Control of the Dipole Cold Mass Geometry at CERN to Optimize LHC Performance

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Index Terms—dipole geometry, feed down, mechanic aperture

I. INTRODUCTION

THE CERN Large Hadron Collider (LHC) main dipole is a 15 m long superconducting magnet, bent to follow the beam trajectory. The structure shows some statistically predictable shape change after transportation from the premises where they are assembled, and after cold tests at CERN. This change of shape is different for magnets produced by different manufacturers (three firms are sharing the assembly of the dipole cold masses). For individual magnets it is not possible to estimate how the shape of the cold mass is going to react to the actions performed on it (e.g. cold test or transport).

These shape changes must be carefully controlled and we have to insure that the magnet shape is within tolerances not only at the installation but also that the shape of the cold mass stays within tolerances during the machine operation along the life-time of the LHC.

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II. THE LHC DIPOLE COLD MASS GEOMETRY

In Table I are shown some important parameters for the geometry of the twin aperture LHC main dipole [1].

TABLE I
PARAMETERS FOR THE DIPOLE GEOMETRY

Parameter	Warm	Cold	Unit
Bending angle per dipole	5.1	5.1	mrاد
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 core of the cryodipole, i.e. the dipole assembled in its cryostat, is the cold mass which contains all the components cooled by superfluid helium. The beam tube, the cable, the collars and the laminated iron yoke are surrounded by the two austenitic steel half cylinders welded together around the yoke on a welding bench, on which the magnet is bent to a shape such that when it comes out of the bench it releases to a shape corresponding to a radius of curvature of 2812 m (balance between the forces in the weld and the rigidity of the magnet structure). The bench shape determines the shape of the cold mass and this shape is regularly controlled at each firm. Each firm has slightly different assembly procedures.

The magnetic field correctors, one sextupolar and one combined decapolar/octupolar corrector, are mounted at each side of the magnet inside the cold mass. The position of the corrector magnet is critical, and any cold mass shape change after assembly influences the position of the corrector.

The cold mass is assembled in a cryostat and its position is blocked, horizontally and vertically, at supports situated at three positions along the magnet. It can slide longitudinally on the two supports closest to the ends. Reference points for the geometry measurements, fiducials, are fixed onto the outside of the cryostat.

III. THE KEY PARAMETERS FOR BEAM DYNAMICS

A. Machine Aperture

The tolerances for the clearance of the beam inside the cold bore tube depend on the beam optics parameters; these vary along the machine circumference. Hence, depending on where the magnet is placed in the machine, the tolerance of the tube excursions is more or less strict. Magnets are put into five classes according to where in the lattice cell and where in the arc the magnet can be placed taking into account also a

number of other sorting criteria (magnetic field quality and other) [2]. In Fig. 1, the crosses represent the position of the cold bore tube center with respect to the theoretical position. The position if the cold bore tube has to be within the “race-track”; in the Fig. the race track represents the “silver” class where the radius of the half circle at the extremities of the race track is 0.75 mm. Other classes are defined by different values of this radius. The radius may also vary along the magnet for some classes. For the largest tolerance the radius is 3.1mm.

Fig. 1. The “silver” class, represented in a plane perpendicular to the magnet axis: the cross is the position of the beam tube center and it has to lie within the race-track shape. Dimensions in mm.

The tolerances used for the class specification are applied on measurements immediately after cold test and all adjustments of the shape, including some contingency for further shape changes (e.g. due to transport, time). Estimated needs to be able to cope with increasing production speed are shown in Table II.

TABLE II
REQUIRED GEOMETRY CLASSES, IN % (AFTER COLD TEST)

Gold	Silver	Silver Left	Silver Right	Mid Cell
>13	-	<14	<14	<10

To fulfill requirements for the aperture in the machine and give the necessary contingency to allow for the logistics needs at CERN the shape of the magnets must be, at least, distributed as shown in Table II.

The horizontal sagitta, see Fig. 2, calculated over the magnetic part, is related to the curvature which is an important criterion to be able to judge the overall geometry. We use also this parameter for evaluation of the magnet shape.

Fig. 2. A Dipole with a slightly too small sagitta; the y-axis represents the theoretical (nominal) curvature at warm temperature, the x coordinate points to the center of the machine. The value for the flange position and the corrector position are expressed relative to the theoretical trajectory (y-axis).

