LHC DIPOLE GEOMETRY PARAMETERS, COMPARISON BETWEEN PRODUCERS

Jerome Beauquis, Marta Bajko, Gregory Bevillard, Rocio Chamizo, Marco La China, Dominique Missiaen, Walter Scandale, Fabien Seyvet, Elena Wildner, CERN, 1211 Geneva 23, Switzerland

1. INTRODUCTION

In the Large Hadron Collider 1232 superconducting main dipole magnets have to bend the two 7 TeV beams along the circular trajectory; they fill more than 2/3 of the 27 km long tunnel. The series production is assigned to three European firms. The specifications for the dimensions of the magnets are checked using a well defined procedure in industry and at CERN. The evolution of the magnet geometry from the measurements in industry, to the storage of the magnet before installation is monitored and will be shown separating data from the three producers.

2. THE LHC DIPOLE MAGNET AND THE MEASUREMENTS

The LHC main dipole magnet is a 15 m long superconducting magnet. The magnet is bent over 14.343 m (corresponding to the magnetic length) corresponding to the bending radius 2812.36m (warm conditions). The corresponding sagitta is 9.143 mm. The magnet is a two-in-one structure and the two LHC beams circulate in opposite directions in the two tubes.

In the initial design the cold mass had not only the possibility to move freely along its axis on the two external supports but it could also move laterally on the central support (figure 1). Measurements have shown that the movements of the cold mass in the lateral direction resulted in exceeding the tolerances. Therefore this lateral degree of freedom is now suppressed [1] [7] by a blocking system. The magnet is blocked at CERN, during the cryostating procedure, and later readjusted to get a shape corresponding as close as possible to the shape measured in industry. During a transition period magnets were blocked at later stages.

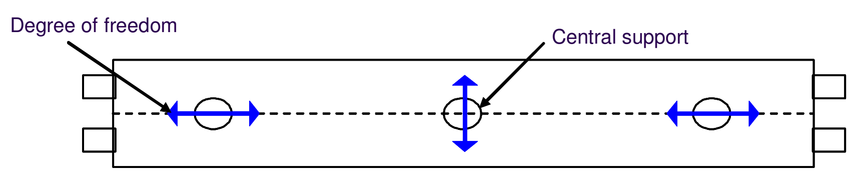


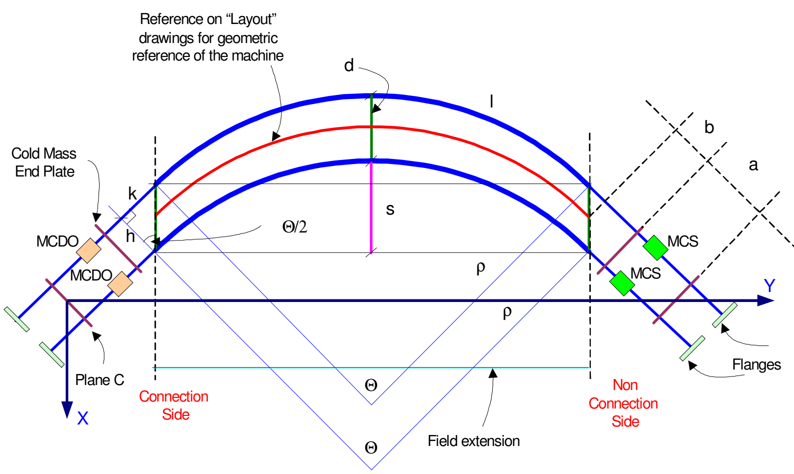
Figure 1: The supporting of the cold mass of the LHC main dipole. The two external supports allow movements in the longitudinal direction. The central support was originally designed to allow lateral movements as shown in the figure, but is now blocked laterally.

The dipole is measured in industry and at CERN. In the beginning of the production magnets were measured at several occasions, at arrival, after cryostating, after tests at cryogenic temperature, after storage etc. Those measurements are today used to analyse the behaviour of the cold mass. In this report we only study the measurements in industry and after cold testing, where the central support is blocked, i.e. magnets in the configuration ready for installation.

