THE ALIGNMENT OF THE LHC DURING THE SHUT-DOWN 2008-2009

D. Missiaen, CERN, Geneva, Switzerland.

Abstract

The first run of the LHC took place in September 2008 and, after only two weeks, was brutally interrupted by a major incident provoked by an electrical short circuit in an interconnection between two magnets. A shut down of one year was decided in order to repair the damaged equipment. The Survey team, involved in the repair of the damaged magnets, took advantage of this period to verify and improve the alignment of the components by smoothing their position in the arcs as well as in the Long Straight Sections (LSS). This paper will cover the different survey operations accomplished and the results obtained.

INTRODUCTION

A global survey of all the LHC was realised between the beginning of 2007 and September 2008, the starting date of the first LHC run. In the vertical direction, the smoothing operation was done, the magnets being under warm conditions but for the horizontal smoothing, all the magnets were cold. The methodology and some of the preliminary results were already presented [1].

The incident that happened in sector 34 of the LHC one week after the starting of the first run triggered a long shut-down of about one year in order to repair the damaged magnets and to take mitigation actions to prevent this unfortunate event to happen again. From the survey point of view, it gave also the opportunity to re-measure, under cold conditions, all the magnets in the arcs and to realise a better geometrical link between the arcs and the LSS, located on each part of the Interaction Points (Figure 1). A particular effort was also done to re-measure using "standard" instrumentation the final focus low beta quadrupoles and to link their geometry to the one of the LSS, including the data coming from the permanent monitoring system.

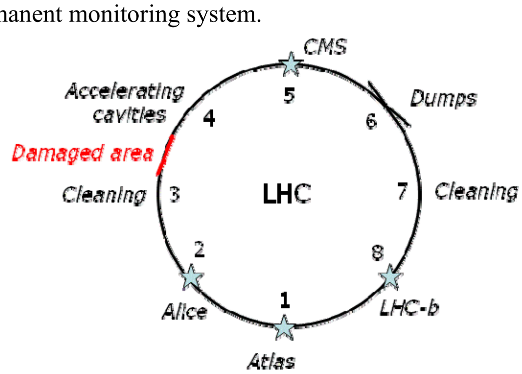

Figure 1: The LHC Interaction Points

REPAIR OF THE DAMAGED AREA IN SECTOR 34

An area of 700m comprising 53 magnets, 14 quadrupoles and 39 dipoles, was considered to have been damaged by the incident. These magnets were taken out of the tunnel and replaced by spare magnets which were to be prepared before their installation in the tunnel.

Fiducialisation

The metrological operations that have to be done on the magnets before their descent into the tunnel are the "fiducialisation", the positioning of the BPM for the quadrupoles and the positioning of all the tubes, included the beam screen, for both types of magnets as it was done before the first alignment. The fiducialisation is the operation which determines the position of the fiducial marks used for the alignment in the tunnel with respect to a reference axis, the mechanical one for the dipoles [2] and the geo-magnetic one for the quadrupoles [3].

The main challenge was to restart these operations after two years of interruption. As a matter of fact, after the completion of the production of LHC magnets in 2007, the infrastructure of the "fiducialisation" benches has been dismantled, the software, running on old platform, remained without maintenance and even worse the contractor manpower has gone away from CERN. These problems were solved thanks to the good reactivity and the strong involvement of the CERN staff. After a period of re-learning the methodology, the operations were completed in four months at a rate of three dipoles and one quadrupole per week.

The relational database containing all the measurement data and also used for the quality control of the magnets by the Magnet Evaluation Board (MEB) had also to be reactivated. The data structure, now under the responsibility of SU, was still working but the interface had to be modified to cope with newer versions of java.

Alignment in the tunnel

Even though it was not foreseen to use any longer the initial geodetic network, the magnets themselves constituting the "best" network, it was decided to use it for the initial alignment of the magnets because in this area there was no discrepancy detected between the smoothed position of the magnets and the geodetic network. The instruments and technologies used for this operation are the ones used for the first alignment of the whole LHC, i.e. optical levels, offsets to a stretched wire and EDM.

Before authorizing the interconnection team to start their work, a local smoothing was then performed on a length of 100m, even if some magnets were missing.

Smoothing of the whole sector

The smoothing of the whole sector was then realised in September 2009, the magnets being under cold conditions, in the Vertical and in the Horizontal direction.

