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The LHC Dipole Geometry as Built in Industry

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***Abstract*— The LHC dipoles magnets are produced in 5 industrial production sites in Europe. The production is well underway and more than half of the total quantity has been delivered to CERN. One of the important characteristics of the dipole magnets is their geometry. To achieve the requested mechanical tolerances on the magnets, which are 15 m long and have a ≈28 t mass, the final assembly operations includes precise optical measurements. To ensure the good quality and high production rate, the final assembly procedure has been automated as much as possible. The authors report here about the assembly procedure, the features of the software that guides the optical measurements (and consequently the assembly operations) and the results obtained on the geometry in the different sites.**

Index Terms— LHC, superconductivity, dipole magnets, geometry, survey

I. Introduction

MORE then half of the production of the LHC dipole magnets is done. The production is equally shared between 3 European suppliers: the consortium Alstom-Jeumont in France, Ansaldo Superconduttori in Italy and Babcock Noell Nuclear in Germany, in the following referred to as the firms [1] . The 3 firms are working with slightly different configurations of their assembly benches and tools, but with the same assembly procedure, achieving similar results concerning the most salient characteristics of the dipole cold masses including their geometry. All 3 firms are producing dipole cold masses well within the required geometrical tolerances with a very small number of non-conformities. The feasibility of the optical measurements-assisted industrial assembly procedure is confirmed thanks to the semi-automated operations guided by home made software called Dipole Geometric Measurements (DGM).

II. Requirements for the Geometry of the LHC Dipoles

In order to preserve the beam aperture of the LHC machine, the local deviation in the transverse plane of the cold bore tubes (CBT) with respect to the theoretical reference orbit must fulfill a tolerance in the vertical plane of ±0.75 mm and in the vertical plane up to ±1.55 mm. To assure the interconnection of the magnets in the tunnel, the ends of the cold masses should be within a circular tolerance of 0.87 mm. For very specific locations in the LHC ring, like in the dispersion suppressors or in the first two half-cells of each arc, the above tolerances are more severe, not exceeding ±0.8 mm in horizontal plane and ±0.5 mm in the vertical plane [2], [3]. In order to achieve the above described requirements, the magnets are built in industry with a similar reduced tolerance range. During pre-series production, we evaluated with the firms the feasibility in an industrial environment of the initial tolerances specified for the dipole cold mass series production. Following this assessment most of the tolerances were revised by about 30-50%. The shape tolerance in the vertical plane was reduced from the initial ±1 mm to ±0.8 mm while in the horizontal plane was relaxed from ±1mm to ±1.5 mm. The tolerance on the position of the corrector magnets was kept in a circle of 0.3 mm radius and, for the extremities of the CBT, was relaxed from a circular tolerance of 0.3 mm radius to one of 0.6 mm radius [3].

III. Measuring System

A. Hardware

The tight tolerance range that is required was one of the two main arguments when the measuring system has been chosen. A second argument was coming from the definition of the reference plane of the twin aperture LHC dipole cold masses that is given by the axes of the two CBTs. The inner diameter of the CBTs being of 50 mm and the length of about 15 m, the sole system capable of making the measurements with a sufficient accuracy was an optical-measurement based Laser Tracker (LT) equipped with an Absolute Distance Meter (ADM). The instrument use target reflectors. Each of the 3 firms was equipped with 2 LTD500™ instruments and with the ancillary equipment that was developed at CERN: three mechanical moles equipped with reflectors and a couple of tripods with motors and electromagnetic clutches. The mechanical mole driven by the motors and clutches can travel inside and along the CBT taking measurements to reconstruct the axes of the CBTs off-line [4].

B. Measurements accuracy

Although the measuring system would enable us to take measurements in a continuous mode on a moving mole, the axes are measured at fixed mole position, to gain on the accuracy of the measurements. The measuring system in such

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condition can guarantee an accuracy of 0.2 mm.

