THE METROLOGY OF THE LHC PROJECT: WHAT NEWS ?

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INTRODUCTION

The Large Hadron Collider (LHC) [1], under construction at CERN, uses superconducting magnets operating at a temperature of 1.9 K to guide the circulating particles. A specific feature of the main magnets (dipoles and quadrupoles) is the two-in-one design with two magnetic channels in one common retaining structure. Indeed, the accelerator is made of two rings, mechanically linked, that have to be simultaneously aligned during the installation in the already existing LEP tunnel. This unprecedented feature has profound consequences on the geometrical tolerances of the magnets during the assembly procedure and on the precision required in positioning them in the tunnel. The geodetic survey of the LHC tunnel itself is another crucial issue, required to define the referential for any alignment operation.

The survey data of LEP ring show in a clear manner that the ground of the tunnel is slowly moving with time. This phenomenon is eventually enhanced by the on-going construction of two experimental caverns for ATLAS and CMS and of two tunnels for the injection lines from the SPS to the LHC rings. Since the LEP ring is being dismounted in the following years, it is very important to keep track of its geodetic network based on the present position of the LEP main quadrupoles. To this extent, the position of these quadrupoles has been recently measured again with a gyroscope and new reference points have been fixed on the floor of the tunnel for future uses.

The assembly tolerances of the LHC main magnets have been reconsidered to take into account the tight constraints on geometry. The dipoles are bent to follow closely the curvature of the circulating particles and to make a larger mechanical aperture available for the circulating particles. In order to minimise the geometrical errors the dipole assembly procedure is assisted by high precision survey measurements based on laser trackers. By this we hope to reduce to ± 1 mm the positioning error along the axis of the magnets. In addition the ends of the dipoles and quadrupoles should be aligned with even better precision to reduce to below ± 0.3 mm the displacement of the bellows in the magnet-to-magnet interconnection. All these precautions are expected to make easier the installation and to improve the LHC machine operation.

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In Section 2, we discuss the survey activity related to the civil engineering work. In section 3 we discuss the alignment of the dipoles in their cryostats. In Section 4 we present our geodetic network and in Section 5 we draw our conclusions.

2. CIVIL ENGINEERING ACTIVITIES

The main on-going activity in civil engineering consists in building two new experimental caverns, two new injection tunnels linking the SPS and the LHC, and two 600 m long beam dump caverns. At the end of 1999 the tunnel TI8 will be completed up to the safety radiation limit from LEP and half of the tunnel TI2 will be bored. In the same time, the level of the vault of the cavern for ATLAS will be reached.

From the beginning of this activity, a particular attention has been paid to monitor the induced ground motion in order to prevent detrimental effects for the operation of LEP which is supposed to run up to the end of the year 2000, [2], [3].

The LEP tunnel is eventually affected in the points 1 and 5 by the excavation of the caverns for ATLAS and CMS respectively. Extrapolating from our previous experience, we expect that the maximum displacement of the ground will take place at the center of the caverns and about 40 % of the maximum displacement will take place at the ends. In a more quantitative form, we expect a maximum displacement of 30 mm in the vertical upward direction at the center of ATLAS and of 20 mm in the vertical upward direction and of 10 mm radially at the center of CMS. Indeed, we decided to monitor permanently the deformation of the floor of the tunnel in these two areas. A wire has been stretched in the plane of the LEP from posts about 130 m apart. As the suspension points are in stable areas and because of a frictionless suspension system, the wires provide a reference both in X and Z directions [4].

The wire is in carbon fibre and kevlar, and is installed in an aluminium channel to protect it from the air turbulence in the tunnel. Eleven double sensors are installed along the wires on small translation tables that allow the fine positioning of the sensors and the compensation for movement of the floor.

The accuracy of the measurement is 0.1 mm r.m.s. and the range is ± 5 mm. Due to the intense synchrotron radiation emitted during the operation of LEP, a radiation resistant monitoring system based on capacitive detectors has been chosen. The positions in X and Z of the sensors and the temperature at the end of the wires are regularly measured and stored in the database for accelerator survey. Some of the results of the last six months are summarised in Figure 1.

