Review of the Metrology Aspects of the LHC Alignment

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1. INTRODUCTION

The construction of the LHC, the future Large Hadron Collider, is under way at CERN. In this accelerator, the particles circulate in two separate channels, are guided by superconducting magnets, and collide in four points. A two-in-one design has been adopted for the superconducting magnets, whereby the two beam channels and their corresponding sets of coils are inserted in a unique structure and in a single cryostat. The magnetic length of the dipoles is 14.3 m, for a total mechanical length of 17 m.

The collider will be installed in the LEP tunnel, after dismantling of the existing machine, and two new transfer lines will be built to inject the protons into the LHC in the two directions. Their total length is about 5.5 km; the equivalent of 80 percent of the Super Protron Synchrotron built in 1974.

After an intensive R & D period, the construction of the LHC now begins, with the first civil engineering activities in winter 98, even if the studies continue.

This paper presents a review of the metrology aspects of the project, and four particular points are highlighted. After some considerations regarding the internal metrology of these long two-in-one cryomagnets, the underground geodetic network as well as a preliminary study of a possible permanent control of the alignment of the elements all along the machine are presented. Then, a global approach of the alignment of the insertion quadrupoles will be presented.

2. INTERNAL METROLOGY OF THE CRYOMAGNETS

To obtain the maximum physical aperture for the beams, the cryodipoles are bent in the horizontal plane, which contains the two beam lines, with a radius of curvature of 2784 m. Their total length is 17 m, between the two ends of the vacuum pipes, and three cold posts inside the cryostat support the cold mass.

To study the process of the fabrication of the magnets, CERN has built a facility area, where prototypes are built. Several controls are made at each step of the construction of one cold mass, and in particular, the curvature is measured, as well as the vertical sag. Then, the ends of the cold mass are welded with respect to the global geometry of the cold mass.

It is not only important to get the correct curvature, but also to build the ends of the cold mass with the correct geometry, to allow the connections between two adjacent magnets to be made possible with a minimum of discrepancy. In addition, corrector magnets are located at the ends of each cold mass and must be precisely aligned with respect to the magnet.

2.1 Principle

The measurement of the curvature of the cold mass of a dipole is made through the two beam pipes, considering that the cold bores are the first mechanical elements, which can limit the aperture [1].

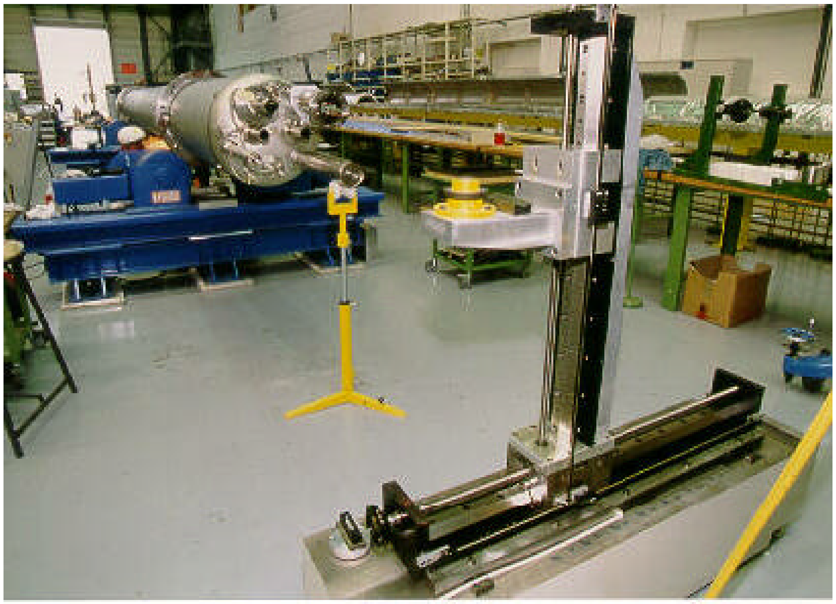

Fig. 1 Measurement of the curvature of the cold mass of a dipole

The two profiles are measured with a probe in a same coordinate system, as well as external fiducials, which are located on the ends of the cold mass (Fig. 1). These last points are used to position the end covers as well as the correctors using a portable 3-D measuring machine. The probe, which is inserted into the pipes, is equipped with six sensors to measure three inner diameters of the pipes, two inclinometers, which control the roll of the probe along the pipes, and a PSD sensor, which detects the laser beam.

2.2 Improvements

Measuring such elements with a system based on the principle of tooling docks, similar to that which is often done in aerospace industry for example is powerful, but the main drawback is the lack of redundancy in the measurements. This is why we are looking for another method based on classical triangulation with motorized theodolites. The aim of this evolution is to be able to control the quality of the manufacturing process remotely by analyzing the measurement reports. Redundancy in the observations seems to be the only way to provide a reliable check.

Today, the ends only are located with respect to the geometrical axis of the cold mass, and this method also needs to take account of the results from the warm magnetic measurements carried out during the manufacturing process.

