3-D METROLOGY APPLIED TO SUPERCONDUCTING DIPOLE MAGNETS FOR LHC

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1. INTRODUCTION

The construction of the Large Hadron Collider (LHC) requires the manufacture of 1232 superconducting dipole magnets containing two beam channels in a common mechanical structure. These dipole magnets, which produce the required magnetic field to deflect the particles along a circular trajectory, have to be bent in their horizontal plane in order to ensure the largest mechanical aperture.

Very tight tolerances on the geometry of these magnets have to be imposed during their fabrication in order to minimise, during operation, the possible losses of particles, which circulate in rather small channels and to ensure the alignment of the adjacent magnets in the ring tunnel. This necessitates a thorough metrological inspection of the magnet geometry and an accurate positioning of some of its components.

This paper presents the measuring system and the developed methodology to realise these operations. The results on the first 15m long dipole magnet are shown.

2. THE OBJECT TO BE MEASURED AND THE TOLERANCES

2.1 The cold mass

The cold mass can be seen as a long bend cylinder of 15 m long and of 0.57 m diameter. It is composed of superconducting coils which produce the magnetic field. They are surrounded by non-magnetic collars and an iron yoke which ensures a mechanical stability. The shrinking cylinder, composed of two half shells welded together, rigidify the magnet and together with the end covers constitute the He vessel.

2.2 The theoretical geometry

The dipole magnets have a magnetic length of 14.343 m, which imparts to the beam a horizontal deflection of 5.099 mrad, corresponding to a bending radius of 2812.36 m in the curved part of the cold mass. In the horizontal plane the sagitta is therefore 9.14 mm. The two axes of the cold bore tubes shall have the same geometry and be separated transversely by 194.52 mm. Beyond the arc the theoretical geometric axis of each aperture is prolonged along the local tangent to the arc. These extremities are the straight ends.

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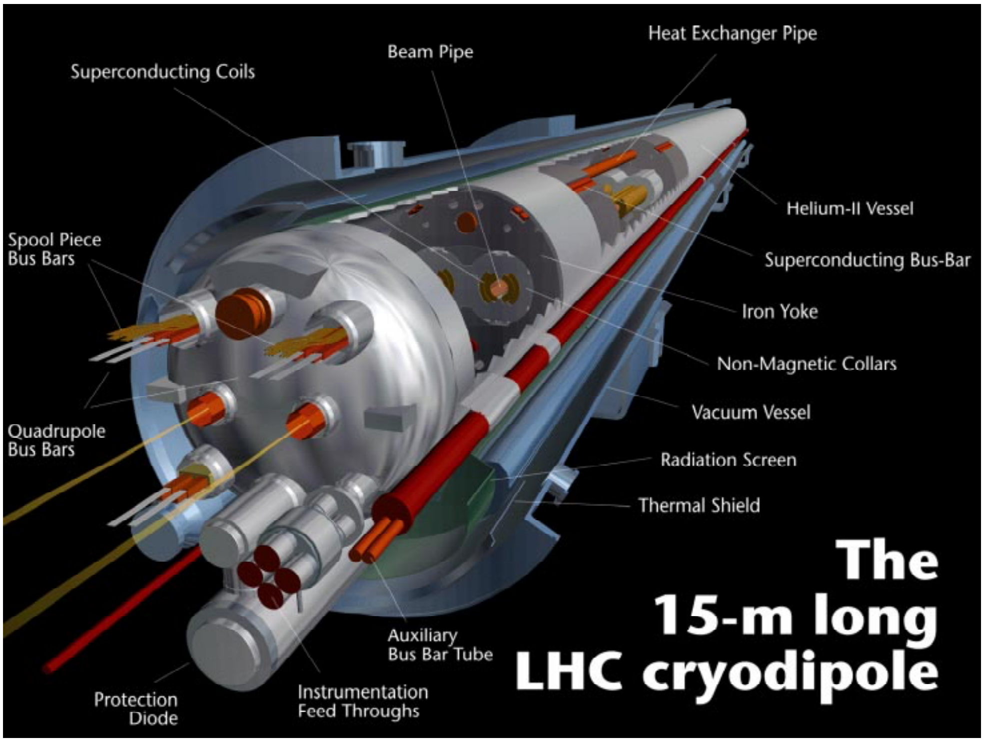

