THE FINAL ALIGNMENT OF THE LHC

D. Missiaen, T. Dobers, M. Jones, C. Podevin, J.P. Quesnel, CERN, Geneva, Switzerland

Abstract

The Large Hadron Collider (LHC) project is progressing well. All the cryomagnets and the elements of the long stretched sections (LSS) have been pre-aligned and are connected and the cooling of the machine is under way. The final alignment of the machine is planed when the machine is cold. This paper presents the methodology used for this phase of the alignment. The smoothing process is described, as well as the results obtained based on the various sectors already aligned.

THE LHC PROJECT

The LHC, a circular collider of 27 km circumference, is composed of more than 2000 “cold” components interconnected in which protons will circulate in two cold bores tubes and collide in four interaction points. It is divided in eight sectors, each one comprising a standard Arc and 2 half LSS as shown on figure 1.

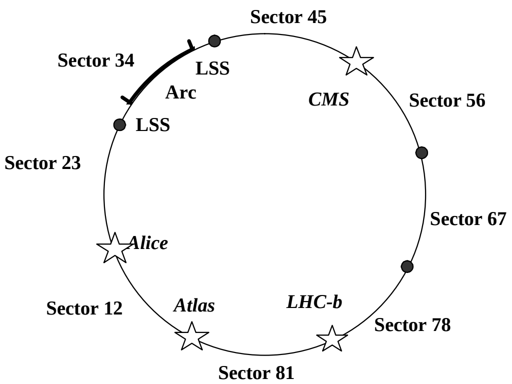

Figure 1: The LHC project

THE FIRST ALIGNMENT

The initial alignment of the components is done using a geodetic reference network which was determined from the position of the main quadrupoles magnets of the Large Electron Positon (LEP) located in the same tunnel as the LHC. The alignment of the LEP, which run from 1989 to 2000, was improved during the various shut-downs and its position in 2000, before its dismantling, was considered as the best that could be achieved. Levelling measurements, horizontal angles, offsets with respect to a stretched wire, gyroscopic measurements as well as mekometer distances were combined in order to determine the co-ordinates of the geodetic network.

Eight deep references have also been anchored in the rocks 20-25 m lower than the tunnel level. They are located very close to each sector extremity and will be used as stable references during the levelling measurements. The first determination of their heights was done during the complete levelling of the geodetic network in 2004.

All the components have been aligned from this geodetic network in order to achieve a relative accuracy of 0.2 mm at 1 σ [1]. It is realised in two steps:

- In the vertical plane with direct levelling done with the NA2 optical level,
- In the horizontal plane with offsets with respect to a stretched wire and distances measured with the TDA5005. In order to avoid any steps between consecutive magnets, a local smoothing was also realised.

The alignment of the components of the arcs is now totally completed while it has been realised at 95% in the LSS.

THE SMOOTHING OPERATION

The smoothing is the operation during which the relative position of the components is improved in order to avoid any steps between magnets that could create perturbations to the particle beam. Therefore the measurements are done directly on targets located on the components and the geodetic reference network is no longer used, the absolute position being considered as already achieved. The goal is to obtain a deviation w.r.t a smooth line of 0.15 mm at 1 σ in a 150 m long sliding window [2].

All the cold magnets are interconnected by many pipes and relatively rigid bellows and therefore any movement of magnet, due to ground motion for example, could produce big damage in this interconnection. For this reason it has been decided to measure, and realign if necessary, all the components and not only the main quadrupoles as it was the case for the previous accelerators like the LEP. The LHC final alignment is as important for mechanical constraints as for physics purposes.

Initially, the smoothing measurements were planned to be done the magnets being at a temperature lower than 80K. At this temperature all the mechanical movements and constraints due to the cool-down have occurred. But due to planning and co-activities reasons some sectors were measured at cold while for some others, the measurements were anticipated and done under warm conditions.

The operation is done in three steps: a control and adjustment of the roll angle, then a vertical and a horizontal measurement.

THE ROLL ANGLE MESUREMENTS

The roll angles, also called tilt angles, were measured for all the sectors under warm conditions except for sector

45 and 78. Table 1 shows the deviation to the nominal after the initial alignment and during the final smoothing.