The plane that best fits the measurements is referenced to as the mean plane. In this plane we define the x- and the y-axes by a "best fit" of the projected measurement points to the theoretical geometry shown in figure 2. See [2] for the construction of the reference system. We get a vertical and a horizontal plane and those are, for most parameters, studied independently. In figure 2 are shown the sextupole (MCS) and the octupole/decapole (MCDO) correctors that are assembled inside the cold mass and the flanges for the connectivity. Aperture 1 is the upper aperture in the figure.

All measurements are collected and stored as documents in an engineering data management system [3], from which they are extracted and uploaded to a relational database (ORACLE).

The results of the measurements are expressed as the deviation from nominal values.



Parameter	Symbol	Value	Unit
Bending angle per dipole	Θ	5.099	mrad
Magnetic length	l_m	14.343	m
Radius of curvature	r	2812.36	m
Separation of tube centres	d	194.52	mm
Sagitta	s	9.143	mm

Figure 2: The theoretical geometry of the dipole and some important geometry values (warm conditions). The measurements extend roughly from "Plane C" (C stands for connection) to the corresponding plane at the Non Connection side. The coordinate system is right handed and the vertical direction, z, ideally points opposite gravity.

3. PARAMETERS AND CRITERIA FOR THE COMPARISON

The measurements include about 20 measurement items of which most have tolerances. Here we have selected a few parameters, crucial for the accelerator performance. A calculation package is activated at each data base upload to calculate a certain number of geometric criteria for geometry analysis. They are simultaneously loaded into the data base.

We have chosen to study the position of the flanges (important for the interconnectivity) for both apertures and for both sides (connection, non connection, also called lyra) of the magnet. The positions of the corrector magnets are important for the performance of the LHC and we study both apertures. The shape of the magnet is important to guarantee a sufficient aperture for the beam. The global shape is represented by the sagitta (s in figure 2). The sagitta is studied by using the derived parameter “dsagitta”, which is the deviation of the value of the actual sagitta from the nominal value. The deviation of the sagitta is calculated over the part of the measurement corresponding to the magnetic length, by fitting the difference between the nominal sagitta and the measurement points with a 2^{nd} degree polynomial [4], using the difference between the values obtained at the end points and the value at the mid point of the magnetic length. The mean value of the two cold bore tubes is used to represent globally the magnet. For the study of the stability of the shape we also use the maximum difference between two measurements (“Δmax”). This is calculated by sampling the two measurements approximated by fitted 10^{th} degree polynomials [4] every 0.1 m and taking the maximum value of the corresponding samples of the two measurements. What is important to verify is that the magnet shape is not changing after the adjustment towards the measurements in industry. The measurement in industry is a reference measurement in particular because of the assembly of the corrector magnets and the flanges at their theoretical values.

The position of the corrector magnet cannot be measured at CERN (the corrector is mounted inside the cold mass and fixed on its support by welding). Therefore the position is estimated by assuming that the corrector position relative to the cold mass end is constant even if the cold mass end moves.

The twist of the magnetic field is important for the steering of the beam. This parameter is correlated to the geometric twist. The geometric twist is calculated as the convolution of the local twist with respect to the mean value of the twist for the measurement [5]. The local twist is calculated as the angle between a line parallel to a plane containing the x and the z axis, through the two cold bore centres and the horizontal plane, at a certain longitudinal position.

The movement of the magnet in the cryostat is monitored via a parameter representing the angle of the mean plane (the horizontal plane) with respect to the cryostat fiducials projected on a plane containing the z and the x axes (the “georef” angle).

We have taken all available measurements in industry (135, 101, 211 for firm 1, 2, 3 respectively) and a selection of measurements at CERN where the central support is blocked and adjusted towards the measurements in industry (18, 24 and 35 for firm 1, 2 and 3 respectively). We believe that this represents the situation at the installation of the magnets. When we look at the difference between parameters in industry and at CERN we use those magnets that have been measured both in industry and at CERN. All figures refer to those if not differently metioned explicetely.

4. THE HORIZONTAL SHAPE

4.1. The stability of the cold mass

The shape of the magnet is not sufficiently stable for a magnet that is not supported. After transport to CERN, cold tests and storage, the shape of a single magnet can change to have a larger or a smaller sagitta in an apparently random way. If we look at all magnets together, we see however a tendency for the sagitta to increase. The situation for all the 46 magnets from all three firms that have been measured at several occasions at CERN, with the central support free, is shown in figure 3. The figure shows the evolution of the difference in sagitta for the different stages in the assembly and tests of the magnet.

