FINAL GEOMETRY OF THE 1232 LHC DIPOLES

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Abstract

The 15 m long main dipoles for the Large Hadron Collider have now been installed in their final positions in the accelerator tunnel. Geometric measurements of the magnets after many of the production steps from industry to the cryostating, after cold tests and after preparation of the magnets for installation, have been made, permitting careful control of the shape of the magnet, the positioning of the field correctors, and the final positioning in the tunnel. The result of the geometry control at the different production stages, from industry to CERN, using different kinds of control procedures and analysis, is reported.

INTRODUCTION

The installation in the LHC tunnel of the 1232, 15 m long, main dipoles [1,2] is now finished (Table 1).

Table 1: Parameters of the LHC Dipole

Parameter	Warm	Cold	Unit
Bending angle per dipole	5.1	5.1	mrad
Magnetic length of each aperture	14.34	14.30	m
Radius of curvature	2812.3	2803.9	m
Separation of tube centers	194.5	194.0	mm
Sagitta	9.14	9.11	mm

The three suppliers, the consortium Alstom-Jeumont in France, Ansaldo Superconduttori in Italy and Babcock Noell Nuclear in Germany, have produced magnets with similar results for the most salient geometry characteristics and only relatively few non-conformities have been detected [3].

Requirements on the Geometry

The reference axes of the dual bore dipole are the theoretical beam orbits and they also define, by best fit, the reference plane. The two measurements of the mechanical centre of the cold bore tubes are best fit to the theoretical beam trajectories. The reference plane and this best fit define the magnet mean plane and the reference coordinate system of the magnet [4]. The system is curvilinear and the y-axis follows the theoretical orbit. The magnet is positioned in the tunnel using this reference coordinate system, which after the magnet cryostating is referred to external fiducials.

Requirements of the geometry of the dipoles, related to the LHC beam characteristics, together with the reduced tolerances required in industry to achieve the final requirements of the assembled dipole before descending into the tunnel, are listed in Table 2 for the beam aperture and in Table 3 for feed down effects from multipoles, and, in addition, for the interconnectivity (circular tolerances) of the magnets. In Table 2 the requirements for dipoles in positions in the machine with special requirements [5], for example dispersion suppressors, are also shown. These special magnets have been selected in the normal production. The requirements are related to the final geometry measurement, at ambient temperature, of the magnet after cold testing. The final requirements for the corrector magnet in the tunnel is 0.3 mm average (avg) and standard deviation (std) 0.5 mm (this includes contingency for installation, ageing etc.)

Table 2: Requirements for the cold bore tube centre, maximum excursion from reference

	Final [mm]	Produced [mm]	Final (special) [mm]
Horizontal	1.55	1.50	0.80
Vertical	0.75	0.80	0.50

Table 3: Requirements for the corrector magnet and end flange positioning, at the last measurent.

	Correctors final avg [mm]	Correctors final std [mm]	Correctors produced [mm]	Flange final [mm]	Flange produced [mm]
Hor.	0.2	0.40	0.30	0.87	0.6
Vert.	0.2	0.40	0.30	0.87	0.6

For the dipole only the mechanic centre of the magnet is measured. From measurements on the magnets from the pre-series, the difference between the magnetic and the geometric axis of the magnet could be estimated to be in the order of 0.1 mm.

Geometry Control

Magnets produced with a sagitta different from the nominal had the cold-bore tubes adjusted to permit flanges to be mounted on the nominal positions. Figure 1 shows a magnet with a cold bore tube excursion out of tolerance and with the cold bore tube end adjusted to the mean plane.

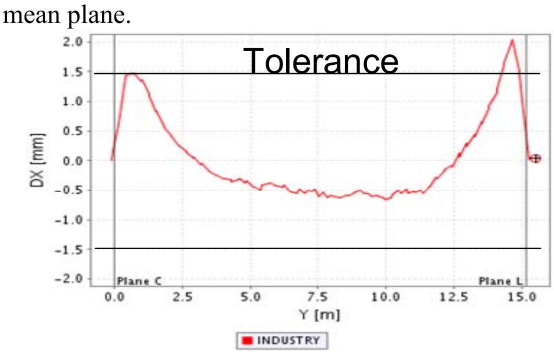

Figure 1: Example of magnet produced with too large sagitta and with shape out of tolerance.