Table 1: tilt deviations

Sector	Initial alignment		before smoothing	
	Avg (mrd)	**Stdev (mrd)**	**Avg (mrd)**	**Stdev (mrd)**
12	0.00	0.04	-0.01	0.07
23	-0.01	0.04	0.00	0.06
34	0.00	0.06	-0.02	0.09
45	-0.01	0.04	0.03	0.09
56	0.00	0.04	0.01	0.08
67	0.00	0.04	-0.01	0.10
78	0.00	0.05	-0.04	0.08
81	0.01	0.05	0.05	0.11

Table 1 shows that there is a slight degradation of the roll angle of the magnets between the initial alignment and the final one, the average deviation changing very little while the standard deviation changed from 0.045 to 0.085 mrd. In sector 78, this survey showed a big angle movement of two adjacent stand alone magnets which was due to a rupture of the fixation of their jacks during the cool-down. Their roll angles were taken out of the statistics. Except from these two cases, the cool-down didn't generate any important effect on the transversal inclination of the magnets.

All the magnets with a deviation larger than 0.1 mrd were corrected.

THE VERTICAL MEASUREMENT

Methodology

The measurements are made using the digital level DNA03 and a CERN made illuminated staff. The sequence in the standard arc is shown in figure 2

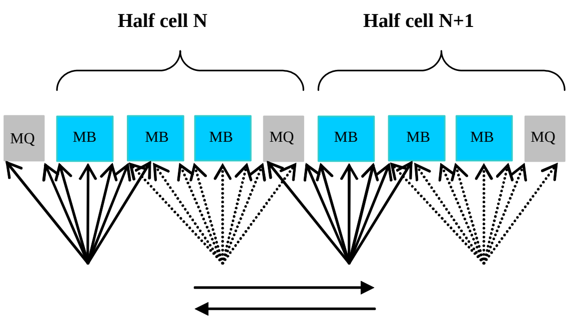

Figure 2 : levelling sequence

The distance between two quadrupoles being 53 m, two positions of the instruments are needed to cover one half cell. There are two common turning points taken from station n and n + 1, the points of the quadrupoles being always part of these common points. This sequence makes that the distances from the station to each measured points are not equal at all and fluctuate from 2 to 14 m, which doesn't eliminate an eventual collimation error.

The measurements are executed in a double run process.

Scale factor error

An important and linear deviation between the heights of the measured points and their theoretical value appeared in particular in the sectors where the slope of the tunnel was important. This was due to the CERN made staff used for this levelling which is constituted of an invar ribbon integrated in a mechanical assembly equipped with red leds. Unfortunately the invar ribbon was a little bit too tight during its assembly. The deviation appeared to be +0.2 mm on a length of 800 mm which generated a factor scale of 1.00025. The problem was solved and the measurements corrected.

Collimation error

Then, a collimation error which was not properly taken into account by the instrument was detected.

Every morning, the "check and adjust" operation is done with the DNA03 and the new collimation stored in the instrument. There were some important fluctuations of the collimation values from day to day. The influence was clearly seen during the comparison of the difference of height of the turning points taken from station N and the same value taken from station N+1, the distances between the stations and the measured points being very unequal as show on figure 3.

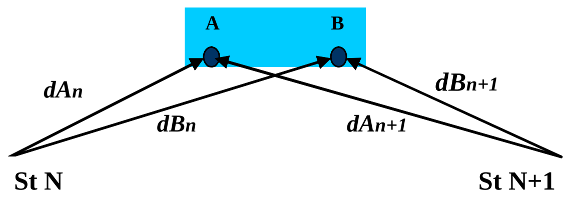

Figure 3: Collimation error

Due to a difference of distance of about 5.5 m between A and B, the collimation calculated is significant and all the measurements have been corrected by this value for each day or period.

The measurements were finished using a NA2 optical level.

Results

Sectors 7-8 and 4-5 of the LHC were measured under cold conditions while the six others were measured the magnets being at room temperature.

The levelling was compensated sector by sector. The comparison between the two runs shows discrepancies which don't influence the relative position of the magnets [3]. This phenomenon has still to be explained.

Finally the altitudes were adjusted on two deep references located at each extremity of the sector.

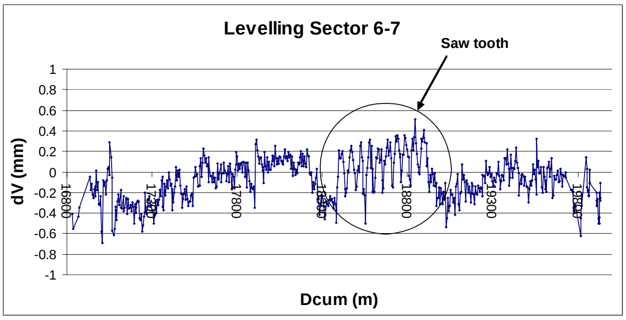

Figure 4: Levelling of sector 6-7 blocked on deep references

The figure 4 shows that there are no important relative deviations between the magnets. In the middle of the graph, a saw-tooth phenomenon can be seen which was probably due to a collimation error of the NA2 used during the initial alignment, although the instrument was compared every day to a "collimator". This collimation is probably due to the instability of the optical axis, the distances of the station to the measured points varying from 2 to 15 m. This error was detected, afterwards, by comparing the differences of height of the references measured during this alignment and the same points measured during the network measurements.

