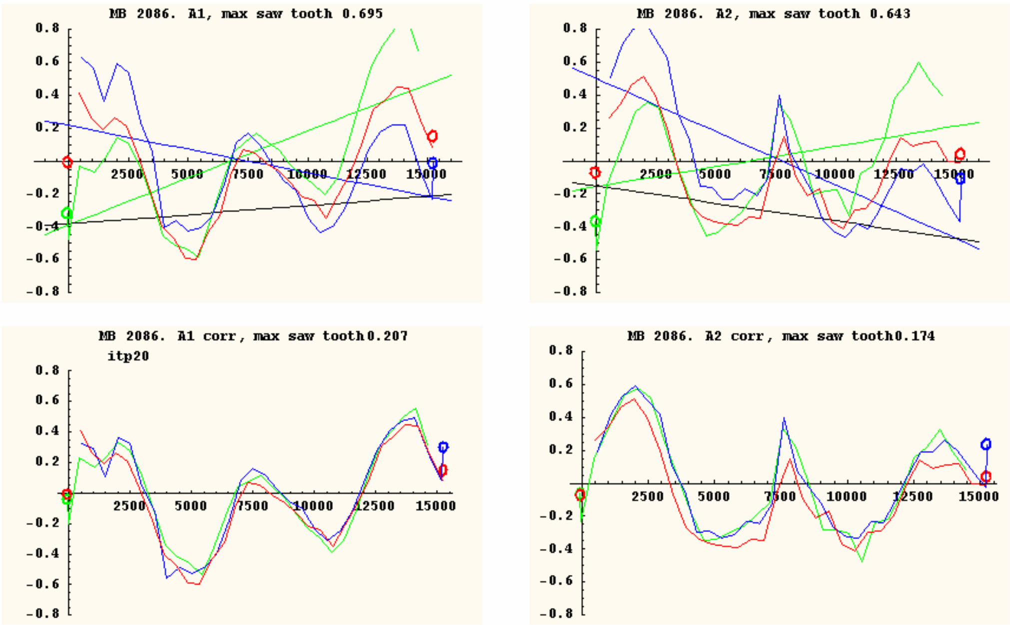


Figure 21 : Magnet 2086: the top two plots show, for aperture one and two the two measurements at CERN (blue and green), the industry measurement and the real magnet mean plane (black line) after correction. When the corrected measurement is put in the new reference system, calculated by a three dimensional best fit, together with the industry measurement (red) we see a very good preservation of the magnet shape.

6. Errors that cannot be corrected using the correction procedure

One criterion to verify the procedure is to calculate the saw tooth after the correction. It should be significantly smaller than before the correction. We also check that the difference between the two measurements is linear, which it would be if our assumption of maximum one convection cell at each side of the CBT is valid. If the difference between the two measurements is not linear we do not apply the method. Figure 22 shows the measurement of the magnet after cold test, the complete measurement, the measurement with the two partial measurements separated and the difference between the two measurements. We see that there are local measurement problems at the connection side of the magnet (the difference between the two measurements is not linear). The criterion we have taken for a good linearity of the difference is that the linear fit of the difference has an rms < 0.07 mm between measurement points and the fit line, corresponding to the bundle adjustment). We see another example in Figure 23, where the difference is clearly not linear. The explanation why we do not have linearity may be other temperature effects or movements of the equipment during the measurement.

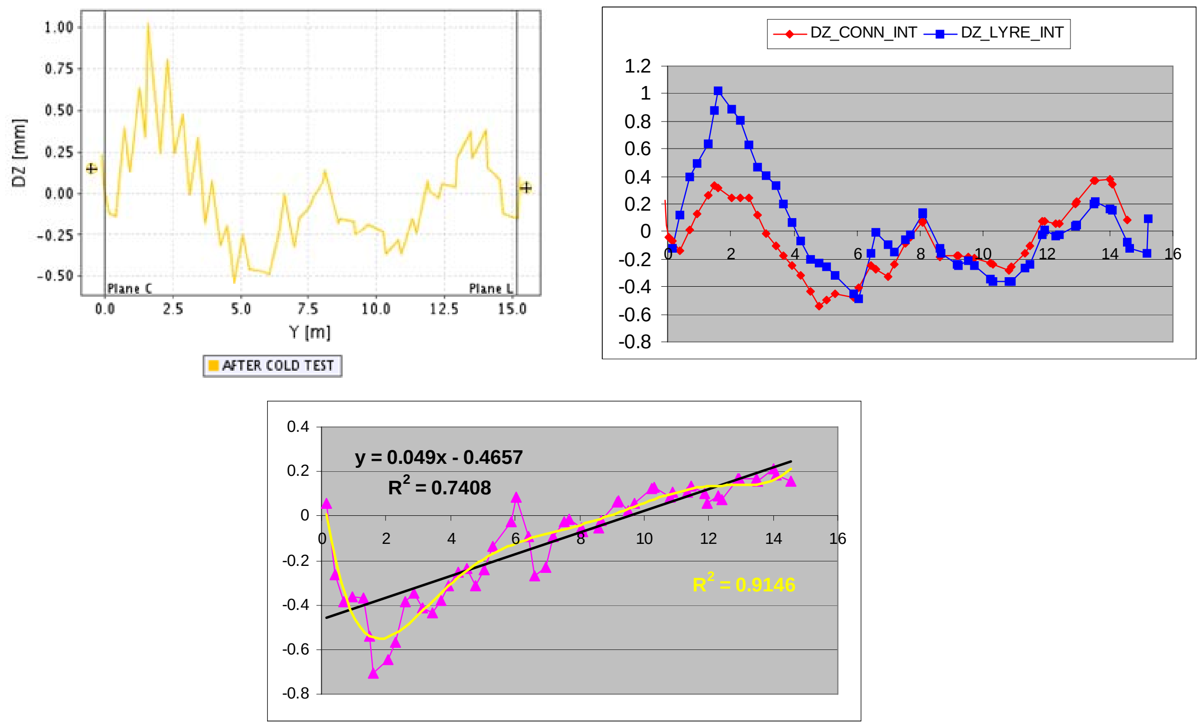


Figure 22 : Dipole 1045, aperture 1, measurement after cold test. Upper left: complete measurement, upper right: the two measurements separated and bottom: the difference, linearly interpolated and interpolated using a x-order polynomial.