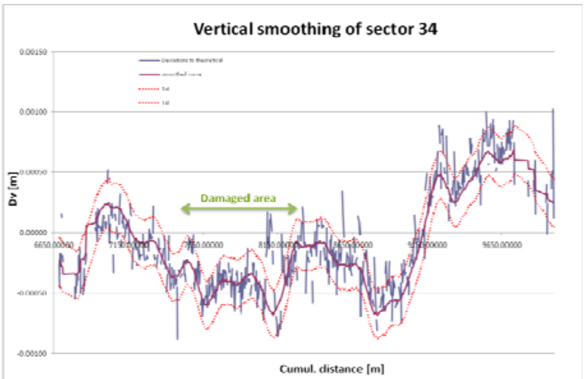

Figure 2 : Vertical position of magnets in sector 34

The deviations of the magnets to their theoretical position and to the smooth curve calculated by the PLANE software [1] are shown on Figure 2. 49 magnets were realigned which corresponds to 22% of the sector. This is exactly the average of displaced magnets during the first smoothing of the LHC [1]. No more displacements in the damaged area than elsewhere in the sector.

Figure 3 shows the horizontal deviations with respect to their nominal position. 41 magnets had to be realigned as their position with respect to the smooth curve was bigger than a threshold of 0.25 mm. This is also a consistent value comparing to what was seen during the first smoothing in 2008. It can also be seen that one magnet is at more than 1.5 mm far from its nominal. This is the Entry point of the dipole MB.A29L4, it is not in the damaged area and there are no explanation concerning the reason of this important deviation. No realignment was done because of the risk of provoking a leak in the interconnection.

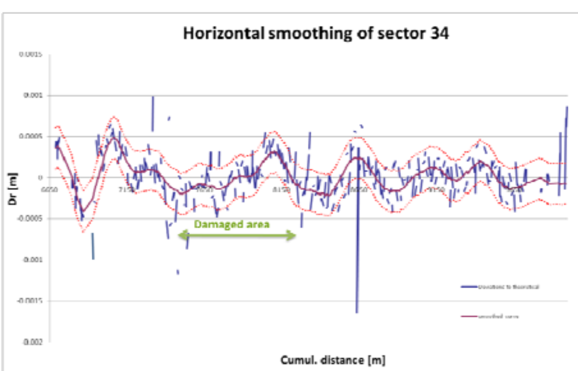

Figure 3: Horizontal position of magnets in sector 34

ALIGNMENT MAINTENANCE

The LHC being such a critical machine from the point of view of the aperture in both H and V directions, it was always claimed by the SU management that during the first three years after its installation, survey measurements have to be performed regularly in order to detect any important movement due to ground motion and to improve the smooth position of the magnets. This unforeseen long shut-down of the LHC was therefore an opportunity to start a complete campaign of measurements.

Roll angle measurements

Before measuring the magnets in V or in H, the roll angles of all the magnets are measured and eventually corrected in case their deviation to the nominal exceeds 0.1 mrad.

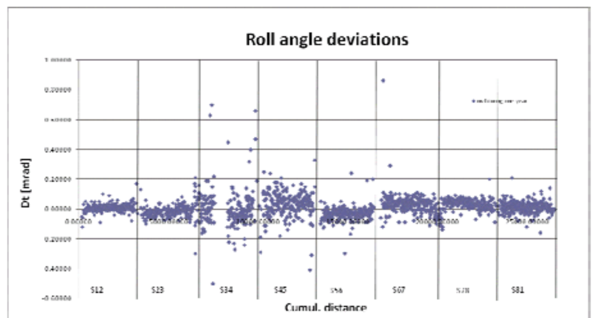

Figure 4: Roll angle deviations

Figure 4 shows the difference between the roll angle measured in 2008 and the one measured in 2009. The most perturbated sector was sector 34 due to the incident, even though the damaged area was not taken into account for this comparison. The others magnets where the movement was important are always located in the LSS and are mostly the so called “semi-standalone” magnets which are directly linked to the cryogenic line and where a strong effort due to vacuum is applied. In sector 67, a deviation of 0.8 mrad was found on the MQ.8R6. It appeared that in this area there was a problem with the concrete floor which had to be reinforced.

An average of 55 magnets per sector had to be realigned except in sector 34 (damaged area) and 78 (hole) where almost 100 magnets were concerned by a roll angle realignment.

Vertical smoothing of the whole LHC

The vertical measurements were performed for all the sectors of the LHC, all the magnets being under cold conditions. The sector 34 has been measured after the reinstallation of the damaged magnets as explained above.

In sector 78, the “hole” that was discovered at the beginning of the 1990’s at the time of the LEP (Large Electron Positron) and which was not visible during the first smoothing of the LHC in 2007, was observed again this year as shown on Figure 5.

