

INSTRUMENTAL UNCERTAINTY IN MEASURING THE GEOMETRY OF THE LHC MAIN DIPOLES

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Abstract

In the Large Hadron Collider 1232 superconducting dipoles will bend the two 7 TeV energy beams along a 27 km-long circular trajectory. The series production (assigned to three European firms) requires a well-defined procedure to check, in every magnet, the respect of the dimensional specifications. To verify tolerance of some tenths of millimeter over the 15-meter length in each cold mass, a laser tracker is necessarily used. To access the two beam apertures and to increase the measurement accuracies, the laser tracker is placed in different stations around the dipole defining a 'multi-station measuring procedure'. The noise affecting all the data taken so far suggested a careful analysis of the procedure itself. Through the computer modeling (based on a Montecarlo algorithm), the statistical error was quantified and compared to the experimental error. From this comparison the critical aspects of accuracy limitations from the multi-station procedure were better understood.

INTRODUCTION

The LHC superconducting dipole is a 15-meter long cylindrical structure, approximately half a meter wide, hosting two apertures whose theoretical geometry in the horizontal plane is visible in Fig. 1. The 14343 mm-long central part of the cold mass is bent in the horizontal plane and contains the main field coil whereas its two 408.5 mm-long straight prolongations contain the multipolar correctors. The theoretical shapes of the beam channels in the vertical plane are straight lines belonging to the horizontal plane of the LHC.

At the industrial stage the manufacturing tolerance range is shaped as a torus of 1 mm-minor radius in the bent part of the magnet, and as a cylinder of only 0.3 mm-radius in the straight ends [1] for the reason that the multipolar correctors need to be placed very precisely around the beam orbit. Tolerance range is then relaxed after cryostating and cold test.

As the magnets are manufactured in series in three distinct firms, a careful procedure was defined to check in situ the compliance of the geometrical tolerance. The requirement for high precision and portability pushed toward the use of laser trackers and moles sliding along the apertures [2]. To increase the accuracy of this kind of measurement, the 3D shape of the cold mass is acquired from different locations (from now on called stations) around the object itself so that, to merge the different sets of data, a common reference system must be set through the definition of fixed points (network) common to all the different

stations.

This paper focuses on some critical issues related to this procedure providing explanations supported by numerical computations. The multi-station measuring procedure is presented in Section 2. The data analysis and the related discrepancies are described in Section 3. Section 4 presents the numerical simulation used to identify the potential error sources. Conclusions are summarized in the fifth and last section.

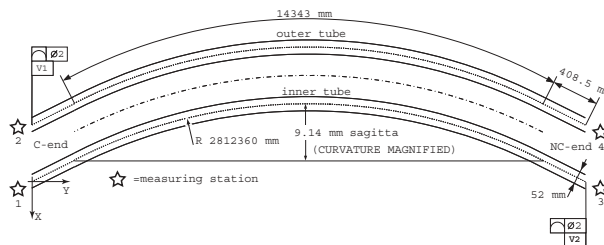


Figure 1: The theoretical geometry of the cold mass in assembling condition. Horizontal plane.

THE MEASUREMENTS

Multi-station measuring procedure

The dipole axis is, indeed, the cold bore tube axis and, since each dipole hosts two apertures, it will be characterized by two axes referred to as the inner and the outer tube axis. A cold bore axis is measured by pulling a mole, equipped with a reflector, inside the tube and measuring its 3D path by mean of the laser tracker placed in front of the tube itself. Consequently, to measure both the tubes, the laser tracker must be placed in two different stations, each one in front of the tube to be measured. Furthermore, since the laser tracker accuracy is proportional to the closeness of the point to measure, each tube shape is acquired by two opposite stations: from connection (C-end) and non-connection (NC-end) extremities, as visible in Fig. 1, raising to four the total number of stations required to measure each dipole.