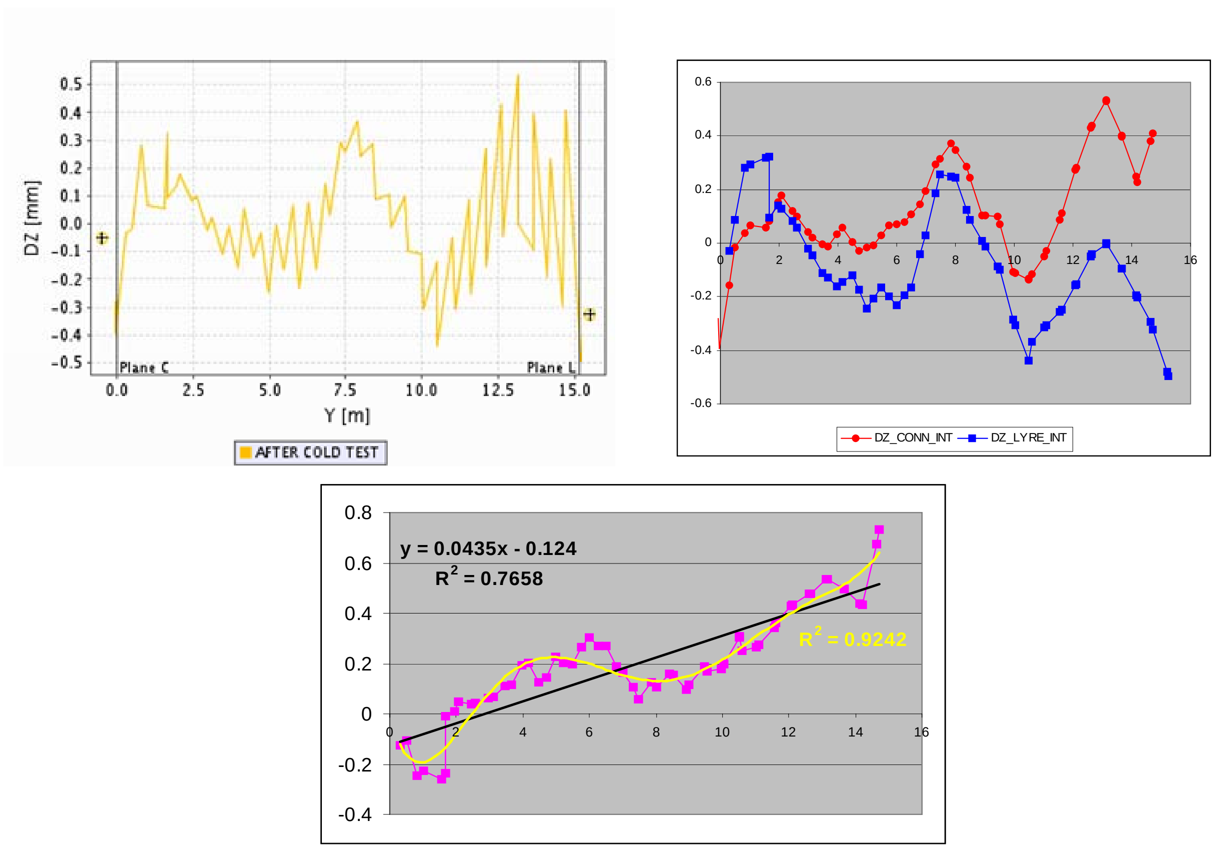


Figure 23 : Dipole 3428, aperture 1, measurement after cold test. Upper left: complete measurement, upper right: the two measurements separated and bottom: the difference linearly interpolated and interpolated using a x-order polynomial.

We must check how the position of the convection cell may influence the results. The value we have used is the value measured in [6]. We have moved the convection cell from 0.2 m to 1.0 metres from the CBT ends and observed how well the curves superpose. Our criterion to find the convection cell is the smallest saw tooth found over the total measurement after correction. We find it, by statistics, at about 20 cm, as measured [6].

7. Checks: Comparing CERN geometry to geometry in industry.

To validate the method we apply the procedure to a set of magnets by doing the following:

1. Correct the measurement according to the procedure in 4.2. Check the corrected value of the saw tooth. It should be small and comparable to the measurement errors for one measurement and the bundle error.

2. Compare shape at WP08 (CERN) with shape at ITP20 (industry), including position of end cover. If we can recover the shape at ITP20 by this method (for this we compare the geometry classes) we have confidence that the method gives a good correction. We have to take into account the slight difference in shape due to the tolerance in the positioning of the central support even if the magnet is adjusted to the industry shape. Checks are made also for one case in industry where two measurements were made for magnet 2273. The end cover position indicates the relative position of the mean plane between the two measurements if the shapes are identical and the end cover is well measured.

3. A set of 33 magnets have been chosen for the test

    a. large saw tooth for CERN measurements (WP08)

    b. measurement in industry with small saw tooth (final measurement at ITP20)

    c. adjusted at CERN to their industry shape (ITP20) to minimize shape changes of the cold mass.

Another test on 174 magnets with big saw tooth at last step at WP08, ready to be installed in the tunnel has also been made.

In Figure 24, measurements ordered with increasing end cover position in industry (blue diamonds), we see that for the end cover position, (yellow triangles, moving average red curve) we recuperate statistically the position in industry (blue diamonds) after correction. The magenta line and squares correspond to the measurements at CERN. The yellow line and triangles are the correction of those measurements. There is also a moving average of 5 magnets plotted for the measurements at CERN, black for the original and red for the corrected measurements. There is most often a negative bias of the end cover position before measurement data correction. For this test we have used the complete three dimensional procedure described in 5.3 for the first of the “worked out examples”. So, the moving average of the corrected data (red line) corresponds better to the industry measurement than the moving average of the original measurement data at CERN. The correction is larger at the non connection side.