C. Software

1) Axyz™

Axyz™ is essentially an industrial system used for large-scale 3D metrology. It can generate on line, the 3D co-ordinates of selected object points and provides a wide range of analysis functions to process the object point data. Two modules mainly compose Axyz™: a first one responsible of the communication with the hardware (LTD500), and a second one handling the database and the analysis module.

2) DGM

Considering the number of cold masses to be produced and the complexity of the assembly operations it was necessary to develop a script that commands the measuring system, restricting its functionalities to those used for the dipole cold mass assembly. The goal was to homogenize the production, increase the manufacturing speed and minimize human errors. Although the Axyz™ is equipped with a Process Automation Module for programming sequences of commands and available functions, CERN has chosen the solution of programming the Axyz™ software through OLE[1] commands, by using Visual Basic™ programming language. The DGM is completed by a Lab View™ programmed graphical user interface for online analysis and graphical data representations. By integrating the DGM script into the assembly procedure, the measurements can be done by on-shift qualified operators and the measurements accuracy and reliability is guaranteed [5]. The automation of the measurements could be made thanks to the ADM, to the function "Find" of the Axyz and the DataBase module of the DGM. In each firm and for each measuring bench a fixed network of reference points was created and their positions with respect to the possible positions of the measuring instruments were recorded into the database. In doing so, the laborious tracking[2] by an operator has not been necessary and the reference points targeting could be done automatically from the PC whereby saving time in the operation.

IV. The Assembly Process Guided by the DGM Software

The cold mass geometry is determined when the two half cylinders, making up the main part of the helium vessel are welded together [6]. The CBT axes are measured followed by an on-line analysis that links and then compares the cold mass shape to the virtual theoretical shape. Once the cold mass shape is known with respect to the theoretical reference system, the cold mass components can be aligned with respect to their theoretical position.

A. The Reference Coordinate System

The reference co-ordinate system is a right-handed orthogonal system having its origin in the geometrical center of the end cover situated at one end[3]. In this coordinate system, the theoretical axes of the CBTs are coincident with the theoretical trajectory of the beam and, therefore, are defined as two portions of an arc, of radius of 2812.36 m and of a length equivalent to the magnetic length of the dipole cold mass: 14.343 m [3], [4].

B. Measurements of the Dipole Cold Mass Geometry

Measurements are taken from both sides of the CBTs in order to gain in accuracy from about 10 ppm to 6 ppm. Since the measuring system requires to be moved with respect to the cold mass, an external reference network is necessary to link the measurements between them. The different sets of measurements are then transferred into a common coordinate system by performing a "bundle adjustment".[4] To compare the measurements with the theoretical geometry, the measurements are transformed into the theoretical co-ordinate system by a 3D best fit [4]. This operation is done on-line by the DGM, allowing the operators at any moment to check the acceptance of the dipole cold mass shape [5].

C. Positioning of the Components

The main components to be positioned with respect to the reference coordinate systems are the corrector magnets, the end covers, the cold support post pads and the extremity of the CBT's. The DGM program guides the operators with instantaneous graphical representation of the measured objects and gives indications about the acceptance and the necessity of further adjustments.

D. Data Reporting

During the full assembly of the magnets, the relevant information about the cold mass shape and the components position are kept in an encrypted[5] file that is automatically filled up by the DGM. At the end of the assembly, the documentations is done by the DGM that copies from the encrypted file into a write-protected Excel file called "traveler" all information that is then submitted for acceptance.

V. Results Obtained in Industry

By the end of July 2005, 805 dipole cold masses out of the 1232 needed for the accelerator had been delivered to CERN.

A. Non-Conforming Magnets

Most of the parameters are well within the required tolerances. Nevertheless there are about 95 nonconformities

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[1] Object Linking & Embedding

[2] The tracking makes reference to the technique of moving the reflector while the laser beam is locked on the reflector. This feature is specific to the LTD instruments.

[3] The end cover is part of the helium vessel that closes it in a leak tight way once it is welded to the half cylinders by a circular welding.