Reference system and Network points

The common reference system has its origin in the starting point at the connection end (C-end) of the inner tube and it is oriented as shown in Fig. 1. This referential, fixed to the magnet, needs in principle to be shared by all the four measuring stations but it is not directly visible from every station. For this reason a set of 8 to 10 fixed points called 'network' and common to all the stations is conveniently

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defined around the magnet. The network, being fixed with respect to the magnet, is used to identify the common reference system from every station and consequently represents the basis for the multi-station measurement. In other words the network is a set of points needed to operate a coordinate transformation in the 3D space from the local referential of each measuring station to a global referential. In theory, to define the coefficients of the roto-translation matrix for such a coordinate transformation only three common points can be considered. However in the real case, affected by the measuring error, the only way to interconnect the local referential is through a least square fit of the network. Thus, the number of chosen points is higher than the theoretical number of three to grant the necessary redundancy for the least square algorithm.

DATA ANALYSIS

Saw-tooth effect

For each one of the two (inner and outer) tube axis the data taken from two opposite stations are converted to the same coordinate system and then merged. The difference in the vertical and in the horizontal plane between the measured and the theoretical axes (see below) are computed and plotted versus the dipole length as shown, for the inner tube in the horizontal plane, in the top graph of Fig. 2.

Looking at the curve profile in the top of Fig. 2 an evident saw-tooth pattern can be noticed along its whole length but, when data acquired from connection and from non-connection ends are plotted separately, this effect disappears, as visible in the middle of Fig. 2. In that plot the original saw-tooth effect seems to be replaced by a rigid roto-translation between the curves obtained from the two opposite stations. The quasi linear trend of the difference between the curves visible in the bottom graph of Fig. 2 suggested us that the discrepancy between the curves can be traced back to a mismatch between the common reference systems (that should in principle overlap) evaluated by the two opposite stations [3].

Table 1: Statistical values of rotation and shift between opposite stations and saw-tooth height. Values are given in rad for p and in mm for q and h .

Operator	# of meas.		Avg	Std
1	10	p	-3.2E-06	1.8E-05
		q	-0.04	0.24
		h	0.114	0.067
2	14	p	8.1E-07	6.0E-06
		q	-0.09	0.10
		h	0.094	0.045
3	14	p	-2.9E-06	9.0E-06
		q	0.04	0.12
		h	0.079	0.033

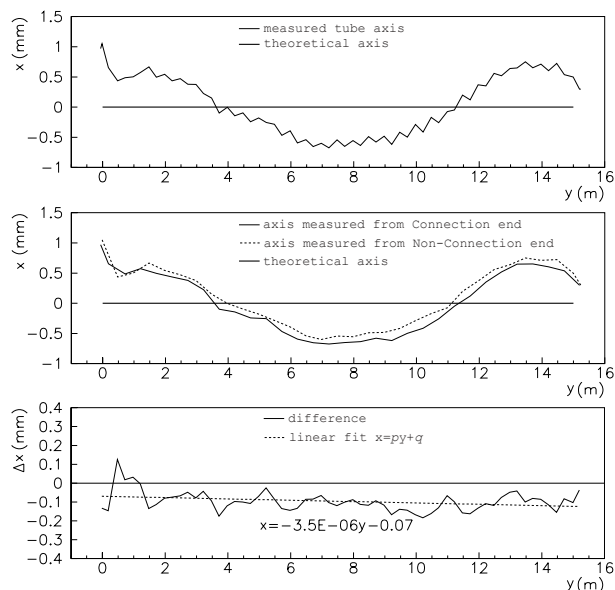


Figure 2: Saw-tooth effect (top) due to the mismatching between measurements from opposite stations (middle) whose difference shows linear trend (bottom).

Parameters for analysis and results

A statistical analysis of the saw-tooth effect has been carried out on the vertical and horizontal plane separately but from now on we will refer to the horizontal plane since it resulted the most critical. The difference between the same axis obtained from two different stations has been evaluated and best-fitted by a 1st order polynomial (see Fig. 2, bottom) for several measuring session carried out by different operators on different magnets. Then the coefficients of the 1st and 0th degree terms have been respectively considered as the rotation p and shift q between the two station's reference systems. The statistical values of p and q in terms of average (Avg) and standard deviation (Std) are reported in Table 1 along with the saw-tooth height h averaged over the length of each aperture.

A first important issue coming from the analysis of the reference system potential roto-translations and of the saw-tooth heights is the absence of coarse errors done by the three operators during the measurements and the substantial equivalence of the three measuring procedures. Other important conclusions will be drawn through the comparison with the numerical simulation described in the next section.