B. Field Correctors

The field correctors are thin windings to compensate for unwanted field components in the dipole coming from chosen design options or by component assembly procedures not fully controlled. Their alignment with respect to the beam trajectory is essential to avoid feed-down effects from the field in the corrector giving unwanted components to the field seen by the beam. The tolerance of their position after geometry adjustment at CERN is 0.3 mm average and 0.4 mm standard

deviation.

IV. MEASUREMENTS

The measurements on the geometry that we are concerned with for the beam performance are measurements of the shape and of the corrector positions. Measurements of the center of the cold bore tube along the magnet and of the interconnecting flanges at ambient temperature of every magnet are performed in industry [3] and at CERN [4]. In industry, the mechanical position of the corrector magnets is also measured. For measurements carried out after the cold mass end covers have been mounted we estimate the position of the corrector by using measurements on the end cover assuming rigid movement of the ends when the magnet is deformed. Magnetic measurement of the corrector axis has confirmed this approach.

V. DEFORMATIONS OF THE COLD MASS

The cold mass has a “natural geometry” when the assembly is finished. This geometry is considered the best possible for the magnet and is the target for further steps in the assembly of the cryodipole. Measurements show that the sagitta of the magnets increases after shipping to CERN and after cold test [5]. This change in sagitta is not the same for the three firms, see Fig. 3. The change of the sagitta is not correlated to the value of the sagitta at the last measurement before shipping to CERN (Fig. 4). The non constrained shape after cold test was measured for 408 magnets allowing a statistical evaluation of the change of shape between measurements in industry and measurements after cold test.

The mechanism behind the sagitta increase is not understood. The curvature of the press during welding is higher than the final value to allow for the “spring back” to nominal geometry when the magnet is released from the press. The increase in sagitta may be related to an equilibrium between the forces from the weld and friction between laminations, and between laminations and the shrinking cylinder. This is being investigated through experiments.

The overall vertical shape is determined by the positioning of the three supports during the measurement. The last measurement in industry is the reference and the reproducibility of this positioning at later stages is important.

Significant local deformations between the last measurement in industry and later measurements, deformations over a limited longitudinal extension, have been detected for one firm only, at early production. The important “mode” of deformation is the change of sagitta. By using a simple mechanical beam model [6], we can distinguish local shape changes from changes of the sagitta. A sagitta change can be corrected by adjustment of the central support, which is the only possible way of shape adjustment when the magnet is at CERN.

The fact that we have no important local deformations but essentially only deformations related to a change in sagitta, makes it possible to control the shape by varying only one

applied constraint: the position of the central support.

Fig. 3. The histograms show the change of the sagitta of magnets from the last measurement in industry to a measurement made after cold test. The graph shows magnets horizontally free at the central support. Magnets change shape differently according to firm.

Fig. 4. The figure shows that there is no correlation between the initial sagitta and the change in sagitta between industry and CERN.

VI. THE ADJUSTMENT PROCEDURE

A. Adjustments of the geometry

The magnet is blocked horizontally and vertically at cryostating, before cold tests. The magnet is placed vertically on its three feet on a horizontal plane. The magnet is blocked, keeping its natural horizontal shape. After cold test the magnet can be adjusted horizontally [7] and vertically by adjusting the position of the central support. Adjustment of the horizontal and vertical position of the central support is the only control

lever for geometry changes once the cold mass is cryostated. In general, this way of adjusting the shape at only one location along the length is good enough to reproduce the original shape in industry within a precision of 0.3 mm on the measurement positions along the magnet.

By measuring the geometry of the magnet after cold test we are able to deduce how much the magnet has to be adjusted to resemble the shape in industry. After adjustment, a new confirming measurement is needed. In this way, by measuring the geometry before and after the adjustment we are very close to our target. This is the adjustment procedure used in the beginning of the production, until February 2005. With increasing production speed and a limited number of measurements possible due to constraints in time and resources, only one measurement per magnet (there is some contingency for special cases) could be made. Since there is no correlation between the sagitta change and the sagitta already measured in industry (see Fig. 4) we cannot deduce the adjustment needed from this measurement. However, statistically we know how much the magnet sagitta increases from industry to post-cold test. Each magnet is adjusted, before any measurement, using the statistical average, different for each firm, of the sagitta change. After the adjustment we measure. In this way we have been able to perfectly adjust the mean value of the sagitta by measuring only once. The sagitta is an important overall evaluation criterion for the shape and determines also the position of the ends of the magnet (including flanges and correctors). If the position of a flange exceeds 0.87 mm after adjustment, the magnet will be re-adjusted to the geometry in industry and re-measured.