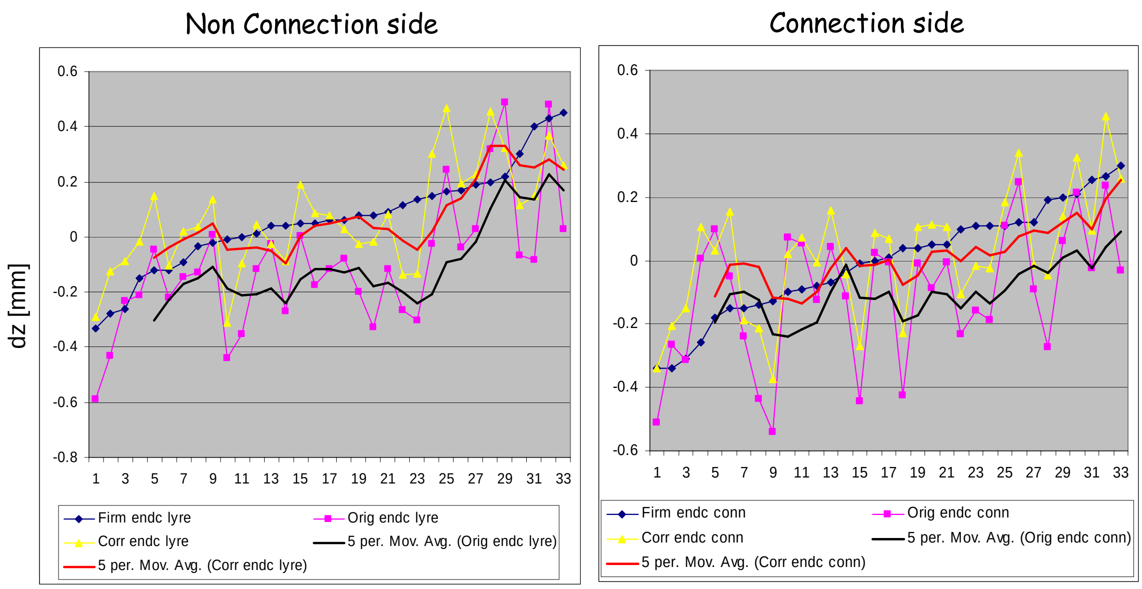


Figure 24 : Result of the three dimensional correction procedure applied to a set of magnets.

For this set of magnets we have a shift in the position of -0.17 mm at the non connection side and -0.10 mm at the connection side (average). For both sides the difference after correction is close to zero (Table 5)

Table 5 : Result of the correction procedure applied to a set of magnets: the position of the end cover at CERN is very close to the position in industry after measurement data correction.

Difference CERN industry				
	Orig connection	Orig non connection	Corr connection	Corr non connection
Average [mm]	-0.10	-0.17	**0.02**	**0.01**
Stdev [mm]	0.21	0.19	0.17	0.16

We have also calculated the geometry classes for this set of magnets, for the industry measurement, for the original measurement at CERN and for the corrected measurement at CERN.

In Table 6 we see that, after measurement data correction, we recuperate the classification we had for the industry measurement (the shape is maintained between industry and CERN for these magnets which is the case if the vertical adjustment at CERN is good enough). 15 magnets recuperate the class they had in industry (red), 12 magnets keep their class after correction (black), 5 are better after correction (blue), and one magnet degrades (green). The horizontal plane influences the classification, saw tooth effect in industry as well, and this explains degradation or improvement of class with respect to industry for a small number of magnets.

Table 6 : Class recuperation after measurement data treatment.

magnet	Original CERN	Corr/itp20
1080	silver	golden/golden
1105	silver	silver
1123	silver	silver
1135	silver	golden/golden
1153	mid cell	silver/silver left right
1154	silver	silver
1163	silver	silver
1178	silver right	silver/silver
1211	silver	golden/silver
1213	silver left	silver/silver
1221	golden	golden
1246	silver	silver
1279	silver	golden/golden
2056	silver	silver
2086	mid cell	silver/silver
2096	silver	golden/silver
2118	silver left right	silver/silver
2133	mid cell	silver right/silver right
2152	silver left right	silver/silver
2195	silver	silver
2216	silver right	silver/silver
2247	silver	silver
3035	silver left right	silver/silver
3102	silver left right	silver/silver left right
3152	silver	golden/golden
3158	silver right	silver/golden
3203	silver left right	silver/silver
3209	silver	golden/silver
3238	silver left right	golden/golden
3244	golden	golden
3348	silver	silver
3392	golden	golden
3395	silver left	silver/silver

8. Global results

We check the end cover position (final spool piece position), the class recuperation (aperture), the shift of the mean plane of the magnet induced by the measurement problem (temperature induced saw tooth). We also estimate the change of field angle due to the roll of the mid plane caused by different saw tooth effects in the two apertures. This test was made in April 2006.

A comment about why the adjustment to ITP20 most often gives a correct result even if points measured in the tube may be deflected: the measurement used to calculate the sagitta change is a half fiducialization (measurement from one side inly). The *change* in sagitta used for the correction is well represented by a half fiducialization and not dependent on any reference. Calculation using a half fiducialization is better than a sagitta calculation using a complete measurement with large saw tooth. For the statistically adjusted magnets we use, for the steering of the procedure, points not measured by the mole in the tube but with a more accurate procedure (endcover position).

8.1 End cover position

Magnets ready for the installation, WP08 completed , we have 698 magnets at the time of the analysis.