The central support is now (from March 2004 [1]) blocked in the cryostat so as to avoid important changes of the sagitta of the magnet. In fig 4 the dsagitta of the three firms at industry and at CERN is shown. Figure 5 shows the difference between the measurements at CERN and the measurements in industry. We have to take into account the measurement errors and the errors in the polynomial fit. The 10^{th} order polynomial was chosen as the lowest polynomial fitting the population within ±0.3 mm. ± 0.15mm corresponds to the square root of the quadratic sum of the measurement errors. The tolerance of the cold bore position w.r.t. the mean plane is 1.3 mm.

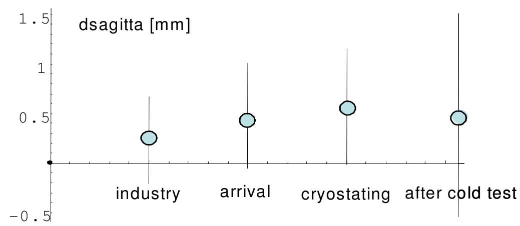


Figure 3: The evolution of the dsagitta for magnets without blocking of the central support. The measurements are from industry from arrival at CERN from after cryostating and finally from after cold testing. The vertical bars correspond to ±1 standard deviation.

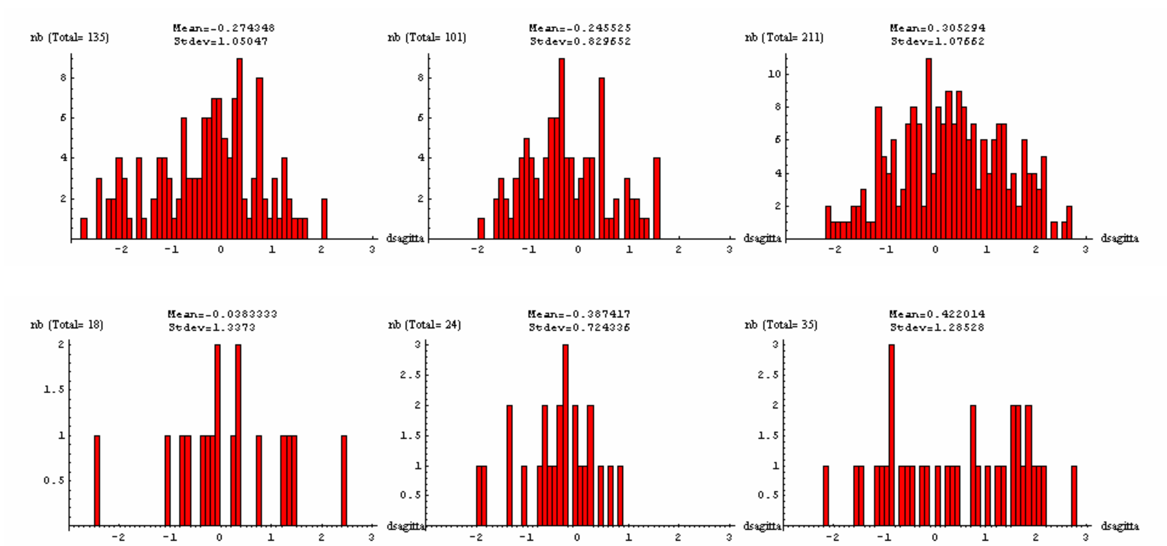


Figure 4: The sagitta with respect to the nominal sagitta in industry from left to right for firm 1, 2 and 3 (top graphs) and at CERN, measured after cold test with central support adjusted like in industry, from left to right for firm 1, 2 and 3 (bottom graphs).

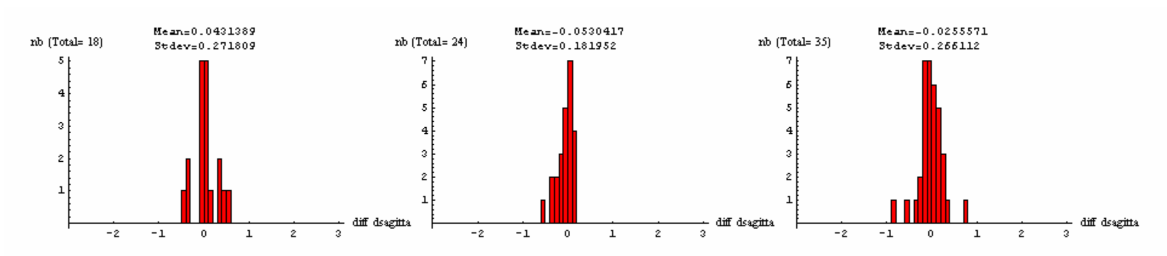


Figure 5: The difference in dsagitta between measurements at CERN and measurements in industry.