With this new procedure we are closer to the limit for the tolerances on the spread for the correctors since no individual control on the shape is made. The spread of the corrector position cannot be controlled by this method. The control procedure aims to have the mean of the flanges at the nominal position which will also minimize the spread. The corrector position follows the flange position. Corrector position has to be carefully monitored to avoid exceeding bounds.

B. Monitoring

The frequency of the set value corrections is governed by changes in production and of the adjustment procedure. Too frequent changes give unstable adjustment. The set value for the control is changed if the moving average of the last 30 magnets exceeds 0.2 mm, see Fig. 5. In the figure we represent the flange position, which is our control variable and which has a linear relation to the sagitta. The calculated initial horizontal set value for firm 3 gave a too high value on the flanges (we aim at 0.0 mm for the flanges); this was adjusted after about 20 magnets. We should observe that, in the figures, magnets with flanges exceeding 0.87 mm will be put close to zero by adjustment of the magnet to industry conditions.

The correct functioning of this method relies on stable production in the three firms [2]. The position of the cold mass supports is important for correct vertical correction. Stable sagitta change for each firm is also important.

Fig. 5. Example of monitoring for correction of adjustment values for firm 3. The moving average over 30 magnets is corrected if > 0.2 mm.

VII. RESULTS

Results for the correctors are shown in Table III from February to June 2005 for magnets adjusted statistically. The positioning tolerances are 0.2 mm, average, and 0.4 mm, standard deviation. We see in Fig. 5 that we are slightly closer to zero for recent magnets, so the result for the final production should be slightly better than the values presented. The whole production, including adjustment to shape in industry made before February 2005, is shown in Table IV.

A. Aperture

TABLE III
RESULTS FOR STATISTICAL ADJUSTMENTS: CORRECTOR POSITION
(DEVIATION FROM NOMINAL)

	dx [mm]		dz [mm]	
	mean	stdev	mean	stdev
Octupole	-0.02	0.38	-0.03	0.18
Sextupole	0.01	0.37	-0.12	0.21

TABLE IV
CORRECTOR POSITION (DEVIATION FROM NOMINAL) OF WHOLE
PRODUCTION

	dx [mm]		dz [mm]	
	mean	stdev	mean	stdev
Octupole	0.05	0.28	0.02	0.23
Sextupole	0.11	0.27	-0.13	0.30

The results show that the final shape of the magnet after cold tests and adjustments are very satisfactory using statistical adjustment (Table V and Fig. 5): Statistical adjustment is now being used as baseline for the LHC. It is important to check that the magnet shape is not altered due to transport and ageing after adjustments. Transport and storage time of one year does not give significant contribution to the mean value of the

corrector position (the mean value is less than 0.1 for the firm showing the largest change and the standard deviation less than 0.2 mm including errors from subtracting measurements).

TABLE V
CLASSES AFTER ADJUSTMENT (WITH CONTINGENCY FOR STORAGE).

Fig. 5. Classification at industry and CERN for magnets adjusted statistically. The class boundaries used here have contingency for additional shape change due to movements at storage and transport after the last measurement.

For the tunnel the tolerance on the positioning of the correctors is 0.3 mm (mean) and 0.5 mm (standard deviation). For the mean, we are close to zero and for the standard deviation we have, including known uncertainties:

$$\sqrt{cmag^2 + ccern^2 + ageing^2 + tunnel^2 + \phi_{tunnel}^2} = 0.42\text{mm},$$

where $cmag$ is the difference between mechanical and magnetic axis of the corrector, $ccern$ is the measured position at CERN, $ageing$ is the stability with time and transports, $tunnel$ is the precision of the position in the tunnel measured on the fiducials and ϕ_{tunnel} is the contribution on the ends from tilting the magnet in the tunnel. The standard deviation will become larger when the production is finished due to a larger amount of statistically adjusted magnets but will likely not exceed the limit. Cold/warm relations are not included: they are not expected to change significantly the picture.

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