We have selected those having

- Measurements from both sides with more than 20 points
- Linear fit of difference standard deviation < 0.07mm
- Max distance between curves > 0.32mm for at least one aperture

We have taken 0.07 mm as the average RMS for all difference linear fits for WP08 + 1 standard deviation. 0.32 mm is the bundle error 0.08 plus possible mole centering error 0.07mm at 3σ

In Figure 25 we show the relation between the average saw tooth and the shift in end cover position. The linear fits have been made, not considering possible outliers. It is clear from the figure that the effect on the shift in the end cover position is significantly larger at the non connection (lyre) side. An explanation for this has not been established, probably due to different conditions for measurements from the two sides. The average difference for large saw tooth (0.25mm) is around 0.1 mm and the total shift at the non connection side is 0.25 mm.

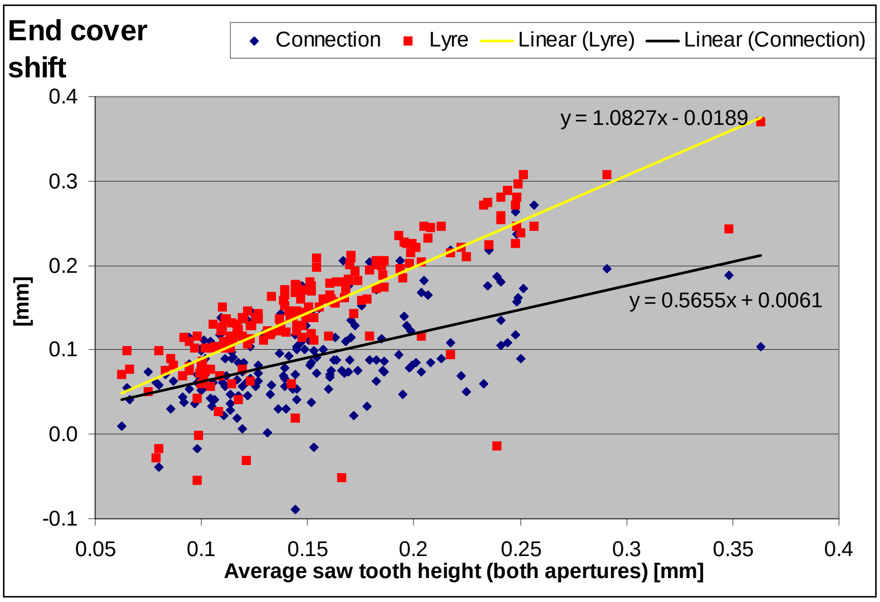


Figure 25 : The correlation of the saw tooth height and the shift of the end cover position. There is a non explained difference between the connection and the non connection (lyre) side.

Connection	0.09 mm
Lyre side	0.15 mm
Average	0.12 mm

This corresponds to the mean plane average shift of -0.09 mm and average slope by Y of -0.004 mrad.

8.2 Class recuperation

Magnets are adjusted either by applying a statistically valid correction to the central support or by an individual correction. The statistical correction is carefully monitored and should, in average, adjust magnets to the shape in industry. The other adjustment method adjusts magnets individually to the shape they had in industry. It is evident that magnets statistically adjusted do not recuperate their shape, magnet by magnet. We have looked at the class recuperation of 88 statistically adjusted magnets and 54 individually adjusted magnets respectively, following the criteria in 5.1. The result is shown in Figure 26. We see that golden magnets are almost recuperated by measurement treatment for the individually adjusted magnets. We also see an improvement for the statistically adjusted magnets, but here the shape change of the magnets influence the result due to the fact that magnets are not adjusted to the industry shape individually but only statistically.

