GEOMETRY AND ALIGNMENT REQUIREMENTS FOR THE LHC MAIN DIPOLE

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Abstract

The 15 m long LHC superconducting dipole magnets, which contain two beam channels in a common mechanical structure, produce a magnetic field of 8.3 T required to deflect protons with 7 TeV/c momentum along a circular trajectory in the already existing LEP tunnel. The dipoles are bent in their horizontal plane to provide the largest possible mechanical aperture to the circulating beam. This paper describes the theoretical geometry of the dipole cold mass and the alignment requirements, which are imposed to satisfy the demands of LHC machine operation. A short description of the measuring and alignment procedures and of the measuring instruments is given. Results regarding a small series of prototype cold masses are presented and discussed.

1 INTRODUCTION

The LHC uses superconducting magnets operating at a temperature of 1.9 K to guide the circulating particles. A specific feature of the magnets is the two-in-one concept with two magnetic channels in a common force-retaining structure. As a consequence, the two accelerator rings are mechanically linked and have to be aligned simultaneously during their fabrication up to their installation in the existing LEP tunnel. This unprecedented feature has important consequences on geometric tolerances of the cold mass assembly (CMA) of the 15 m long, 30 tonnes dipole.

Persistent currents, induced in the superconducting cables by the field variation during the accelerator operation, have detrimental effects on beam stability, especially during the injection plateau. Corrector magnets, placed at the ends of each CMA, may eventually compensate in an almost local manner the non-linear perturbation of the beam trajectories. The key issue is the accuracy of the alignment between the corrector itself and the magnetic axis of the dipole, by which detrimental second-order effect, i.e. uncompensated multipole feed-down, can eventually be limited [1].

In section 2, we describe the geometry and the alignment of the CMA. In Section 3, we present the geometric tolerances required for the CMA. In section 4, we report about the geometric shape of CMA prototypes, assembled at CERN and measured by high precision 3-D laser tracker. In Section 5, we draw some conclusions.

2 DIPOLE GEOMETRY

The specification of the LHC dipole geometry is based on three main constraints:

- The cold mass is to be bent around the beam orbit, to maximize the mechanical aperture, whilst minimizing the aperture of superconducting coils, i.e. their size.
- The corrector magnets at the ends of the CMA must be aligned with respect to the dipole axis, to reduce the multipolar feed-down effect.
- The radial displacement of bellows in the magnet to magnet interconnection should not exceed 4 mm. This issue is critical for magnet installation and implies accurate monitoring of the ground motion during LHC operation.

2.1 Geometrical parameters

The LHC ring contains 1232 dipoles, the main geometrical parameters of which are described in Table 1.

Table 1: Geometrical parameters of the LHC dipole

	1.9 K	**300 K**
Magnetic length [m]	14.300	14.343
Bending angle [mrad]	5.099988	5.099988
Sagitta [mm]	9.12	9.14
Bending radius [m]	2803.928	2812.360
Axes separation [mm]	194.00	194.52

During LHC operation at 1.9 K, two counter-rotating beams follow flat straight trajectories which become circular along the 14.3 m long active part of each dipole. The two orbits are separated by 194 mm, i.e. the nominal distance between the twin-coil axes. The CMA axes should be aligned along them. In assembling conditions at 300 K, one has to take into account the thermal effects, which bring to 14.343 m the magnetic length and to 194.52 mm the distance between the coil axes. The dipole is thus curved in the horizontal plane with an apical angle θ of about 5 mrad, identical to the bending angle of the circulating protons. The length of the curved section equals the magnetic length. The two channels have the same curvature. Indeed, the dipole geometry is determined from the functional specification at 1.9 K, whilst, the temperature-induced variation of the geometry after cool down is determined by both the longitudinal and the transversal thermal contraction of the CMA. The vertical shape should be straight. In fact, the CMA is distorted by about 0.3 mm, between the three supporting pads, by the effect of the self-weight and of the given flexural strength of the shrinking cylinder. During production, the originally straight dipoles are curved as they are assembled with pre-bent shells in an appropriate jig and a welding press. The resulting shape of the cold bore axes is measured with a high precision 3-D laser tracker. The data are used to fit the position of the two ideal cold bore axes above defined, shown in Fig.1 and 2, and to identify the horizontal and vertical CMA reference planes. To optimize this procedure a methodology for the dimensional inspection of the dipole cold mass has been defined. Its particularity is the implementation of 3-D measurements as part of the cold mass assembling procedures. To this scope, a 3-D portable measuring system, allowing all the necessary measurements during the different assembling steps of the cold mass has been specified and tested (also in industrial conditions) on the first three 15 meter long prototype CMA with satisfactory results [2].