For a small number of magnets we have studied the effect of cold testing and transport, for cases when the central support was blocked and when it was free. The result is shown in figure 6. The parameter used is the maximum difference between two measurements. We see, even if the number of samples is small, a beneficial effect of the blocking.

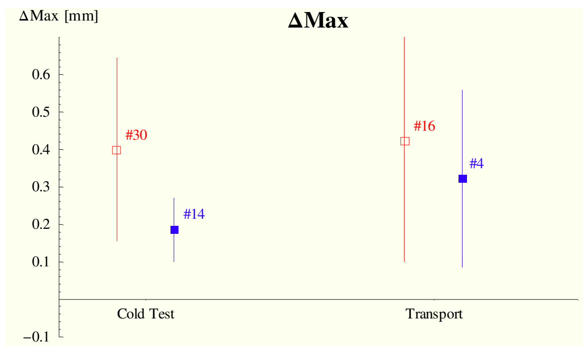


Figure 6: The maximum change in the shape before and after cold test (left) and during transport on the CERN site (right). Red: not blocked magnets, blue blocked magnets. The vertical bars correspond to ±1 standard deviation.

5. THE VERTICAL SHAPE

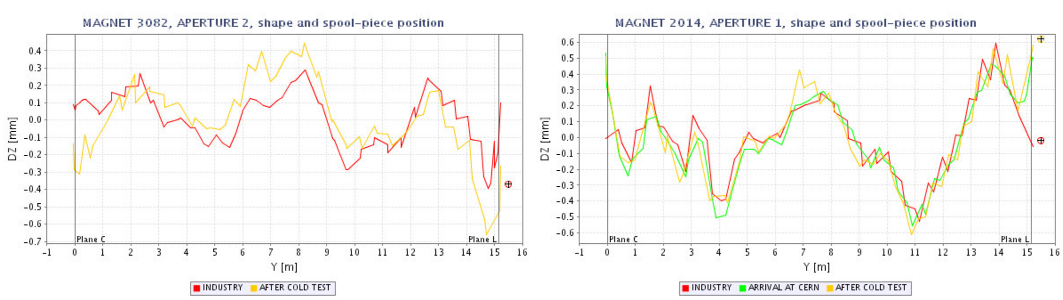


Figure 7: Examples of measurements in the vertical plane: to the left a magnet not perfectly aligned, to the right a magnet well aligned but showing anomalies at the ends. The effect is present also at arrival at CERN.

The vertical shape depends on the supporting. The three supports should be aligned, however, reproducing the shape from the measurement in industry is the target. The gravitational force causes the vertical shape to vary around 0.5 mm depending on the flexural rigidity of the magnet. Local deformations also contribute to the shape. The left graph of figure 7 shows a magnet not perfectly aligned with the measurement in industry. The effect is that the ends of the magnet may be out of tolerance. To the right we observe a change in the measurement of the shape around 1 meter from the ends [6]. This effect is under study and will be further described in next paragraph concerning the flanges.

6. THE ENDS OF THE COLD MASS

A summary of the situation of the flanges can be seen in figure 8. The position of the flange has a tolerance of 0.87 mm. Corresponding histograms for the horizontal plane, measurements at CERN, are shown in figure 9.

The situation for the vertical position with a simulated perfect positioning for the CERN measurement is shown in figure 10. The measurements have been approximated with 10th degree polynomials, superposed by modelling on the industry measurement at the supports and then the difference in the flange position has been estimated.