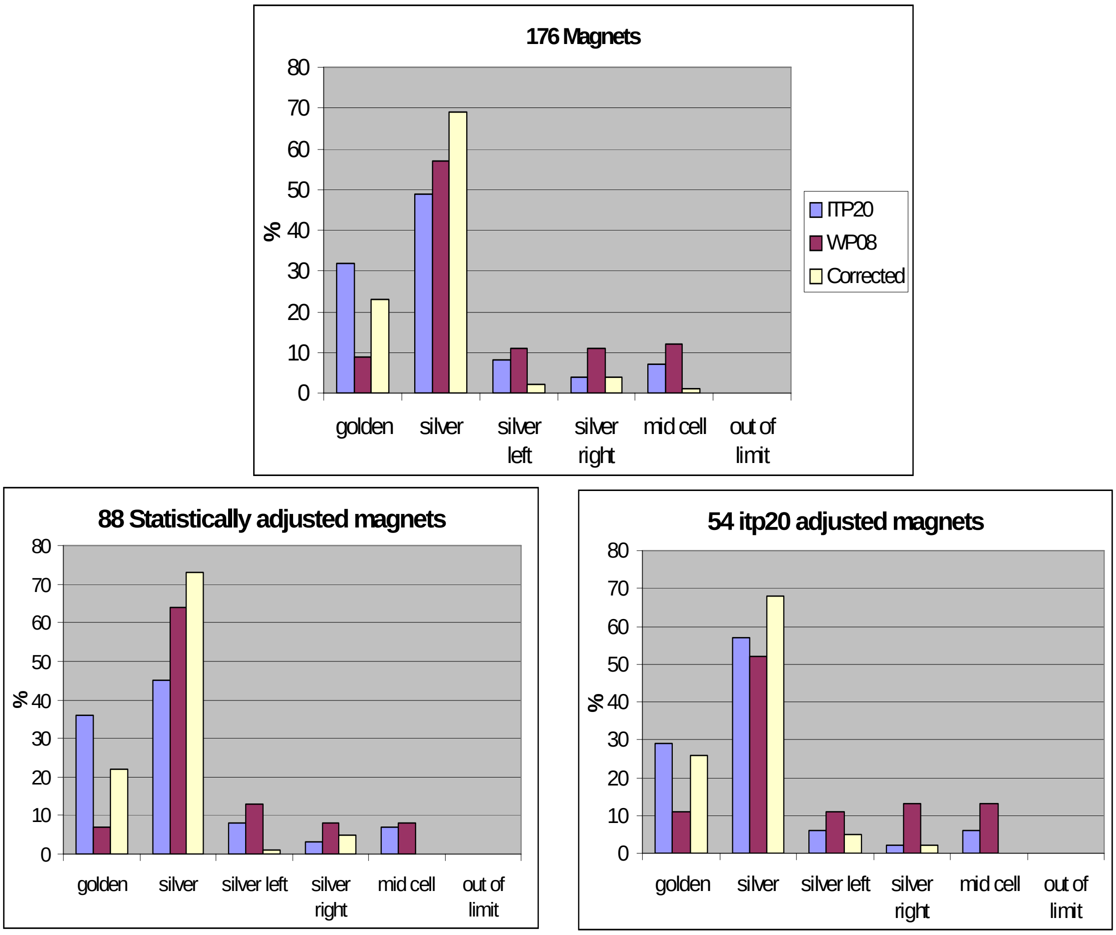


Figure 26 : Magnet class recuperation after saw tooth correction, to the left 88 statistically adjusted magnets and to the right 54 magnets adjusted individually toITP20. Blue is measurement in industry, red is measurement at CERN and yellow is the recalculated result.

8.3 Saw tooth reduction

The results we get for the improvement in the measurements quality, saw tooth reduction is given in Figure 27 for all magnets measured at CERN before April 2006.

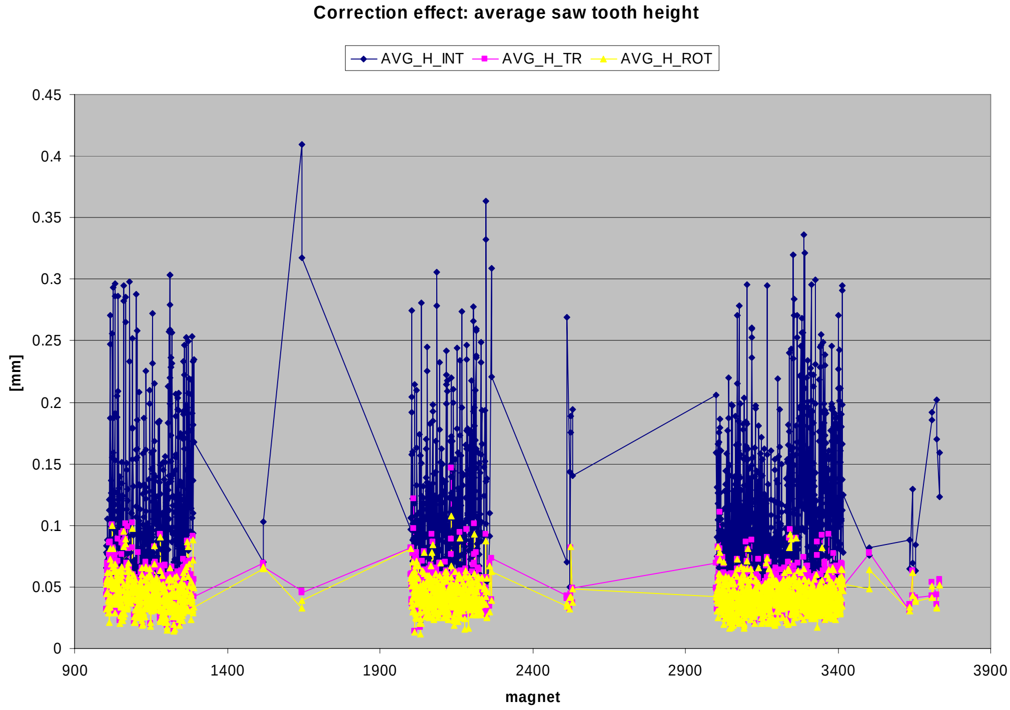


Figure 27 : Result of the correction procedure applied to all measurements after cold test. In blue we show the average initial saw tooth height in purple the result after correction using the procedure described. For comparison we have also included a correction procedure where the difference of the two curves is used to define a rotation of one of the curves (yellow). This gives smaller saw tooth but includes also a "correction" of the bundle-error, which cannot be corrected using the procedure.

We see in Figure 27 that we significantly reduce the effect of the difference between the two measurements and reduce the saw tooth from values often larger than 0.25 mm to less than a tenth of a millimetre in most cases.

8.4 Magnet mean plane shifts

The total statistics (February 2007) for the position of the magnets found by correcting the measurement values can be seen in Figure 28. The mean of the magnet mean plane is -0.06 mm (the magnet mean plane is by best fit of the measurement close to zero) and the standard deviation is 0.06 mm. We have 179 magnets between 0.1 and 0.2 mm (we remind that magnet positioning is controlled with 0.1 mm in the MEB). We have according to this statistical evaluation around 40 magnets with a real mean plane more than 0.2 mm below the measured (Leica) mean plane. The positive tail in the statistics gives us an indication of the contribution from the bundle adjustment. The contribution from the bundle adjustment should be centred about zero mm and have a standard deviation of between 0.04 mm and 0.16 mm according to simulation (see for example Table 1). The effect on aperture of the mean plane has to be evaluated case by case according to the measured shape. Some outliers come from other measurement effects than the temperature effects on the deflection of the Leica beam.

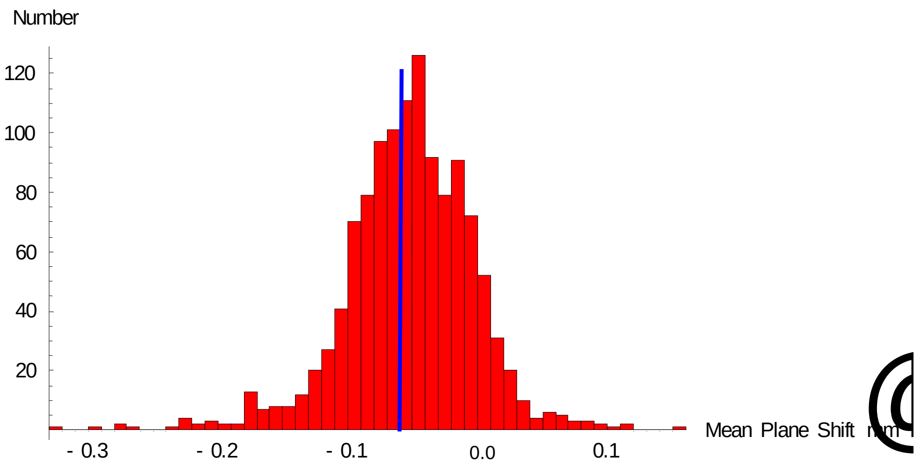


Figure 28 : Total result (1200 measurements at CERN) of magnet positioning after correction of measurement data (saw tooth) including MEB corrections of the shift for aperture.