2.3 Assembly

The next step is the assembly of the cold mass in its cryostat. Three cold posts support this cold mass, and the middle post will have to be adjusted to minimize the vertical sag. At the same time, the position of the external targets located on the cryostat have be determined from the auxiliary fiducials fixed on the ends of the magnet, and could also be controlled during magnetic measurements, and recorded. No adjustment to a theoretical value will be done.

The question of the stability of the cold mass inside its cryostat is still opened, and no test of transportation have been carried out yet, and a method based on closed range photogrammetry is tested.

3. INSTALLATION OF THE CRYOMAGNETS

3.1 The Geodetic Network for the Installation

The LHC machine will be installed in the LEP tunnel, after removal of the LEP components. So it is essential to transfer the geometry of the LEP quadrupoles to other points which will be fixed in the floor of the tunnel. To get the best absolute coordinates of these new points, the LEP quadrupoles are re-measured in radial direction with the gyroscope, and these bearings are combined with the wire offset measurements which are periodically made for the smoothing of the machine. Such a combination of these different measurements provides a very accurate as well as a smooth traverse (Fig. 2 & 3)

About 80% of the LEP quadrupoles were measured during the last winter shutdown and the provisional results show a 20 mm discrepancy between two pits limited to 20 mm, over 3.5 km.

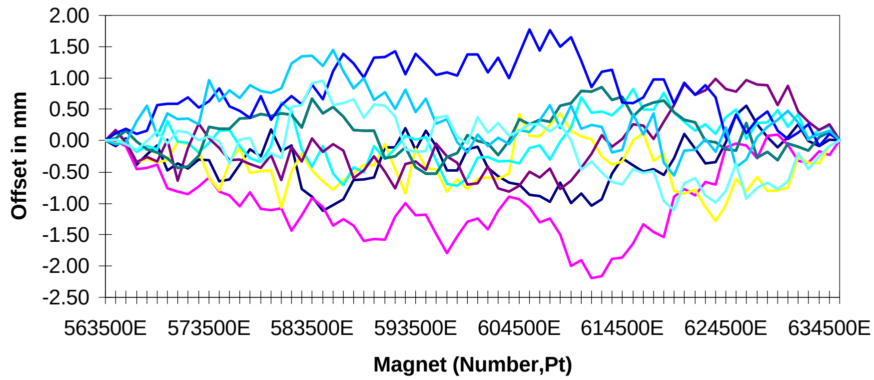

Fig. 2 Simulation with bearings only - observed at 40 m and 80 m

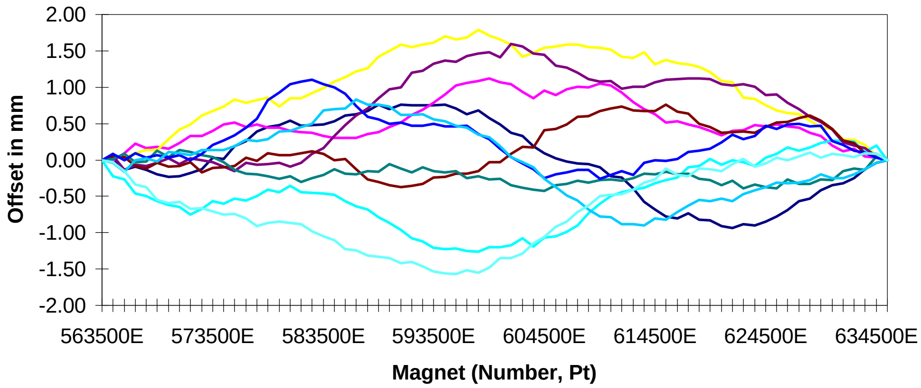

Fig. 3 Simulation with bearings observed at 40 m plus nylons at 120 m

3.2 Alignment

The alignment process will consist of two phases. The first one is the first alignment. At this stage, each magnet will be aligned individually from the geodetic network previously described. After a local smoothing to be sure of the best relative position of neighboring cryostats, the connection of the cryostats will be possible.

The next phase will be the final smoothing, made as late as possible, when the cryostats are connected together and the magnets cooled down. This allows all the external forces, which can act on the cryostats to be taken into account, and this is why the cryostats must be able to be moved under vacuum. This smoothing is made directly on the fiducials of the cryostat, without any measurement from an external network.

3.3 Maintenance of the Alignment

Preliminary studies are under way into the efficient maintenance of the component's alignment. In this way, the objectives are to detect unexpected movements of the cryostats, to minimize the limitation of the mechanical aperture for the beams and to identify the areas to be re-measured during shutdowns. Another aspect is, in addition, to get an external image of the interconnection between two cryostats when realigning under vacuum and cold.