Figure 1 – The cross section of the cold mass

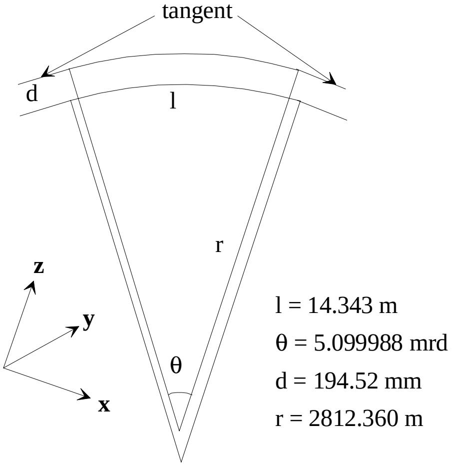

Figure 2 – Theoretical geometry of the cold mass at room temperature

2.3 The tolerances

In order to satisfy the mechanical aperture, the axis of each cold bore tubes has to be contained within a torus of 1 mm radius around its theoretical axis. The positioning of the corrector magnets has to be done with a tolerance of 0.6 mm at 3 σ.

In the interconnection area, the maximum offset tolerable by the below linking the cold bore tubes of two adjacents dipoles is 4 mm. Ground movements, detected in the LEP tunnel, as well as arm lever effects and security margin for the alignment necessitates that the positioning of the cold bore tubes extremities has to be realised with a tolerance of 0.6 mm (3 σ).

3. POSITIONING AND MEASURING OPERATIONS

The positioning and measuring operations, which are executed at the cold mass completion stage require the use of modern 3D technology techniques. They are listed as follows :

- Measurement of the horizontal curvature and vertical straightness of the cold mass
- Alignment of the corrector magnets
- Alignment of the orbital cutting machine
- Positioning of the end covers that will close the cold mass
- Positioning of the cold mass support pads
- Alignment of the extremities of the cold bore tubes
- Measurement of the position of the extremities of the other interconnect lines.

4. MEASURING SYSTEM AND PROCEDURES

4.1 The measuring system

The 3D instrument used to realise these metrological operations is a fully automatic polar co-ordinates system (*laser tracker*). The automatic aiming on a *retro-reflector* is done using the beam return of the laser tracker on a Position Detecting sensor (PSD). Two encoders circles are measuring the angles while the distances are measured with either an Absolute Distance Measurer (ADM) or an Interferometer (IFM). The Cartesian co-ordinates issued from the polar ones are given with an accuracy of 5 ppm (part per million) at 1 σ.

For the measurements inside the cold bore tubes, a “*mole*” was developed at CERN. This mole, which positions itself at the centre of the tube, receives a retro-reflector used by the laser tracker.

This measuring system is really adapted to the metrological operations on an object of so big dimensions. Its versatility allows to realise *all* the metrological measurements mentioned in §3 and especially the measurements inside the cold bore tubes. It is a portable equipment that can be moved around the object during this assembly phase.

The accuracy of the instrument is within the positioning tolerances and the way it measures allows and requires redundancy measurements which improve the accuracy and prevents from errors which is important for the quality control.

The instrument is totally automatic and therefore its use requires only a light training for the operator. Moreover it has not required a specific development and therefore the maintenance is guarantee.

4.2 The measuring procedures

A network of "external points" installed around the cold mass as well as "object points" located on the cold mass is measured from four different positions of the laser tracker and their co-ordinates are calculated using a bundle adjustment program. The "external points" are used to link the measurements taken from different laser tracker positions while the purpose of the "object points" is to transfer outside the object its internal geometry. They are used once the object is no longer known in the "external points" referential.

Simulations programs have determined the best position for the "external points", which must be non coplanar and regularly spread out around the cold mass as shown on figure 3.