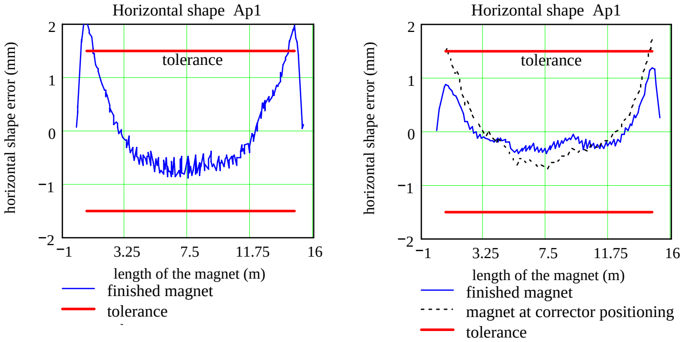
[4] The bundle adjustment is a least square optimization. It is performed by taking the measurement points and making successive adjustments until there is a best fit between the mathematical model and the actual measurements.

[5] The file is encrypted in order to avoid any manual off line change of the data that are reported to CERN.

(NC) opened in industry for geometrical defects. The most typical NC's are those linked to the shape of the magnets in their horizontal plane, due to a curvature that in some cases is higher and in some others is lower than the nominal one with a difference exceeding the tolerance of ± 1.5 mm. An example of a magnet exceeding the tolerance is shown in Figure 1 (a). A second type of NC on about 80 magnets concerns the position of the corrector magnets. It was caused by a bad interpretation of the measuring and assembly procedure and was found only upon delivery to CERN.

1) Possible Repairs on Shape NC

There are two possibilities of repairs on non-conforming magnets: one is to cut the two-welded half cylinders and to replace them with another pair and a second one is to force the magnet shape closer to its nominal curvature by blocking the central vertical support to a fixed place during assembly and later in its cryostat [3], [7]. The first choice was abandoned, as there is no real guaranty for the results of this very costly and time-consuming repair. Moreover no correlation was found between the shape of the half cylinders before welding and the shape of the magnets[8].The second solution is technically feasible in a reasonable time and without extra cost but is limited by the rigidity of the cold support post in its cryostat [7]. This type of repair was applied with success in two cases. See Fig. 1(b).



a. b.

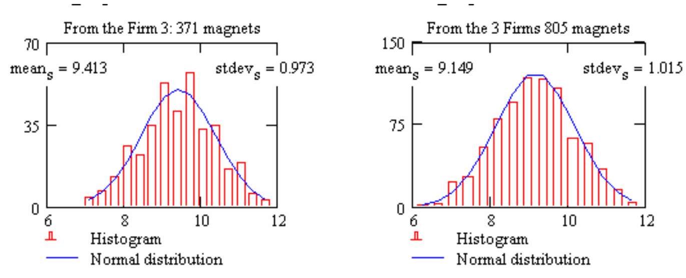
Figure 1 (a.) Example of a non conformity on the shape of a magnet accepted without any repair. (b). example of non conformity on the shape with repair by blocking the central post position ("magnet at corrector positioning" corresponds to the stage before the central foot is blocked).

2) Acceptance of NC Magnets

On 11 magnets, a deviation was reported in the magnet horizontal plane up to 20% out of the tolerance range. These NC's on the shape are considered critical, as the impact of the default is not negligible on subsequent integration of the magnet in its cryostat, on its connection to other magnets and on its location in the LHC ring. Therefore these NC's are treated by a dedicated committee of experts, which tries to find a location for the magnets without repairs. The proposed locations for those magnets are the less critical mid-cell positions where the tolerances are much more relaxed than in other positions in the ring: up to ± 3.1 mm in the vertical plane and ± 3.9 mm the horizontal plane. The error on individual corrector magnet positions are statistically i.e. non critical and the magnets are accepted without repair. This effect was compensated pushing the systematic error below 0.1 mm in the remaining production. For all magnets with NC that were accepted without any kind of repair, the other geometrical parameters were within the required tolerances.