The excavation of ATLAS cavern and of the injection tunnel TI8 will eventually affect also the stability of the SPS tunnel. Already during the construction of the LEP tunnel we observed ground motions of the SPS by about 6 mm at one of the crossing points with LEP tunnel. In addition, the area of the SPS ejection to the west area has been affected by vertical displacement induced by the digging of a pit located 30 m aside. To monitor the displacement induced in the SPS by the LHC civil engineering work periodic controls are performed with wire offset and direct levelling measurements whenever the machine is accessible.

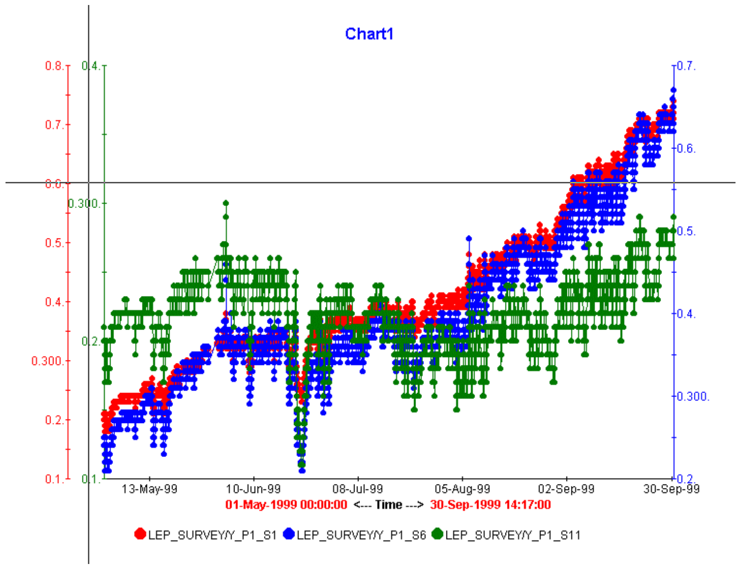


Figure 1 : Ground motion in P1 during six months. Vertical displacement in mm.

3. THE ALIGNMENT OF THE CRYODIPOLES

The alignment tolerances of the dipoles have been studied in detail, taking into account all the known sources of errors, trying to disentangle systematic from random errors. Since the final tolerance results from the composition of the individual errors, we have to specify how we perform the summation.

Random imperfections are characterised by the expected value of their standard deviation. Since in general we deal with independent source of errors we can add the individual standard deviations in quadrature. Tolerances for random misplacements are given by ± three times the standard deviation. The systematic residual errors instead are added linearly and the result provides the expected average error that has to be added to the random tolerance.

3.1. The mechanical errors

The mean geometrical axis of the cold mass fixes the shape of the 17 m long dipoles (measured between the interconnection planes) [5]. This axis is identified by interpolating the measured position of the center of the two cold bores. The ends of the cold bores are adjusted mechanically in order to be superposed to the mean geometrical axis. A technique based on laser trackers has been chosen to cover all the metrological needs during the assembly of the cold masses. The mains advantages of such a technique are the automatisation of the process, the redundancy of the measurements, an easy possibility of post processing the analysis, and the minimisation of the systematic errors.

The deformation of the cold mass and its displacement with respect to the cryostat has been measured during the cooling down or warming up and during the transportation of the cryodipole. The table 1 shows displacements from the cryostat measured during four years on the magnets of the string test. The longitudinal coordinate is X, the radial is Y and the vertical is Z.