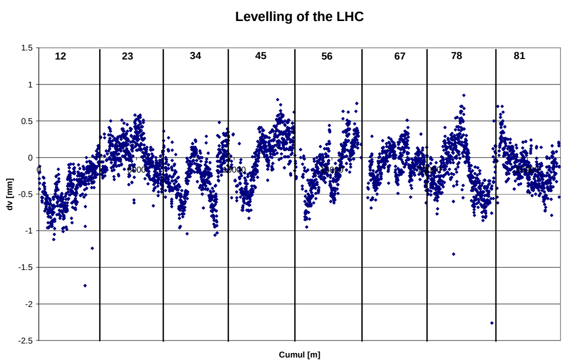

Figure 5: Global levelling

The complete picture of the levelling of the LHC, blocked on all the deep references, is given in figure 5. The absolute deviations are not exceeding 0.7 mm.

The determination of the points to be realigned will be explained in the chapter "Smoothing with Plane".

THE HORIZONTAL MEASUREMENT

Methodology

The measurements are made using a CERN developed instrument called "ecartometer" which measures the offsets to a straight line materialised by a wire, the wire being protected against the wind by a flexible tube of 60 cm diameter suspended to an existing monorail. The wire is stretched on a length of 120 m. No distance measurements are taken, the components are supposed to be at their nominal longitudinal position.

Figure 6: Ecartometry measurements

The sequence in the standard arc is shown in figure 7. It shows that each MQ is measured at least three times while the MBs are measured twice.

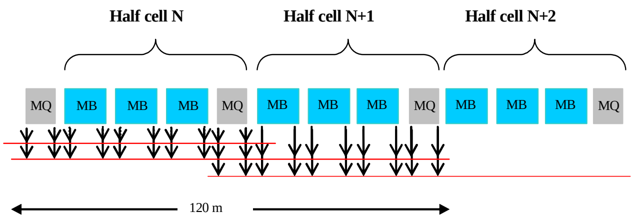

Figure 7: Offset sequence

Results

Sectors 78 and 45 of the LHC have been measured under cold conditions while the six others haven't been measured yet because of delay in the planning.

The calculation was done sector by sector taking a fixed point at one extremity, an orientation point at the other extremity and a radial constraint of 2 mm all along the sector, assuming that the elements are close to their absolute position.

Table 2: residual analysis sector by sector

Sector	Number of measurements	r.m.s (mm)	Average (mm)
45	920	0.051	0.009
78	877	0.040	-0.007

Table 2 shows very small residuals for the two measured sectors which gives good confidence in the quality of the measurements using this technique. For each sector, the measurements are realised in two weeks by a team of two or three persons, despite the use of the protection system around the wire.

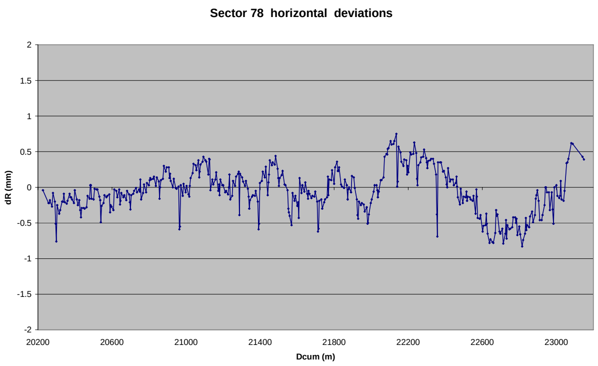

Figure 8: Global shape of sector 78

Figure 8 shows the horizontal deviations of the components to their nominal position in sector 78. It can be seen that, thanks to a local smoothing done just after the initial alignment, the global shape is rather smooth. Only some magnets are a bit far from this shape and have to be realigned using the PLANE software. This will be explained in the next chapter.