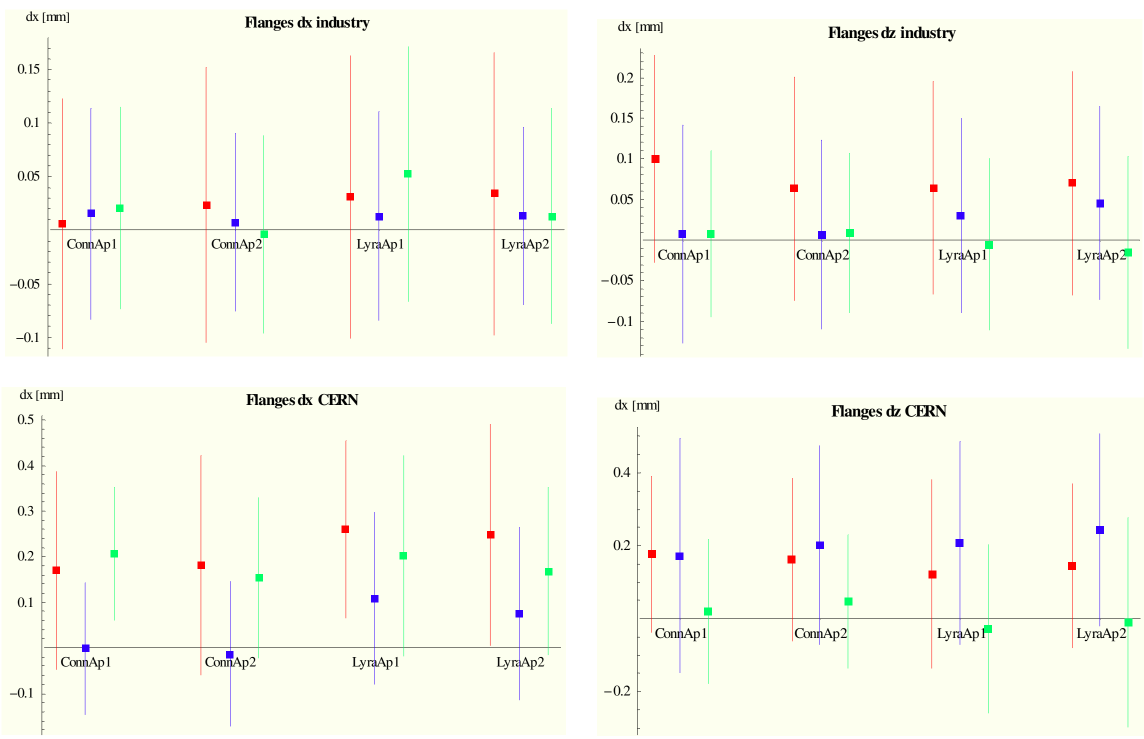


Figure 8: Summary of the measurements of the flange position, top industry, bottom CERN. Red, blue and green represent firm 1, 2 and 3 respectively. Graphs to the left show the values for aperture 1, to the right aperture 2. The vertical bars correspond to ±1 standard deviation.

The diagrams show all magnets having a measurement after cold test, with or without the central support blocked. In this way we estimate the "natural" shape change without influence of positioning. There is a small statistical variation around zero but we can also see, that for firm 2, there is an overlapping distribution (see also figure 7 where we see the effect also for the measurement at arrival at CERN). We also see a slight negative bias for firm 3.