8.5 Field angle change due to saw tooth in geometry measurements

The field angle is affected by the measurement errors by the fact that the two cold bore tubes seldom show the same effect. The result is a roll around the axis of the magnet due to the tilted mid plane. The magnet will be installed on this mid plane and consequently with a roll. The mean is 0.0 mrad and the standard deviation is 0.21 mrad.

For comparison we mention that the error in the roll in industry is estimated as the standard deviation of the difference between the mean plane measured with a jig and the field direction measured by a mole for magnetic field measurements give and standard deviation of 0.3 mrad [MARIC].

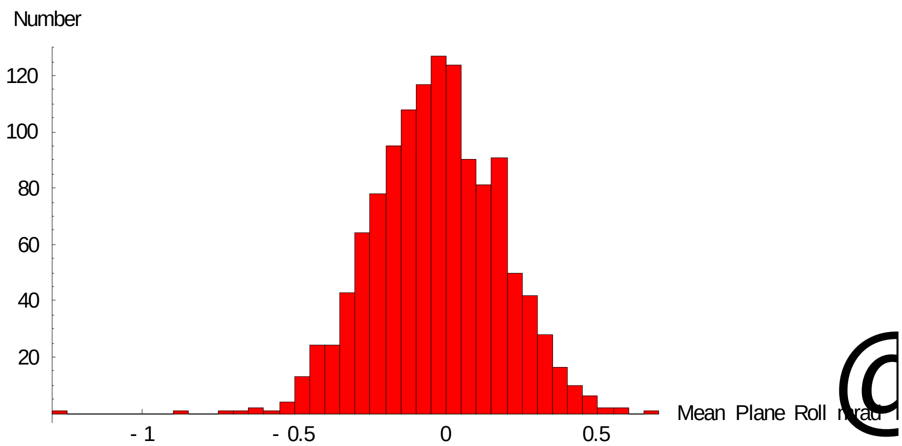


Figure 29: Total result (1200 measurements at CERN) of magnet roll after correction of measurement data (saw tooth).

8.6 Bundle error size

The temperature differences in the cold bore tube in industry may also influence measurements. However since the magnets are kept in an environment with more stable temperature, we believe that the saw tooth effect mostly comes from the bundle adjustment. We would like to use this as a bound for our estimation of the bundle contribution. To evaluate this we have checked the change in the end cover position before and after a measurement correction following the procedure described in section 4.2. However if we apply the correction procedure to measurements not suffering from the temperature effect we should be able to have an idea about the bundle contribution. The error should be considerably smaller, not to induce significant errors and at the best correspond to the specifications of the measurement procedure. The result is shown in Table 7. We see that for firm 1 and for firm 3 the measurement bundle adjustment is very good and the error is in average close to zero. What is important to note here is that we do not see the negative bias we have for the CERN measurements, which we believe comes from a temperature gradient.

One standard deviation corresponds to the maximum values given by the specification of the measurement method (0.08 mm, see section 3). Firm 2 measurements have larger values, which we explain as a less accurate adjustment of the bundle or a temperature effect. We also give the maximum values of the mean plane shift.

Table 7 : Estimation of GA (Geometric Axis) position diffenece between the two measurements (bundle contribution only). Possible rolls and pitches will not be considered, they are small.

#	Firm	Conn max [mm]	Conn avg [mm]	Conn std [mm]	Non conn max [mm]	Non conn avg [mm]	Non conn std [mm]
1	1	0.30	-0.00	0.08	0.28	0.02	0.09
2	2	0.40	-0.08	0.12	0.49	0.12	0.11
3	3	0.19	0.02	0.07	0.26	0.01	0.07
4	All	0.40	-0.02	0.10	0.49	0.05	0.10

An extraction from the database of the measured rms bundle values from 3500 measurements made at CERN, gives a mean value of 0.04 mm and a standard deviation of 0.01 mm. See Figure 30. This is a value well below what we found from the measurements (industry measurements may also contain contribution from convection cells) and gives us additional confidence that the observed large effects come from other sources than bundle adjustment errors. We also see that the bound for a correct measurement in the specification (0.08 mm) is well respected [11].

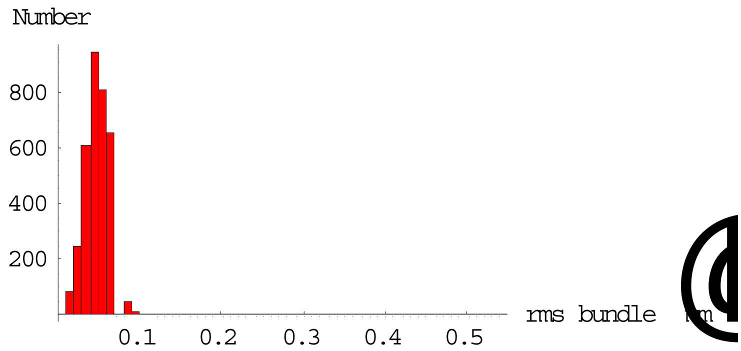


Figure 30: rms bundle values from CERN measurements.