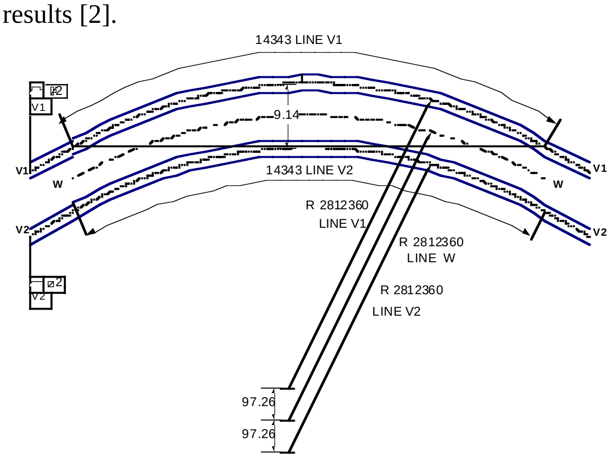

Figure 1: Horizontal theoretical shape of the cold mass in assembling conditions

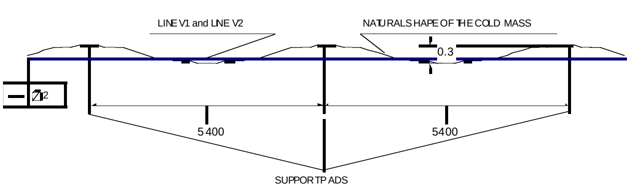

Figure 2: Vertical theoretical shape of the cold mass in nominal supporting conditions (three support pads).

2.2 Corrector magnets

The LHC dipoles are affected by unavoidable field-shape imperfections mostly due to fabrication tolerances, persistent currents and iron saturation. The field errors are minimized by optimization of the coil cross-section. However, the effect of persistent currents is too large to be fully compensated by design. The residual multipoles induce beam instabilities, especially at injection field, which should be locally corrected in each dipole. To this scope, at the connection end of the CMA there is a sextupolar corrector about 150 mm long and at the lyra-side end, there are combined octupolar-decapolar correctors about 110 mm long. Since they are very close to the source of error, they can be very efficient on the condition that they are well aligned to the beam channels. Indeed, a multipolar lens of order n traversed off-axis by a charged particle can be described by an appropriate combination of multipolar terms of order k, with $k \leq n$. This effect is referred to as the feed-down of the multipolar harmonics. In presence of misalignment, dipoles and associated correctors can have unequal displacements from the reference orbit. In this case the feed-down harmonics of a given multipolar error of order n and of the corresponding corrector are different, except at the order n itself. Consequently, the compensation is still very good at the order n itself, but it is imperfect at the lower orders. In [1] there are quantitative estimates for the multipole feed-down due to misalignments and an evaluation of allowed tolerances for the alignment of the correctors at the dipole ends. Random misalignments of the correctors with respect to the dipole axis with standard deviations up to 0.5 mm do not introduce additional detrimental non-linear effects. Systematic misalignments of the correctors may be more disturbing. In particular, the feed-down effect overcomes the upper limit of field-shape errors, expected in the dipoles, for an offset larger than 0.3 mm. In positioning the correctors, we assume that the geometric and magnetic dipole axes coincide within 0.1 mm.

3 GEOMETRY TOLERANCE

In the curved part of the CMA, two toroidal sectors are generated by a circle of 1 mm radius and moved along the circumference of the theoretical geometric axes of each beam channel. In the straight ends, a 0.3 mm radius cylinder represents the tolerance range. The combination of the toroidal sectors with the straight cylinders gives the shape tolerance for the axis of each magnet aperture. The horizontal and vertical ranges of tolerance are also traced in Fig. 1 and 2. The corrector magnets are enclosed in the end covers of the dipole cold mass. Their magnetic centers have to be localised on the straight ends of the CMA axes within ± 0.3 mm. Due to the laminated structure, a twist distribution along the dipole magnet may occur, which means that the geometric axes of the two cold bore tubes do not lie in a perfect plane. The twist distribution in the curved part as well as in the straight ends, i.e. the local twist along the cold mass assembly shall be within ± 1 mrad relative to the CMA ideal axes. These tolerances ensure sufficient aperture for the circulating particles, tolerable harmonic feed-down and limited offset of the bellow at the interconnection.

4 MEASUREMENTS

The 3-D optical system by which the dipole axes are measured is based on the interferometric laser technique and incorporates high-precision absolute distance meter and angular encoders. The measurement of the cold bore axes necessitates a mechanical mole centered on the inner wall of the cold bore and holding a reflector. The 3-D co-ordinates of the reflector center describe the axis of each tube. Thanks to the portable measuring instrument and the adopted measuring technique, the two cold bore tubes and the different elements (correctors, support pads, end covers) are measured and aligned in a common co-ordinates system.