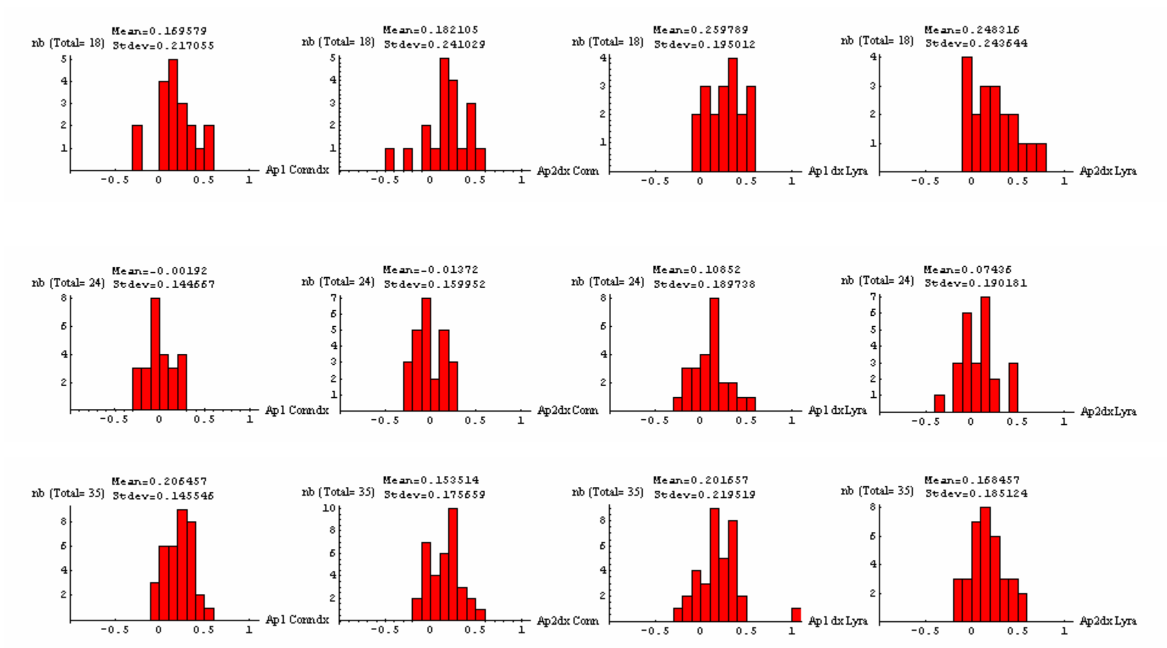


Figure 9: Situation of the horizontal position of the flange at CERN, top firm 1, middle firm 2 and bottom firm 3 (all magnets cold tested and with central support blocked).

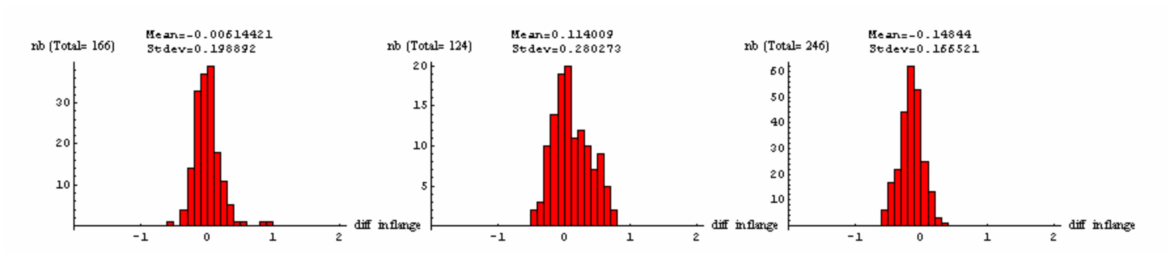


Figure 10: The difference in the vertical flange position between industry and the first measurement after cold test. The influence of the vertical shape due to positioning has been taken out using modelling by which the magnet is positioned like in industry for the measurement at CERN. Observe that the population is larger than in figure 8, since we have taken all available measurements immediately after cold test, regardless if the central support is blocked. From left to right firm 1, 2 and 3.

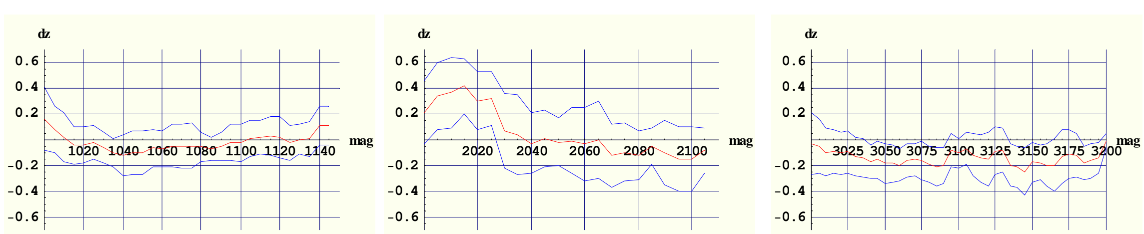


Figure 11: The difference in the vertical flange position between industry and the first measurement after cold test: for each 5th magnet the moving average of 15 preceding magnets is plotted. In red, the mean, in blue, the standard deviation. From left to right firm 1, 2 and 3.