B. *Magnet Shape*

The shape of every magnet produced in industry is checked along the magnet length with respect to tolerances in the vertical and the horizontal plane. To characterize the magnets, we use the so called "fitted sagitta" [9]. The sagitta distribution of the delivered magnets is shown in Figure 2 and Table I.



a. b.

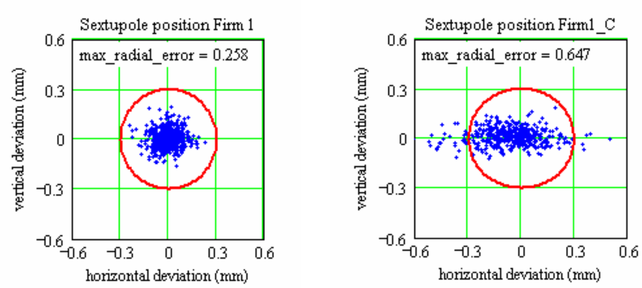
Figure 2 (a). Distribution of sagitta in magnets from Firm 3 (whose production is near completion) and (b). Distribution of the sagitta of the delivered magnets from the 3 firms

TABLE I. STATISTICS ON SAGITTA

firm	mean sagitta	min sagitta	max sagitta	stdev sagitta
1	9.08	6.2	11.8	1.09
2	8.73	7.4	10.9	0.82
3	9.41	6.9	11.8	0.97

C. *Corrector Magnet Position*

The corrector magnets are positioned on the dipole cold mass before the end cover is placed and fixed to the shrinking cylinder by welding. The positioning operation of the correctors gives very good results, as shown in Figure 3 (a), but is done with respect to a reference geometry that is not that of the finished magnets.



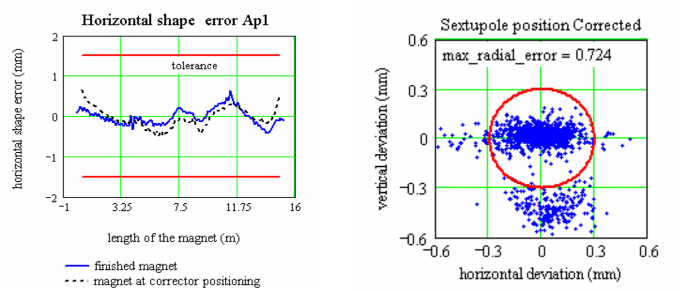
a. b.

Figure 3 Position of the MCS[6] correctors during alignment (a.) and with respect to the final reference plane of the magnets (b.) in Firm 1.

To enable welding the end covers to the shrinking cylinders, the magnet has to be moved and can be changed to a different assembly bench. This movement [Figure 4 (a)] makes that the final position of corrector with respect to the finished magnets is somewhat worse than at the moment of

[6] Sextupolar corrector magnet

positioning [Fig. 3 (b)]. The spread is 0.125 mm, but the mean error value is zero. The NC on the positioning of the corrector magnets in about 80 magnets made that the mean value of the vertical error of the position of the MCS corrector magnets is -0.04 mm, with a relatively high spread of 0.158 mm [Fig. 4 (b)].



a. b.

Figure 4 (a). Change of the horizontal shape of the magnets during assembly causing a spread of the position of the correctors in the horizontal plane and (b). Position of the MCS corrector magnets with respect to the finished dipole cold masses.

D. Position of the End Flanges

The position of the end flanges of the magnets is within the required tolerances. On one non conforming magnet an excess of the tolerance of about 0.1 mm was accepted. Figure 5 shows the position of the end flanges of the magnets in Firm 2 (as an example) and over the whole production.