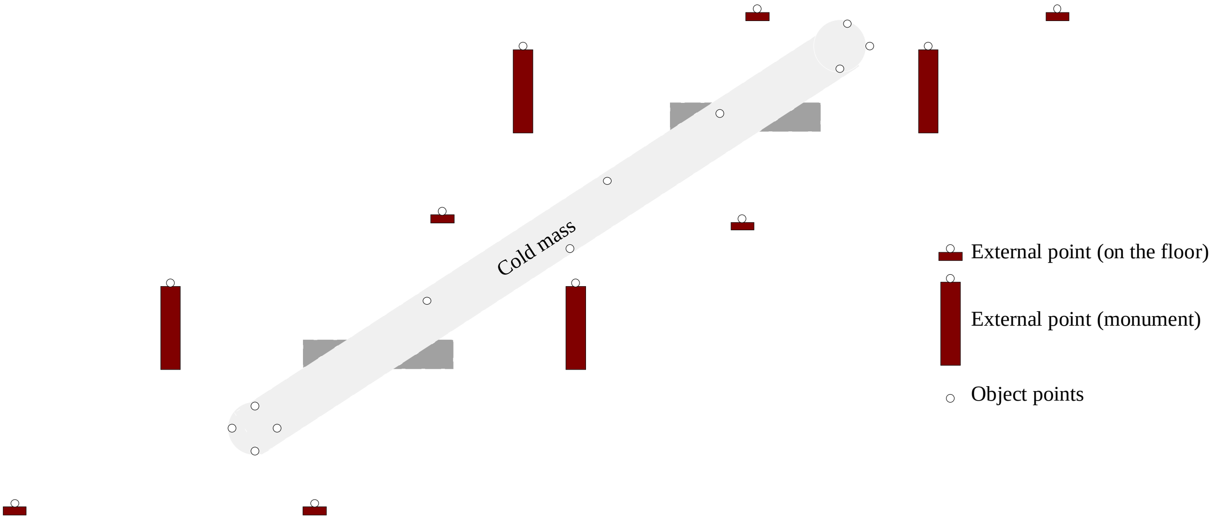

Figure 3 – Network of external and object points

The *measured geometry* of the cold mass is represented by the axis of the two cold bore tubes. From four positions of the laser tracker, one in front of each tube at each extremity, the laser tracker resects on the "external points" and measures the X, Y, Z co-ordinates of the cold bore tubes centre, every 100 mm, by tracking the reflector fixed at the centre of the "mole" described in §4.1. The co-ordinates of the points measured in the two tubes are known in the same referential XYZ.

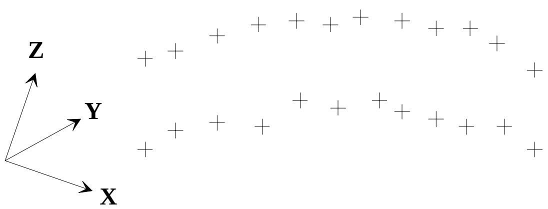

Figure 4 – Measured geometry of the cold mass

The "*adjusted geometry*" of the cold mass is obtained by adapting the theoretical geometry in the local xyz system on the measured geometry in the XYZ system. This is made through a Similarity transform, with least-square adjustment of the parameters, known as "Helmert transform" in geodetic calculations. Therefore, for each measured point, a conjugated point has to be calculated on the theoretical template. The program provides with co-ordinates of this template in the measured pattern as well as the deviations between the adjusted and measured points.[1]

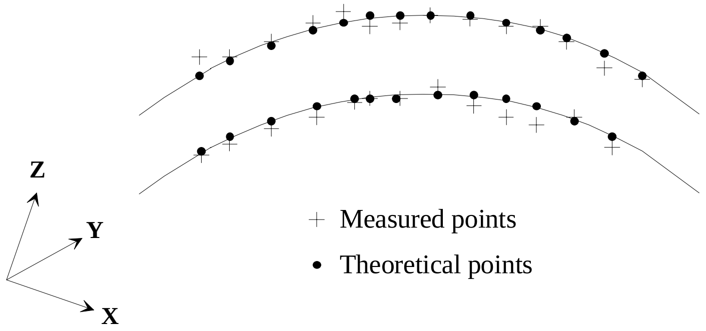

Figure 5 – Adjusted geometry of the cold mass

4.3 Other positioning operations

For all the measurement mentioned in §3, the following method is used. From a position located in front of the component to be measured or aligned, the laser tracker resets on the closest "object points" and measures the position of points well known with respect to the centre of this component. These points are equipped with a retro-reflector. Their measured position is then compared to the theoretical one calculated from the "adjusted geometry" and an alignment is done when needed.