In figure 11 we see the same data as in figure 10. Here we have plotted the moving average of the flange position change against magnet number (time) of the three firms to check if the change in flange position evolves with production. For firm 2, in fact, the flange position deviation from nominal detected at CERN measurements has changed since the beginning of the production. The problem seems to have disappeared, however the spread is still larger than for the other two firms. For firm 1 and 3 the measurements are stable.

7. CORRECTOR MAGNET POSITIONING

7.1. The sextupoles

The measurements of the sextupole positions are represented in figures 12 and 13. A systematic error in the positioning of the sextupoles in the vertical direction that can be seen in figure 11 at firm 3 has now been corrected. The high values of the sextupole positions (vertical, CERN) for firm 2 are related to the displacement of the ends of firm 2 magnets at early production.

Sextupoles dx		Firm1	Firm2	Firm3
Ap1	Mean	0.026	−0.002	−0.034
	Stdev	0.068	0.051	0.077
Ap2	Mean	−0.025	0.014	0.043
	Stdev	0.069	0.052	0.069

Sextupoles dz		Firm1	Firm2	Firm3
Ap1	Mean	0.012	0.017	−0.198
	Stdev	0.051	0.054	0.227
Ap2	Mean	0.002	0.029	−0.193
	Stdev	0.047	0.054	0.232

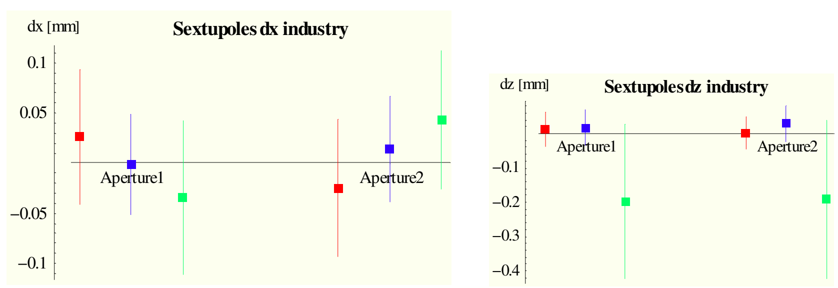


Figure 12: Sextupole positions in industry. The vertical bars correspond to ±1 standard deviation. Red, blue and green represent firm 1, 2 and 3 respectively.

Sextupoles dx CERN		Firm1	Firm2	Firm3
Ap1	Mean	0.203	0.095	0.108
	Stdev	0.199	0.155	0.145
Ap2	Mean	0.219	0.057	0.213
	Stdev	0.252	0.149	0.184

Sextupoles dz CERN		Firm1	Firm2	Firm3
Ap1	Mean	0.066	0.167	−0.143
	Stdev	0.274	0.301	0.296
Ap2	Mean	0.071	0.213	−0.132
	Stdev	0.289	0.243	0.303

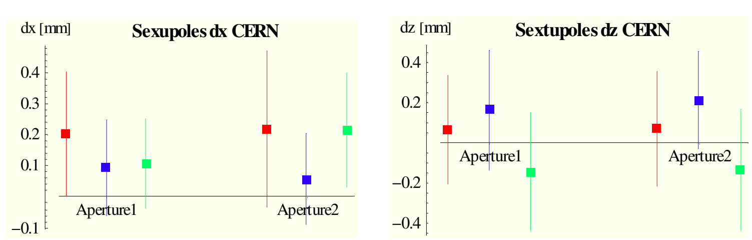


Figure 13: Sextupole positions (estimated) at CERN after cold test and with central support blocked. The vertical bars correspond to ±1 standard deviation. Red, blue and green represent firm 1, 2 and 3 respectively.

7.2. The octupoles

Similarly we observe the octupole positions, see figure 14 for the measurements in industry and figure 15 for measurements at CERN.. We do not observe any similar problem for the octupoles for firm 3 (the assembly is not the same as for the sextupoles). The high values of the octupole positions (vertical, CERN) for firm 2 are related to the displacement of the ends of firm 2 magnets at early production.