SMOOTHING WITH THE "PLANE" SOFTWARE

Principle

The PLANE software is a CERN developed tool that identifies the points which are away from a "smooth" line and need to be realigned. The name is derived from the analogy of the smoothing method with the wood working tool. This name is also convenient in the sense that the software can be employed in any plane, vertical or horizontal [4].

The principle is that, inside a sliding window of variable size, a polynomial of degree between 1 and 5 is calculated to best fit all the points except the middle one which is declared "rejected" if its deviation to the polynomial exceeds a tolerance value.

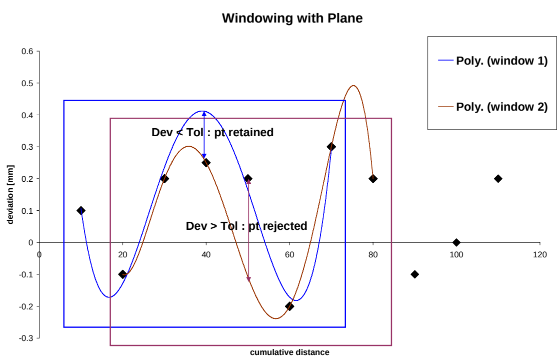

Figure 9: Windowing with PLANE

Then, the window slides by one point as shown on figure 9, the calculation treats the middle point of window 2 and the process continues until it reaches the end of the sector. Then PLANE reiterates the whole process until no points are susceptible to be rejected and recalculates the deviation to the latest "smooth" line even for the "rejected" points, the deviation for these points being the displacement to be done with the opposite sign.

Some tests were done to define the right size of the window and the tolerance threshold in order:

- to reach the deviation of 0.15 mm at 1 σ as specified, after smoothing
- to minimize the number of magnets to be moved

The value of 64 points (8 half-cells) and 0.25 mm were adopted in vertical and horizontal direction.

Results

In the vertical direction, the process was done for all the sectors.

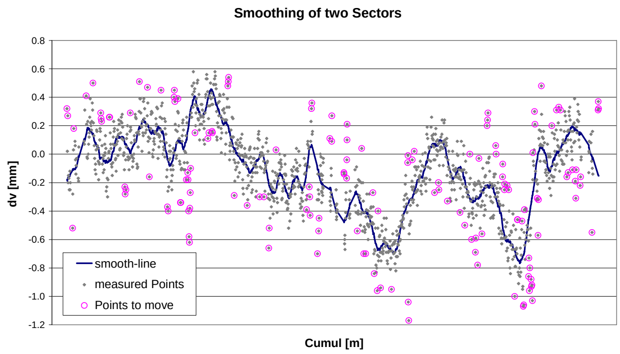

Figure 10: Vertical smoothing over 7 km

Figure 10 shows the position of the magnets after the measurements, the smooth line calculated by PLANE and the points to be moved [5]. Table 3 summarizes, for all the sectors, the deviations before and after the displacements of the magnets.

Table 3

Sector	Stdev before smoothing (mm)	Stdev after smoothing (mm)	Number of points to be moved
12	0.16	0.10	41
23	0.17	0.12	63
34	0.18	0.11	84
45	0.15	0.11	45
56	0.15	0.10	49
67	0.13	0.10	20
78	0.19	0.11	53
81	0.16	0.11	67

The specification of 0.15 mm at 1 σ was reached for all sectors, with an average of 53 magnets (23%) moved by sector.

In the horizontal direction, the process was done for two sectors only up to now.

Table 4

Sector	Stdev before smoothing (mm)	Stdev after smoothing (mm)	Number of points to be moved
45	0.19	0.11	65
78	0.17	0.11	41

As for the vertical direction, the specification of 0.15 mm at 1 σ was reached with the same amount of magnets moved by sector.

CONCLUSIONS

The final alignment is an important operation as it can detect some eventual big misalignments remaining once the interconnections of the magnets are performed and the magnets cold and therefore subject to new mechanical constraints due to the cool-down. The smoothing process provides with the relative accuracy of the magnets and allows the determination of the magnets to be moved in order to improve this relative accuracy.

The operation was done for all the sectors in the vertical plane, not showing major misalignments but some saw tooth phenomenon due to the impossibility to apply the levelling rules. In the horizontal direction, the final alignment was done for two sectors only, the offset measurements were realised with an accuracy never reached before and have proved once again their efficiency to improve the accurate relative alignment.

The work done will allow the machine to be tested. It is planed to realign it, in both planes, in the next two years, in order to minimise the residual misalignments. The levelling process appears, as usual, very simple but is still no easy to do especially because the configuration of the machine is not compatible with the normal measurement process.

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