Table 1 : Stability of the cold posts

		300 K			2 K		
Magnet	**Year**	**X µm**	**Y µm**	**Z µm**	**X µm**	**Y µm**	**Z µm**
Dipole I2_S	1994	26500	1989	4450	10160	1940	4195
	1995	26550	1957	4450	10260	1942	4250
	1996	26270	1962	4437	10405	1970	4180
	1997	26608	1975	4450	10270	1965	4185
	R.M.S.	**148**	**14**	**7**	**101**	**15**	**32**
SSS	1994	23660	2268	-1510	16025	2187	-1915
	1995	23915	2286	-1532	16000	2190	-1975
	1996	23660	2295	-1520	15890	2180	-1975
	1997	23490	2270	-1500	15950	2180	-1965
	1998	23630	2283	-1500	15850	2175	-1975
	R.M.S.	**153**	**11**	**14**	**73**	**6**	**26**

A test of transportation made with a SSS has show a radial displacement of 0.11 mm at one end and a displacement of 0.39 mm vertically and 0.32 mm radially at the other end. These measurements have been made using a photogrammetric method [6].

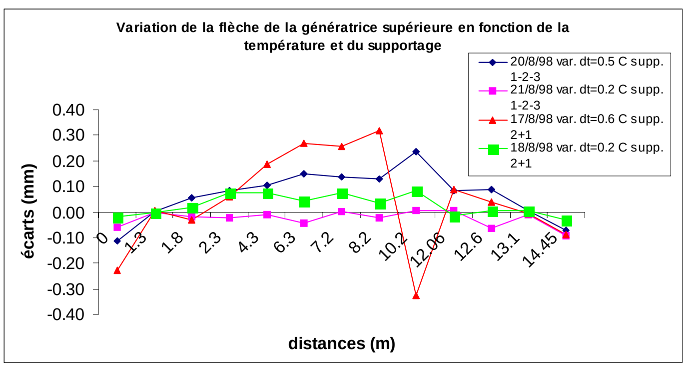


Figure 2 : Thermal effect in the cryostat

The cryostat which supports the cold mass plays a crucial role for the mechanical stability. The three cold posts of the cryomagnet make it sensitive to the variation of temperature in the tunnel. The thermal effect on the longitudinal sag of the cryostat have been calculated, taking into account the influence of the cold mass itself. Tests have been done. In figure 2, we show measurements of the vertical displacement induced by different kinds of supports and thermal effects on the cryostat. The displacement is induced by a temperature gradient between the top and the bottom of the cryostat of about 0.5 C.

For topological reasons, the survey fiducials are located on the top of the cryostats, and fixed on the reinforced areas of the cryostat. Because of this position, the ground motion induces on the targets movements amplified by a factor 1.8 with respect to the cold bore. The fiducials are used as references to position the magnets in the tunnel. They also have to support the metrological instruments, like wire offset device to check the alignment of two consecutive magnets.

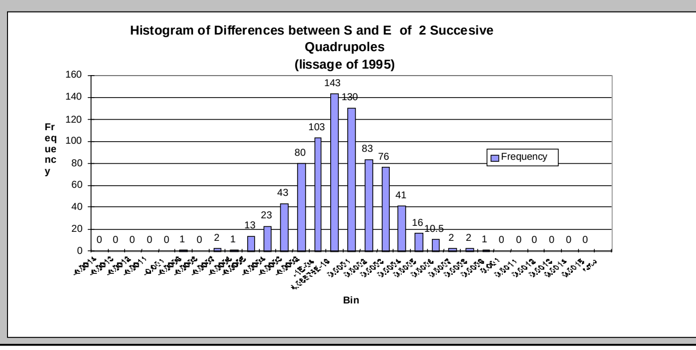
The deformation (ovalisation) of the cryostat under vacuum pressure is not yet known. Its effect is to diplace the position of the fiducials from warm to cold temperature. Its systematic part will be determined on the magnetic measurements bench during the magnet series assembly. The random part of this error is expected to be of the order of 0.07 mm. This value was computed with a numerical simulation based on finite elements method [7].

3.2. Positioning errors

The alignment issues are different during the installation and in the successive smoothing re-alignment required during the following machine operation to correct relative misalignments of neighbouring magnets.