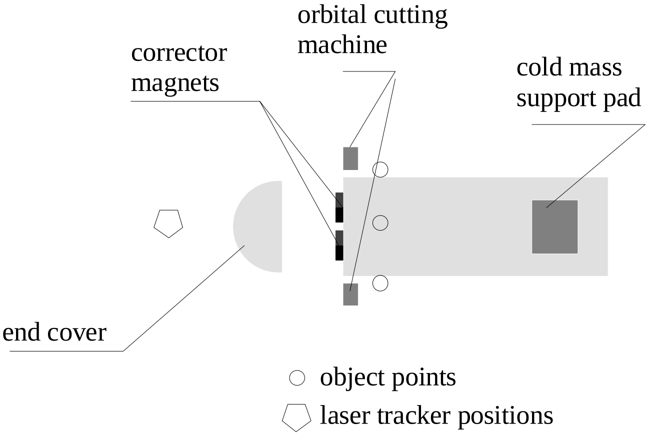

Figure 6 – Measuring operations

The measurement of the position of four corrector magnets is done using this technique, two holes on the plates supporting the correctors being materialised with retro-reflector.

In order to cut the shrinking cylinder at its nominal length, an orbital cutting machine has to be aligned in a plane perpendicular to the theoretical tangent and centred on the theoretical axis of the cold mass determined by the "adjusted geometry". The laser tracker will align the centre of the orbital cutting machine using four holes whose position with respect to its centre has been determined in a metrological laboratory.

The alignment of the end covers against the shrinking cylinder is done using three reference holes. The only possible alignment is a rotation around the longitudinal axis of the cold mass.

The positioning of the cold mass support pads is done using the same method, the support pads being materialised by four holes. As the support pads are welded on shrinking cylinder, the alignment can be realised in the longitudinal direction and in rotation around the longitudinal axis. Neither vertical nor transverse alignment is possible.

The cold bore tubes extremities are aligned on their theoretical position using the “mole” described in §4.1.

5. RESULTS ON THE COLD MASS MBP2N1

MBP2N1 is the first 15-m long dipole magnet prototype to be assembled at CERN. Its assembly was done in Spring 1999.

5.1 The network of points

A network of 14 points was settled up all around the object. Three of them were abandoned because of the proximity of a perturbed area. The co-ordinates of the remaining “external” and “object” points were determined with an accuracy of 0.15 mm at 1σ.

5.2 Cold mass geometry

The measurements of the cold mass were done from two positions of the laser tracker located at one extremity, a point was measured every 100 mm in dynamic mode [2][3].

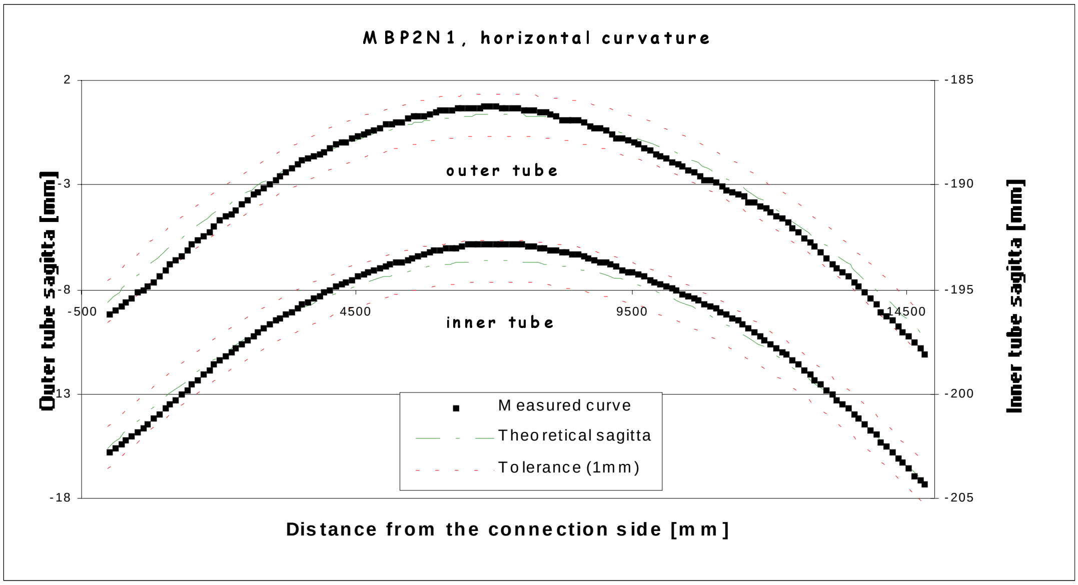

Figure 7 - Horizontal curvature

In the horizontal plane (Figure 7) as well as in the vertical plane (Figure 8), the axes of both tubes are located inside a circle of 1 mm radius around the "adjusted axis" of each tube.