SIMULATION AND RESULTS

To estimate the best accuracy achievable in a multi-station measurement session we implemented a Montecarlo based numerical simulation. For every session step (i.e. network point or axis point acquisitions) the measurement of each single point has been simulated by a random extraction from a normal distribution centered on the theoretical position of the point itself. Following the measuring sys-

tem specifications the *RMS* of each distribution has been computed as a linear function of the distance between the laser tracker and the point itself [4].

These features allow to reproduce the propagation, through the whole measuring procedure, of the error introduced by the laser tracker accuracy. The largest loss of accuracy is in fact due to the definition of the common reference system that is not directly measured (and thus affected by the bare laser tracker accuracy) but it is worked out from the network points measured by opposite stations (and thus affected by a combination of the related errors). After one hundred iterations the simulation provided the statistical discrepancy between the axis profiles obtained by two opposite stations as a function of laser accuracy and network point dispositions.

Before going through the simulation result it must be pointed out that in such an analysis the discriminating parameter is not the average but the standard deviation. In fact the average represents a statistical bias that, because of the random nature of the error, is supposed to go to zero over a large ($\sim \infty$) number of samples ($\langle x_\infty \rangle = 0$). In presence of few (n) measurements, as in this case, it is sufficient that the related average $\langle x_n \rangle$ satisfies the condition $|\langle x_n \rangle - \langle x_\infty \rangle| \leq \frac{3\sigma}{\sqrt{n}}$, where n is the number of the considered cases and 3σ is three times the standard deviation of the measurements to ensure a 99.7% confidence level. Since this condition is satisfied for all the three sets of measurements, the asymptotic value of the average is zero and the relevant quantity is the standard deviation.

The numerical simulation results in terms of rotation p , shift q and tooth height h are summarized in the 'Steady' section of Table 2. The values show that a finite rotation between the curves is intrinsic in the ideal measuring procedure. However the related saw-tooth effect h is smaller with respect to the experimental one, given in Table 1, both in terms of average and standard deviation. More in detail whereas a good agreement can be found between the simulated and the measured rotations p a bigger discrepancy is noticeable between the simulated and the measured shifts q . We can explain this discrepancy by assuming that a phenomenon arising during the measurements causes a virtual shift without rotation of the reference systems i.e. a movement in the horizontal plane of the laser tracker head between the network and the axis measurement. This kind of shift can be provoked by the

stabilization of the tracker base in contact with the ground during the first part of the measurement on a new station i.e. during the network point measurement as was occasionally detected by the Operator 2 [5]. To model this effect a distribution of laser tracker shifts in horizontal direction was introduced in the simulation between the network and the axis measurement. By assuming a normal distribution of these movements centered on 0 mm with a σ of 0.1 mm (corresponding by lever effect to a base-ground accommodation of ~ 0.03 mm) the simulation results shown in the 'Not-Steady' section of Table 2 become in good agreement with the experimental values of Table 1 (according to the hypothesis rotations are not affected by the horizontal movement).

CONCLUSION

The superconducting dipole for the LHC must obey severe manufacturing tolerances. The magnet shape and the precise geometrical specifications make the tolerance checks themselves a challenge to approach using laser trackers and multi-station measurements. In spite of the smart approach to improve the measurement accuracies a noisy saw-toothed signal is, to some extent, always present. The statistical analysis of three sets of measurements taken by different operators pointed out the critical definition of a unique reference system in each multi-station measurement so far carried out. To estimate the best accuracy achievable in a multi-station measurement, a Montecarlo based numerical simulation has been implemented. The partial agreement between simulation and measurements pointed out the presence of an additional source of error not rooted in the ideal measuring procedure. A potential cause was identified in small laser tracker displacements due to the interaction with the ground as already experienced by some operators during measurements. The implementation of this feature in the simulation thus provided a good statistical agreement with the experimental data.

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Table 2: Results of the numerical simulation after 100 iterations. Values are in rad for p and in mm for q and h .

	Steady		Not-Steady	
	Avg	Std	Avg	Std
p	-2.98E-07	4.59E-06	-2.36E-07	3.97E-06
q	0.004	0.04	-0.015	0.16
h	0.065	0.01	0.125	0.095