A certain number of magnets out of tolerance could be accepted thanks to the possibility of sorting according to the position of the magnet in the machine (other criteria

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than geometry had also to be taken into consideration for this sorting) [5]. The sorting was done using race track shaped tolerances (Figure 2) for the nominal tolerances. Magnets outside these tolerances were classified as “silver left”, “silver right” or “mid cell” according to the possible location in the machine half cells. The magnets with special requirements, 0.8 mm horizontal and 0.5 mm vertical, belong to the “golden” class. Around 13 % of golden magnets were needed and not more than around 10 % of mid cell magnets could be accepted to ensure the sorting.

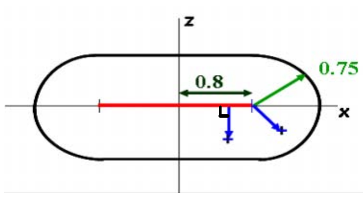

Figure 2: Tolerances for the dipole. The tolerances define the “silver” class, represented here in a plane perpendicular to the magnet axis: the cross is the position of the beam tube centre and it has to lie within the race-track shape. Dimensions in mm.

The sagitta of the magnet, as produced, is controlled by careful adjustments of the welding press. However, there are trends and spread of the sagitta during production. Different characteristics of the two-welded half cylinders have been analysed without showing any correlation to the sagitta [3] of the produced magnet, neither to the change of sagitta that has been observed between the last production stage and the measurements after cold test.

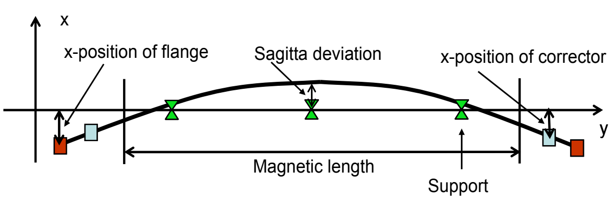

Figure 3: The sagitta change of an assembled magnet changes also the position of the correctors and the flanges. The magnets were blocked at the central support to avoid the shape-change.

The sagitta of the magnet changes between the final production stage and the reception at CERN (Figure 3). The change is not predictable (values up to 3 mm in exceptional cases) and the magnet shape evolves during storage and transport at CERN.

The change of the sagitta is not correlated to the value of the sagitta at the last measurement before shipping to CERN [6].

However, the change was found having a constant mean value and keeping the same the spread, per firm, during the production (Table 4).

Table 4: Change in sagitta between measurements before shipping (industry) and CERN reception

	Firm I [mm]	Firm II [mm]	Firm III [mm]
Average	0.71	0.33	0.51
Standard deviation	0.77	0.58	0.60

The final remedy of the change of the sagitta from the final production stage to the final complete measurement at CERN, was to block all magnets at the central cold support during cryostating at CERN, preventing the magnet from changing its shape in the horizontal plane. The support could be blocked in a way to adjust the sagitta to a value corresponding to the shape in industry [7]. The adjustment value was limited, to not damage the support [8]. Some magnets from early production were blocked “as is”; no adjustment was applied. The procedure to adjust the magnets to industry shape demanded two measurements, one to measure the shape before adjustment to calculate the adjustment, and one after, to measure the final shape. To speed up the production, the fact that the magnet shape change has a constant mean value per firm was used [6]. Magnets were then “adjusted statistically” by applying the value for the adjustments corresponding to the mean value of the sagitta change, without measurement before. This procedure only needs one measurement. The spread of the sagitta-change between industry and CERN is then still present. Consequently, some of the magnets were out of tolerance for the flange positioning after the statistical adjustment. The shape of these magnets was adjusted to their industry-shape, and one, final, measurement was done after. The spread around the nominal value of the corrector position for the statistically adjusted magnets is larger than for those adjusted to industry shape, but within specification. Some magnets, produced with a very good shape, were selected to be adjusted to their initial shape for aperture needs in positions, critical to beam dynamics. Measurement problems related to temperature effects in the cold bore tubes, giving the impression of a shape change of the dipole, could be explained and corrected [9]. The accuracy of the measurements is 0.1 mm [10] and this accuracy could be retrieved after correction for these temperature effects [9]. A partial measurement after the final complete measurement is performed where the end-cover movements w.r.t. the final, complete measurement are measured. The end-cover movements indicate the stability of the magnet shape. All measurements, important actions and conditions, and control criteria, have been recorded in a data base.