9. Conclusion

We have shown from analysing the geometrical measurements of the cold bore centre position of the LHC MB dipoles that part of the “saw tooth” effect in the measurements comes from a phenomenon inside the cold bore tube. The aim of this work was to propose a correction procedure for this effect. Using this correction procedure for the measurements we come very close to the measurement accuracy specifications taking into account other contributions to the saw tooth effect related to the problem of expressing two measurements from each side of the magnet in one unique reference system. We also show that by using the procedure we can avoid a bias in the magnet positioning in the tunnel and improve aperture and change of field angle due to fiducialization uncertainties coming from temperature effects during measurements.

The idea should be verified and could be improved by carrying out experiments and verifications. During the year from making this analysis and the final write-up there were no possibilities to carry out the tests planned with TS/SU (high production rate or no visible saw tooth effect in the measurements).

Annex 1: Estimation of random measurement errors for the measurements from one side

We have made a simple estimation of the measurement errors by looking at the measurements from each side individually. In Figure 31 we see the vertical measurements of the magnets and we have included the nominal vertical shape.

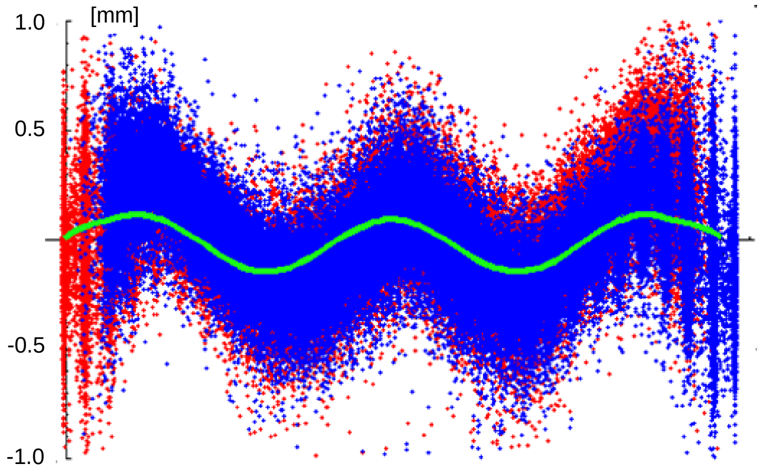


Figure 31 : Red: points measured along the magnet from the connection side, Blue: points measured from the lyre side. The green curve represents the nominal vertical shape.

For the estimation of the errors we define first curve smoothness. It is the distance from the point linearly interpolated at same y-coordinate between the previous and the next points (red segment in Figure 32).

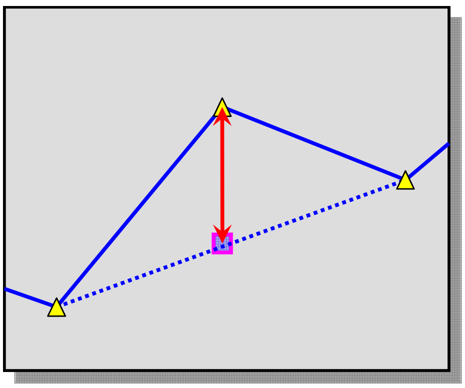


Figure 32 : Definition of curve smoothness

We analyze the difference between the measured and nominal smoothness (taking values of the nominal curve with the same sampling interval as the measured curve). We see that there is a larger variation of the data between successive measurement points at the entrance of the tube for both sides (the measurement device not entirely in the tube, some dependence of the weight of the mole etc.).

Figure 33 shows the average and the standard deviation of the "smoothness" over each 20 cm interval of the tube for all measurements.

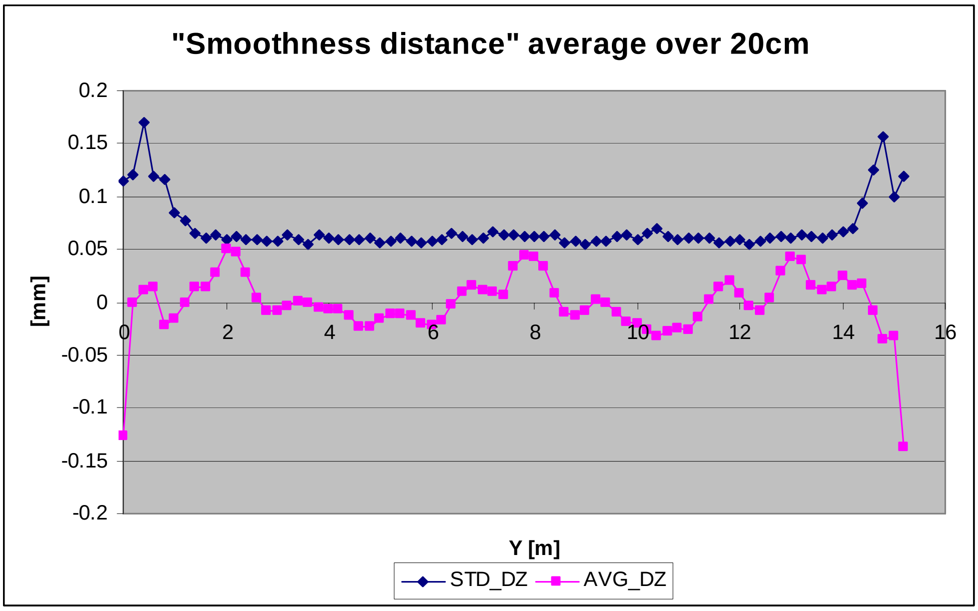


Figure 33 : Smoothness of the measurements. We take the stable region as the region of constant standard deviation

We have, based on figure 31, chosen as stable regions y > 1.4 m for connection side and y < 13.8 m for the lyre side.

We now analyze separately the connection and the lyre side curves. The result is shown in figure Figure 34. Each point represents the standard deviation over 20 cm interval.