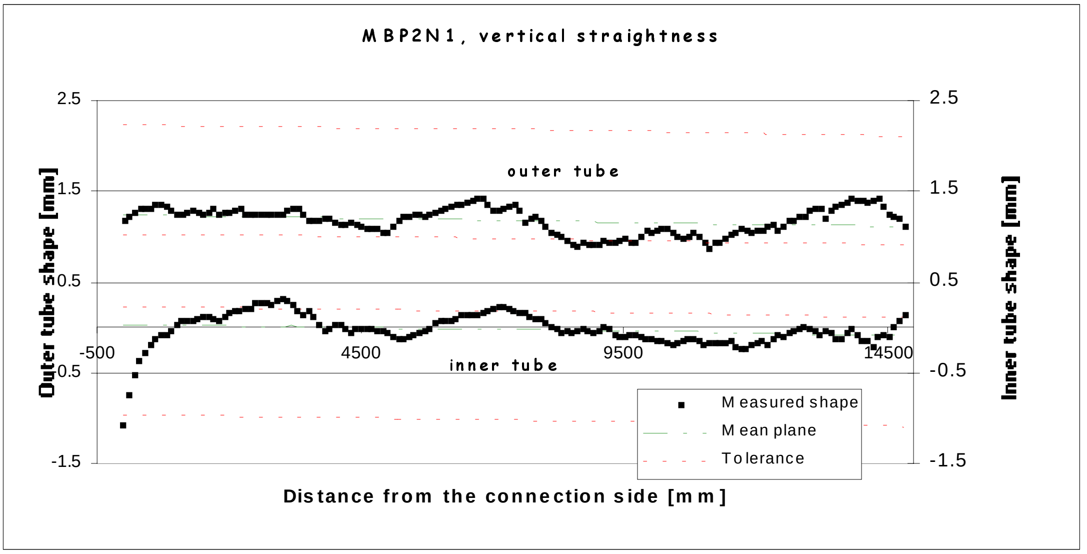

Figure 8 – Vertical straightness

5.3 Alignment operations during the assembly phase

Four corrector magnets, two decapoles and two sextupoles, were measured. Their position in Z is not within the tolerances (0.6 mm at 3σ) because the alignment system, under development, was not available at that time.(Table 1).

Table 1 – Position of the spool pieces

	dY (mm)	dZ (mm)
D1	0.00	-0.70
D2	0.02	-0.25
S1	-0.13	0.66
S2	-0.20	1.03

The orbital cutting machine was aligned at its theoretical position and its plane was set perpendicular to the “mean plane” and to the tangent with an accuracy better than the specifications. Therefore the end covers were aligned with the following results :

Table 2 – Position of the end covers

	dY (mm)	dZ (mm)
Connection side	0.19	0.15
Lyre side	-0.17	0.15

The cold bore tubes were aligned within the specifications (0.6 mm at 3σ). The results are shown in Table 3.

Table 3 – Position of the beam tubes at the extremities

		dY (mm)	dZ (mm)
Connection side	V1	0.05	-0.10
	V2	0.16	-0.12
Lyre side	V1	0.12	0.07
	V2	0.03	-0.05

The cold mass support pads were aligned at the position presented in Table 4. The positioning, possible only in the X and inclination (Tilt) direction, was realised with the tolerances. In the Y direction, the deviations are due to the difference between the theoretical geometry and the measured geometry while in the Z direction, the deviations are due to difference of thickness of the shrinking cylinder.

Table 4 – Position of the cold mass support pads

	dX (mm)	dY (mm)	dZ (mm)	dtilt (mrad)
Connection pad	0.61	-0.48	-1.25	-0.24
Middle pad	0.01	0.82	-0.92	0.20
Lyre pad	-0.19	-0.16	-0.04	-0.37

All the measuring operations were realised with the measuring system with the required accuracy. But the tables above show that the positioning of some of the components was not achieved within the tolerances, not because of the measuring system, but due to their alignment system. At the present time the measuring system is more accurate than some of the alignment systems, this is a point that has to be worked out.

7. CONCLUSION

In order to manufacture the future LHC magnet dipoles within very tight mechanical tolerances, a new instrument has been found and the relevant method developed. Both instrument and methodology have been tested on the first 15 m long dipole magnet prototype and it has been proved that the measuring specifications can be reached with this measuring system. The method will be improved during the assembly of the coming prototypes. For the first time, metrological operations will be included in the process of magnets construction, process which will be applied by the different manufacturers of the 1232 dipole magnets of the future LHC.

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