RESULTS

The final result for the corrector positions (Table 5) are well within requirements. The end cover movement of the magnet´s connection side is in average 0.11 mm. This may reveal a tendency to an increase of the sagitta, which works against the force on the central support for many magnets. The spread of the movement should be compared to the spread of the movement after re-measurements of the end-cover positions after different kinds of transport on the CERN site, which is around 0.12 mm.

The control of the shape of the magnets needed important efforts. The required number of magnets for the sorting could be achieved with small margins (Figure 4).

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Table 5: Corrector magnet positions

	Sextpoles avg [mm]	Sextpoles std [mm]	Octupoles avg [mm]	Octupoles std [mm]
Horizontal	0.08	0.30	0.05	0.30
Vertical	-0.03	0.27	0.02	0.23

Table 6: Endcover movements and rotation

	Side of magnet	Average [mm][mrad]	Standard deviation [mm][mrad]
Horizontal	Connection	0.11	0.21
	Non Connection	0.02	0.18
Vertical	Connection	-0.04	0.12
	Non Connection	-0.02	0.12
Rotation	Connection	0.03	0.23
	Non Connection	-0.01	0.19

654 magnets are adjusted to industry shape. Some of them needed several adjustments. Some were adjusted to industry shape after a statistical adjustment "failure" or being out of tolerance after an "as is"-adjustment at reception. We estimate that less than 4.5 % of the magnets were out of tolerance after statistical adjustment; those had to be re-adjusted to industry shape.

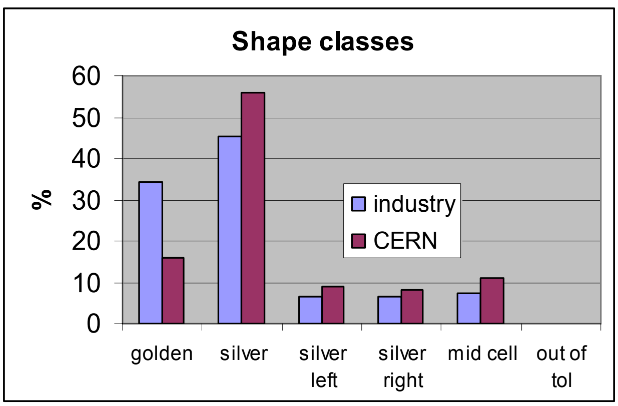

Figure 4: Magnet shapes in industry and after last measurement at CERN.

Final Geometry Control

Once the geometry of the cold mass in its cryostat was fixed and measured, the assembly was closed and stored in open air for up to 2 years, for some of assemblies, before transported into the tunnel. As a final step before installation, it remained to install the beam screen in the two cold bores. This step required a further set of measurements in order to center the beam screen. We used this opportunity to check the overall geometry by comparing the cartography of the reference marks engraved at the extremities of the cold mass and the position of the survey targets to the final full measurement describe here above. Thirty assemblies exhibited apparent movement either horizontally or vertically which were above the allocated budget of 0.5 mm, which is reserved for 'dynamic movements' of up to 2 mm. Most of the cases were explained by the displacement of survey target supports due to water damage due to faulty welds (water penetration). Some supports were rusted and deformed. In one case a screw was broken. All were repaired and a new cartography mapped and compared to the original measurement allowed to retrieve a good reference data-set for alignment and the original position of the extremities was always found to be within the tolerance budget.

The most probable cause for some remaining cases is related to an insufficient release of the transport restraints, which can induce a substantial torque on the cold mass extremity; those were all recovered after necessary actions and re-measurements.

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