Table 2 : Misalignements measured from 1993 to 1997

year	between the targets of a quadrupole (mm)	between two consecutive quadrupoles (mm)
1993	0.15	0.16
1994	0.15	0.18
1995	0.14	0.18
1996	0.14	0.19
1997	0.13	0.17



The first alignment will make use of the geodetic network in the tunnel (see § 4) as the absolute reference. In the following years of operation, the initial alignment will be slowly lost because of ground motion. It is important to predict how fast eventually is this degradation. We could obtain this information by statistical analysis of the levelling measurements of the LEP quadrupoles in the past years, shown in Table 2. The misalignment accumulated in one year has a Gaussian distribution with a standard deviation of 0.15 mm in the vertical plane. In addition, the tails of the distribution are more populated that expected since there are special areas of the tunnel where the ground motion is more pronounced [8]. The misalignments are measured from 1993 to 1997 before the annual LEP ring re-alignments. The results are the same for relative misalignments between two consecutive quadrupoles or between the two targets of each quadrupole.

These results suggest the alignment policy for the LHC during operation: the tilt and the vertical position of all the cryomagnets (dipoles and short straight sections) will be eventually readjusted every year. As a consequence, in the budget of the alignment tolerances the ground motion will contribute with random effects characterised by a standard deviation of (at most) 0.2 mm. The cryostats will be equipped with positioning sensors – measuring sensors or alarms- to detect relative movements in excess of three standard deviations, that may occur in specific positions of the ring where the ground motion is fast.

The budget of the alignment tolerances for the LHC cryodipoles is shown in Table 3. We also emphasise the tolerances at the magnet-to magnet interconnections for two reasons. First of all, the lever arm effect on the survey target increases strongly the errors in the ends of the magnets. On the other hand, the interconnections must be aligned more carefully to improve the mechanical aperture to have a good positioning of the multipolar correctors and to avoid distortions of the interconnection bellows.

Table 3 : Alignment error table for the dipoles

Alignment errors table for the Dipoles		(i)	(ii)		(iii)
	All r.m.s. values, in mm.	Mean (mm) In the plane of the fiducials	Ends (mm)	%	Correctors (mm)
Cold mass construction	Mean magnetic axis/ideal geom. axis	0.1 (1)			
	Auxiliary fiducials / ideal geom. axis	0.2 (1) (2)	0.2	6.2%	
	Magn. axis / Spool pieces fiducials				0.1
	Magn. axis of spool pieces / ideal geom. axis of the dipole				0.2
	Cold bores / ideal geom. axis of the dipole	0.33 (2)	0.1	1.6%	
Beam screen	Beam screen / cold bore axis	0.3 (2)	0.3		
Cold mass in the cryostat	Thermal effects on the cold posts	0.1 (1) (2)	0.2	6.2%	0.2
	Ovalisation and straightness of the cryostat	0.2 (1) (2)	0.4	24.9%	0.4
	Mesures of the fiducials / ideal mean axis	0.1 (1) (2)	0.2	6.2%	0.2
	Adjustment of the central post	0.2 (1) (2)	0.2	6.2%	0.2
positioning in the tunnel	Radial pos. of the fiducials / theoretical orbit	0.28 (1) (2)	0.56	48.7%	0.56

(i) (1)	Mean magnetic axis / theoretical orbit	0.48 mm r.m.s.
(i) (2)	Mechanical aperture limitation in the dipole	0.65 mm r.m.s.
(ii)	Mechanical aperture limitation at the ends without beam screen	0.80 mm r.m.s.
(ii)	Mechanical aperture limitation at the ends with beam screen	0.86 mm r.m.s.
(iii)	Magnetic axis of the correctors / theor. orbit	0.80 mm r.m.s.

Nota : Flexibility in the RF bellows of the beam lines : 0.80*1.414*3+1=4.4 mm

4. THE GEODETIC NETWORK

The actual geodetic network in the LEP tunnel is based on the alignment targets of the quadrupoles of LEP. It will disappear with the removal of the LEP elements To preserve this geometry, the network has been transferred on reference sockets sealed vertical in the concrete of the floor of the tunnel. The model allows the forced centering of the metrological instruments and is protected against dust and impacts with an iron plate. As these points will be used for the first alignment of the elements of the LHC, attention has been paid to their location with respect to the elements, to avoid too short distances between the reference points and the alignment targets. In the arcs, they are located in front of the middle of the second bending magnet of each half cell, and are spaced by about 53 m. In the straight sections, the distance between two reference points is shorter. These regions are located at the bottom of the pits and around the experiments, and their stability will be strongly affected by the civil engineering works. So in these areas, the new geodetic network will be used also for the control of the stability of the tunnel.