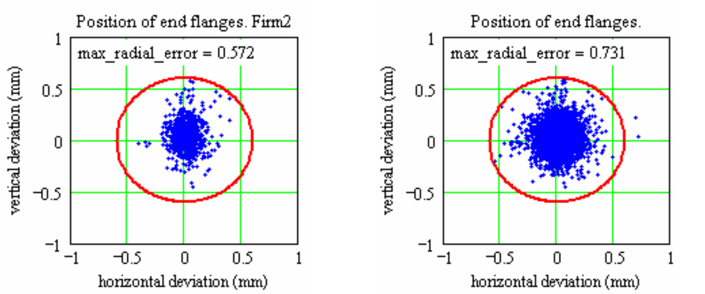


Figure 5 Flange position (a) on Firm 2 magnets, (b) on all firms

E. Other Geometrical Parameters

Other geometrical parameters are measured and compared with tolerances as: the position of the MCDO[7] corrector magnets, the position of the end covers with different interconnecting lines welded and the position of the cold support post pads. No NC was reported on any of those parameters.

F. Classes

The geometrical shape of the magnet along the axis has an impact on the aperture of the accelerator. More or less strict requirements on the magnets are necessary according to their final positioning in the machine. The magnets can, by using these different requirements, be classified into three categories that we call "gold" for critical positions in the machine, silver, and "other" for the less critical mid-cell positions. The limits of the "gold" and "silver" classes are given in [2]. About 30% of the built magnets are classified gold and only 10% as mid-cell position magnets. The actions taken at CERN during the cryodipole assembly to keep the magnet classes obtained in industry are described in [10].

VI. CONCLUSION

More than half of the overall production is done in the 3 firms. The semi-automatic final assembly procedure has given successful results regarding the feasibility of the operations in an industrial environment and regarding the precision of the cold mass geometry. Globally the shape of the magnets is good and the sagitta distribution is centered on the nominal value of 9.14 mm. In spite of the NC on about 80 MCS corrector magnets the global production is well within the statistical tolerances. About 30% of the magnets have an extremely good geometry and only 10% of them have to be installed in the mid-cell location where geometry requirements are less critical.

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REFERENCES

[1] F. Savary et al., "Status Report on the Series Production of the Main Superconducting Dipole Magnets for LHC", *Submitted to IEEE Trans. Appl. Supercond*
[2] S. Fartoukh "Classification of the LHC main dipoles and installation strategy,"*Proceedings of the LHC Project workshop, Chamonix XIII*, pp. 148-158, Feb 2004
[3] M. Bajko et al. "The LHC Pre-series Dipole Cold mass Geometry", *IEEE Trans. Appl. Supercond*, 14 no. 2, pp.215-218, 2004.
[4] M. Bajko, R. Chamizo, Measurement and Analysis Methode of the LHC Dipole Geometry in the Industry, CERN LHC AT Internal Note 2002-03, Geneva, Sep 2002
[5] R. Chamizo et al., "Automation of 3D Measurements for the Final Assembly Steps of the LHC Dipole Cold Masses" *IWAA 2004*, Geneva, Oct 2004.
[6] Technical Specification for the Supply of 1158 Cold Masses of the Superconducting Dipole Magnets for the LHC Collider, CERN ref. LHC-MMS/98-198 Rev.2.0, EDMS document N°312601
[7] J. B. Jeanerret et al., " Executive summary of the workshop of the LHC Dipole geometry and stability and preparation for the implementations for changes , "CERN LHC Project Note-340", Geneva p. 4, Mar 2003
[8] M.Bajko, "Geometry of the dipole cold masses. Results of the first 20 magnets produced by Ansaldo," CERN, AT (MAS) Technical note, Geneva, Aug 2003-04, EDMS nr. 636645
[9] E.Wildner et al., "The Geometry of the LHC Main Dipoles", LHC-Project-Report-729, Geneva CERN, 2004.
[10] E. Wildner et al., "Control of the LHC dipole cold mass geometry at CERN to optimize LHC performance," *Submitted to IEEE Tran. Appl. Supercond*

[7] Decapolar and Octupolar combined corrector magnet