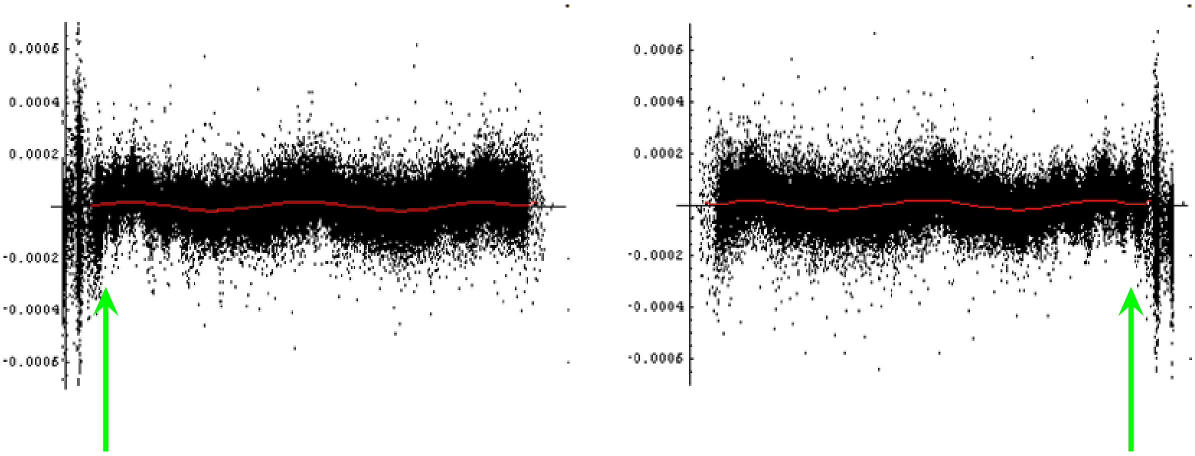


Figure 34 : Stable region (green arrow) for the measurement is y > 1.4 m from the connection side and y < 13.8 m from the non connection side.
Units are metres.

The smoothness is very similar for the two sides (Figure 35).

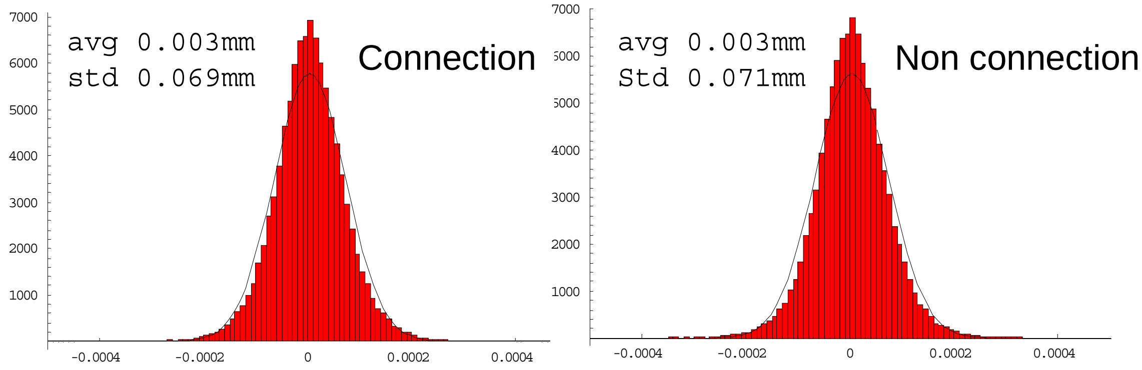


Figure 35 : Histogram of curve smoothness, abscissa units in metres.

Connection and non connection measurements sets are fitted in the "stable" region with a function which describes the standard deviation that we expect varies with the distance x and where the parameters are the repeatability of the measurement (parameter a) and the dependence with the distance b. For the standard deviation dependence on the distance from the two sides respectively:

$$\sigma_{dist,nonconn} = \sqrt{a^2 + b^2 (x-16)^2}$$
$$\sigma_{dist,conn} = \sqrt{a^2 + b^2 (x-1)^2} \qquad (4)$$

Where we assume that -1 and 16 m are the positions of the laser tracker. We obtain the following result of the fit for the parameters (see Figure 36):

connection side — a = 0.057 mm, b = 0.004

non connection side — a = 0.058 mm, b = 0.004

This should be compared to the specifications, 0.05 rms is the repeatability of the measurements [10] and the dependence with distance is 5 ppm [2].

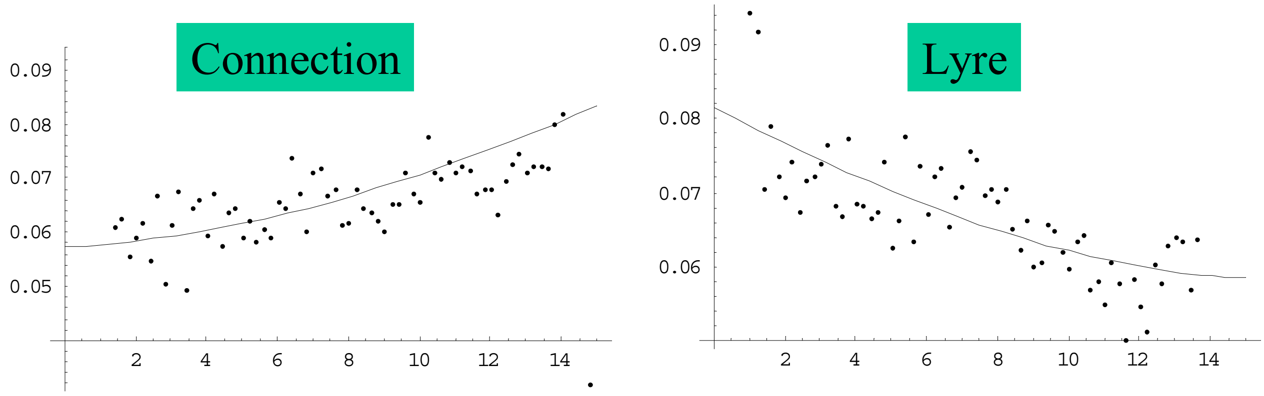


Figure 36 : Measurement error estimation (one sided measurement) along the magnet [mm]. The horizontal axis shows the length of the magnet [m].

References

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