Octupoles industry dx

		Firm1	Firm2	Firm3
Ap1	Mean	0.006	−0.003	−0.022
	Stdev	0.051	0.056	0.062
Ap2	Mean	−0.024	0.023	0.041
	Stdev	0.056	0.049	0.072

Octupoles industry dz

		Firm1	Firm2	Firm3
Ap1	Mean	−0.002	−0.003	0.023
	Stdev	0.058	0.049	0.047
Ap2	Mean	0.009	0.023	0.018
	Stdev	0.051	0.031	0.029

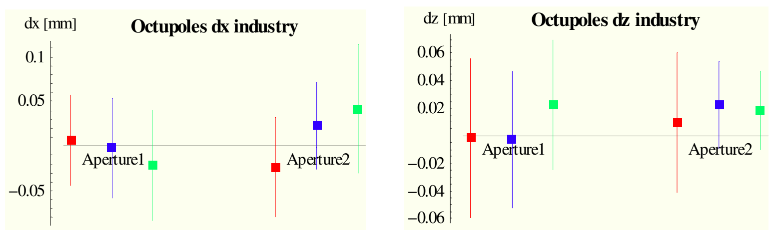


Figure 14: Octupole positions in industry. The vertical bars correspond to ±1 standard deviation. Red, blue and green represent firm 1, 2 and 3 respectively.

Octupoles dx

		Firm1	Firm2	Firm3
Ap1	Mean	0.205	−0.000	0.108
	Stdev	0.296	0.121	0.133
Ap2	Mean	0.141	−0.011	0.139
	Stdev	0.290	0.139	0.153

Octupoles dz

		Firm1	Firm2	Firm3
Ap1	Mean	0.035	0.291	0.013
	Stdev	0.246	0.384	0.194
Ap2	Mean	0.035	0.339	0.017
	Stdev	0.234	0.349	0.177

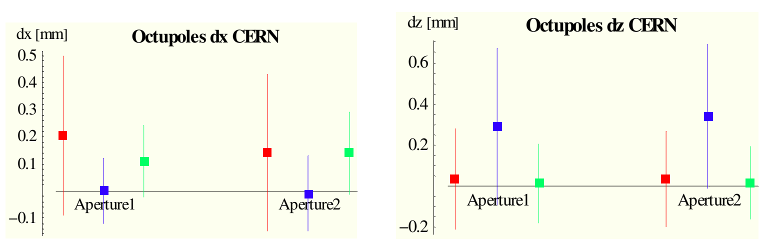


Figure 15: Octupole positions at CERN (estimated). The vertical bars correspond to ±1 standard deviation. Red, blue and green represent firm 1, 2 and 3 respectively.

The tolerance for the corrector positioning is 0.6 in industry. For beam performance the mean has to be less than 0.3 mm and 3 standard deviations have to be less than 0.5 mm in both planes [5].

8. MOVEMENTS IN THE CRYOSTAT

The difference of the angle between the fiducials and the mean plane are displayed in figure 16 for magnets that were measured before the blocking procedure and after. The change we observe is not correlated to the change in sagitta imposed on the magnet at blocking. 23 magnets were studied.

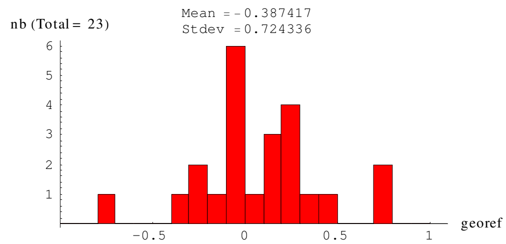


Figure 16: The change in the angle between the fiducials and the mean plane for measurements before and after the blocking procedure.

9. THE TWIST

The convolution of the local twist along the magnet is visualized in figure 17. The tolerance of this value is 0.18 mrad·m^2. No significant difference between the measurement in industry and the measurements at CERN can be observed. All firms are within tolerances.

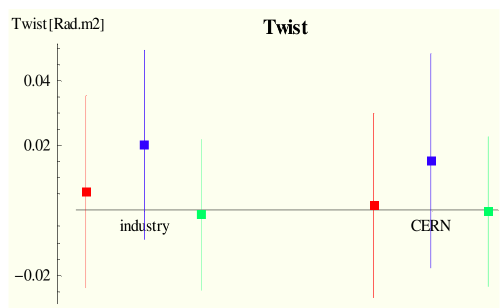


Figure 17: The twist of the magnet at industry and at CERN Red, blue and green represent firm 1, 2 and 3 respectively.

10. CONCLUSION

For the different criteria we have chosen to characterize the quality of the geometry the production is now stable and we are within required tolerances.

References

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