A gyroscopic traverse has been measured on the alignment targets of the quadrupoles of the LEP. The gyroscope was stationed on one magnet over two, and all the quadrupole magnets in the LEP tunnel have been linked by azimuths observed using a gyro-theodolite. Combining the wire offset measurements made for the classical smoothing of the magnets with the azimuths allows a very efficient control of the accuracy of the azimuths and is useful for detecting the wrong gyroscopic measurements.

The distances between the new points together and the LEP quadrupoles are measured with the Mekometre ME5000 and the TDA5005. A particular attention has been paid on these measurements, as they influence directly the radial position of points in the adjustment. The redundancy of the measurements was such that a self control of the constant calibrations was possible all along the traverse for each instrument and also allows a comparison between the instruments. Figure 3 shows the histogram of the comparison between the long distances and the sum of the short ones for each instrument.

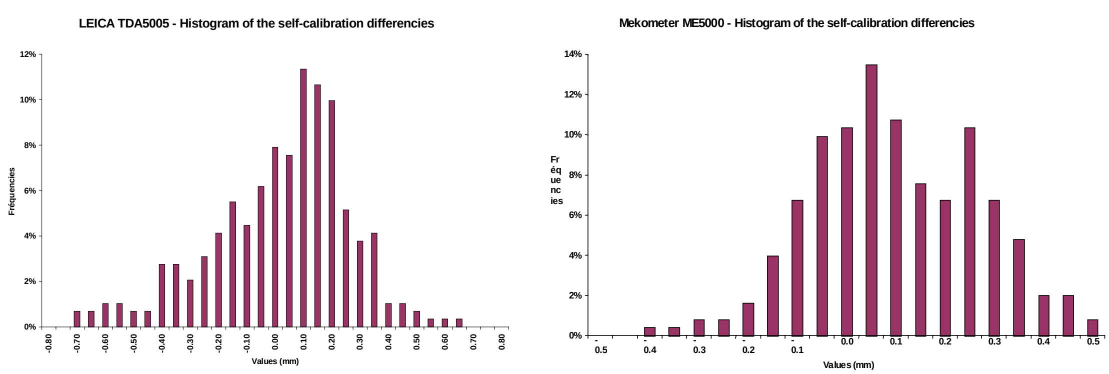


Figure 3 : Dispersion of the constant calibration of the ME5000 and the TDA5005

In addition, the Mekometer, considered as the reference, in the tunnel, was regularly compared to the invar wire in situ. A calibration of the TDA5005 gave also the cyclic errors for this instrument. Wire offset measurements have also be made between points. A first analysis seems to show systematic differences with angles, due perhaps to air turbulences in the tunnel, and more studies have to be done to integrate these measurements in the computation.

The measurements have now to be computed in order to get the real coordinates of the geodetic network.

5. CONCLUSION

Vertical movements of 30 mm for ATLAS (P1) and 20 mm for CMS (P5) as well as a radial movement of 10 mm at P5 are expected in the LEP tunnel and a realignment of the elements of the LEP will have to be performed this year in these areas. A monitoring system based on a 120 m long stretched wire and bi-directional capacitive sensors has been set up for the detection of the movements in each area.

The assembly tolerances of the LHC main magnets have been reconsidered, taking into account the tight constraints on the geometry, all mechanical aspects included, and the position of the fiducials on the cryostats has been optimised.

Studies have shown that a metrology based on geometrical measurements and adjustments is more efficient and cheaper than a metrology based on machining on so long component.

The positioning errors are based on an annual survey and realignment, and a detection of the abnormal movements will have to be installed on the cryostats.

The new LHC geodetic network has been set up and measured, adjusted on the geometry of the LEP quadrupoles, with a particular attention to the distances and gyroscopic measurements.

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