To meet these aims, a solution under study consist in stretching wires along each half cell (about 51 m), with an overlap of one dipole (17 m) and fixing wire sensors at each end of each cryostat [2]. As no radiation problems are expected in this machine in the arcs, low cost optical sensors with integrated electronics could be used. The results from the linear regressions are very poor when considering each wire separately, because of the rather small number of measurements on each wire (10). The method seems to be much more efficient when considering several overlapping wire measurements, by adding condition equations in the fitting analysis (Fig. 4).

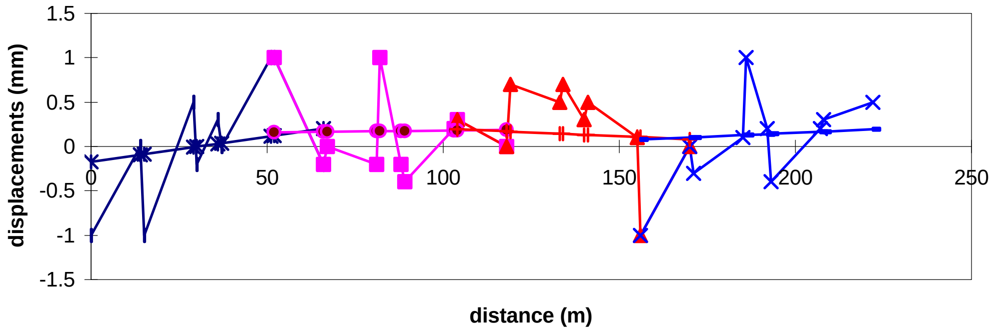

Fig. 4 Simulation with four wires

4. ALIGNMENT OF THE LOW BETA QUADRUPOLES

To correctly align the machine components around the experiments is always a challenge for surveyors. The shielding, the complexity of the areas, and the experimental equipment itself usually block the lines of sight and force the surveyors into acrobatic measurements.

Two problems have to be solved. The first one is to be able to align one triplet of quadrupoles with respect to the other triplet (left/right side) and to the main elements of the ring. A tolerance of ± 0.5 mm (3*σ) is required for this alignment [3] to get the vertex at its theoretical position.

After several studies -mainly involving the possibility of aligning using an optical reference line in the vacuum pipe- it has been decided for the two main experiments of LHC, ATLAS and CMS, to build a gallery parallel to the beam and dedicate it to surveying. The enormous civil engineering activity in these two areas will strongly affect the stability of the ground -deformations of several cm are expected- and this justifies the decision. A permanent reference line will be installed in this gallery and across the experimental area.

As shown on Figure 5, another auxiliary line installed in the main tunnel and linked to the gallery in three points will allow the magnets to be connected geometrically on each side of the experiment with a maximum of flexibility.

For the control of the radial movements in the horizontal plane, the reference line as well as the auxiliary line will be stretched wires, and invar bars equipped with sensors will do the link between the wires. Hydrostatic levels will be used for the elevation determination.

For the two other experiments, as no civil engineering work will affect the stability of the area, the underground network will be densified, remeasured after removal of the LEP experiments, and then regularly checked.

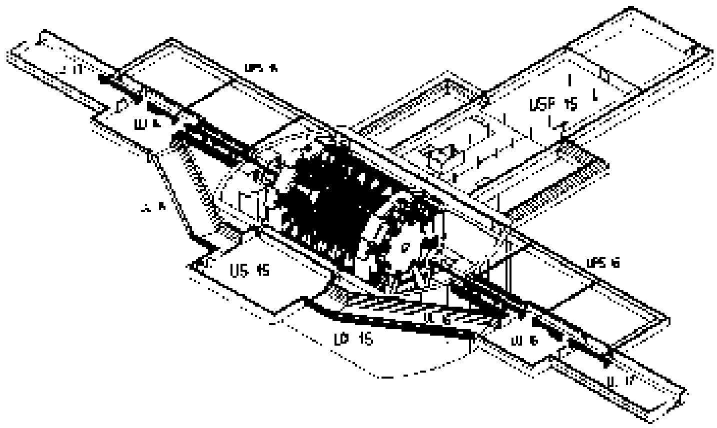

Fig. 5 Experiment Atlas

The second point is to align one quadrupole inside the triplet. In order to have orbit corrections possible, the tolerance for the position of one quadrupole with respect to the others is 0.35 mm ($3^*\sigma$). Nevertheless the stability required for the alignment is much more demanding and will probably need permanent remote controls and a closed loop adjustment with the jacks of the cryostats. Attention will also be paid to the stability of the cold mass inside the cryostat.

5. CONCLUSION

The main framework of the alignment process has now been established. The geodetic network will come from the LEP quadrupoles, and we already now that the results of the gyroscopic measurements confirm the good original alignment of the quadrupoles, and a major decision to use survey galleries has been taken for the alignment of the low beta quadrupoles. Nevertheless, a lot of points, sometimes fundamental points, are sill pending. The inner metrology of the cryomagnets, the jacks for the cryostats, the stability of the cold mass in its cryostat, the detailed concept of the alignment process, for example have to be studied, and this is not an exhaustive list. A lot of work is still to be done!

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