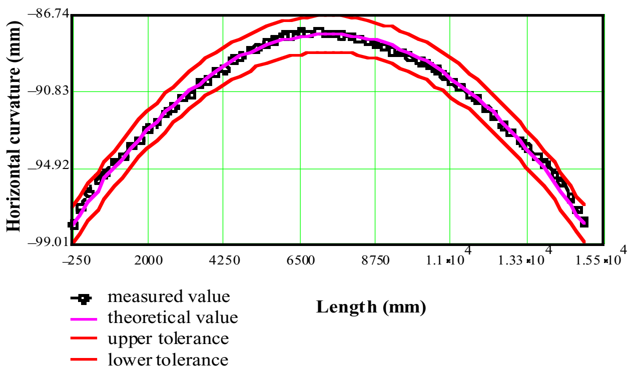

Figure 3 a: The curvature of the MBP2N2 prototype

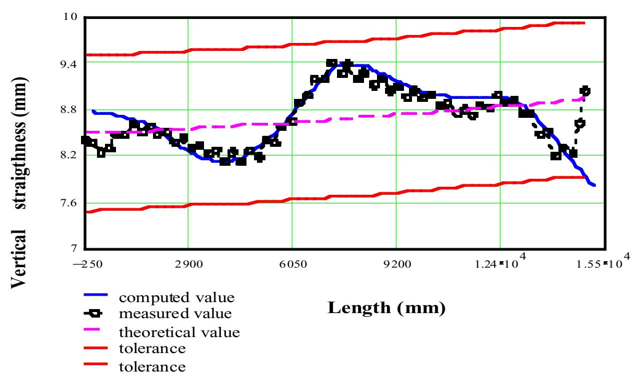

Figure 3 b: The straightness of the MBP2N2 prototype

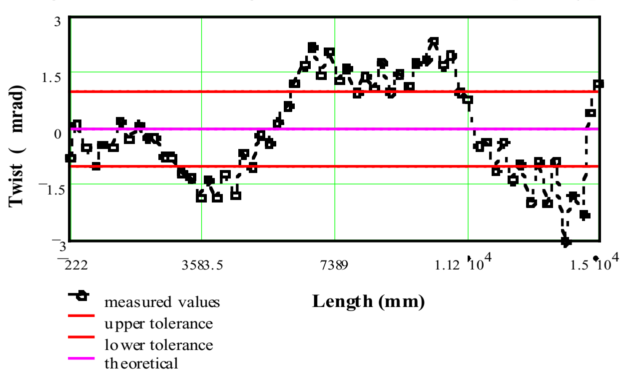

Figure 3 c: The twist of the MBP2N2 prototype

By using typical co-ordinates transformation methods, the measured points are best fitted to the ideal geometry and the corrector magnets, the support pads and the end covers are aligned with respect to the ideal geometry.

Fig. 3 show results obtained on MBP2N2 prototype. Fig. 3a and 3b give the horizontal and vertical real axis, ideal axis and range of tolerance in one aperture. Fig. 3c shows local twist and its range of tolerance. This magnet satisfies the geometrical specifications, with the exception of the twist, which exceeds the tolerance in some points.

The two other dipole prototypes MBP2N1 and MBP2O1 have similar features shown in Table 2.

Table 2. Errors on the geometry of the prototype CMA

MBP2-	**N1 min/max**	**N2 min/max**	**O1 min/max**
Horizontal curvature [mm]	-0.8/+0.8	-0.4/+0.7	-0.8/+1.7
Vertical straightness [mm]	-0.4/+1.0	-0.4/+0.8	-0.4/+0.4
Twist [mrad]	-1.1/+3.0	-3.0/+2.5	-2.5/+3.0
Radial offset of correctors [mm]	V2/V1 0.67/1.03	V2/V1 1.23/1.10	V2/V1 0.19/0.18

5 CONCLUSIONS

We described the main features of the LHC twin dipole geometry, horizontally curved around the beam orbit. We also presented the changes expected during the cool-down from assembling conditions at 300 K to operational conditions at 1.9 K and the effect of the dipole self-weight. The tolerance on alignment is very tight since the dipole is very long and contains multipolar correctors to improve beam stability. This imposes an assembling strategy assisted by high precision geometrical measurements. Laser tracker technology is well suited for this scope.

Three 15 m long dipole prototypes, assembled at CERN with the measuring assisted procedure are well within geometrical specifications both for the horizontal and the vertical plane. The twist distribution instead is in some points still out of tolerance and should be improved for the forthcoming pre-series production.

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M. Duret, J. Garcia Perez, P. Gillieron for their help during geometrical measurements.

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[2] M. Bajko, F. Savary, W, Scandale “LHC Dipole Magnets Assembling Driven by Dimensional Inspection”, LHC-MMS, Internal Note to be published.