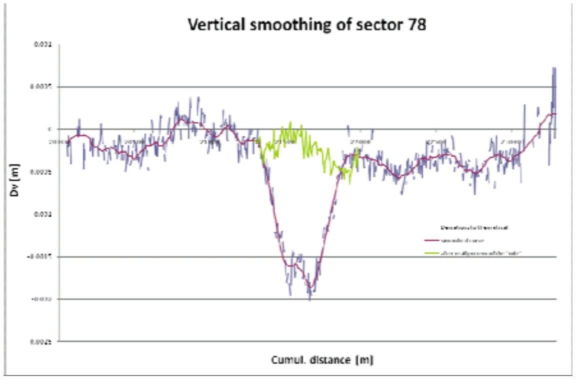

Figure 5 : Vertical position of magnets in sector 78.

The sinking is in the range of 2 mm on a length of about 600m. This is a long wave movement and it can be seen that the smooth curve follows closely measured deviations. It should have been left with this shape as, from the physics point of view as well as for the aperture one, there is no impact. But as this movement is expected to be in the range of 2 mm per year it was decided to realign all the concerned area on the nominal position. This realignment took place without warm up of the magnets and by small steps of maximum 0.5 mm to avoid any damage at the level of the interconnection. A total of 70 magnets (50 for the "hole") were displaced during this operation. This is, without any doubt, an operation which will have to foresee during every shut-down.

The measurements of all the LHC sectors were put all together and the closure was +2.42 mm. After a compensation calculation, a translation was applied so that the average of the deviations is equal to 0. The deep references located around each Interaction Point (IP) were not considered as fixed points. The graph of the vertical position of the magnets, calculated with the previous described hypothesis, can be seen on Figure 6.

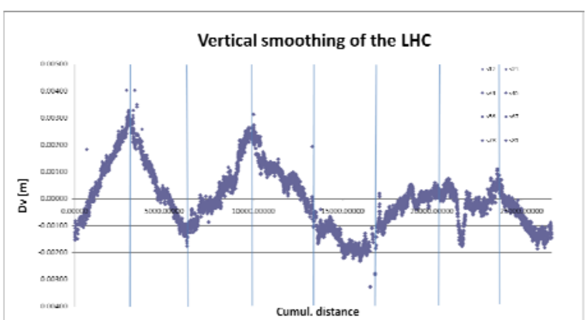

Figure 6: Vertical shape of the LHC magnets

The "mountainous" vertical shape of the magnets is coming from the fact that the first alignment of the magnets was done with respect to the geodetic network including the deep references. The closure of the levelling traverse, done in 2004 in order to determine the altitude of these references, was not very good, most of the measurements being taken at a distance not far from 26.5 m which was discovered later as a critical distance for the DNA03.

Nevertheless the relative position of the magnets with respect to their neighbours is more critical for the beam aperture and for the interconnections. That is why, sector by sector, a smooth curve was calculated with PLANE [1] and the magnets which were more than 0.20 mm away from this line where realigned.

Table 1: Vertical smoothing

Sector	r.m.s after smoothing 2008	r.m.s before smoothing	r.m.s after smoothing	Realigned magnets
12	0.10 mm	0.16 mm	0.09 mm	63
23	0.12 mm	0.16 mm	0.09 mm	53
34	0.11 mm	0.17 mm	0.10 mm	49
45	0.11 mm	0.13 mm	0.10 mm	26
56	0.10 mm	0.13 mm	0.09 mm	48
67	0.10 mm	0.14 mm	0.09 mm	36
78	0.11 mm	0.13 mm	0.11 mm	70 (hole)
81	0.11 mm	0.14 mm	0.09 mm	63

Table 1 shows the deviations of the magnets with respect to the smooth curve. From the columns 2 and 3, it can be seen that there is no important degradation in the alignment in a period of almost one year.

From column 3, it can be seen that our specification of 0.15 mm at 1 sigma was almost reached for all sectors, without realigning any magnet. Then columns 4 and 5 shows that, with a total of ~400 magnets realigned (23%), the position of the magnets is at 0.1 mm at 1 σ from their ideal position. Columns 2 and 4 show also that the position after smoothing in 2009 is slightly better than the one after smoothing 2008. These very encouraging results shows that the stability of the magnets is excellent and that with our regular measurement campaigns, such an accurate position is achievable, but with a non negligible effort.

Vertical survey of the low beta quadrupoles

Around point 1, 2, 5 and 8, where the huge LHC experiments are located, the "standard" levelling measurements were combined with the measurements issued from HLS and WPS installed to monitor permanently the position of the low beta quadrupoles [4]. The measurements were linked on the deep references inside the accelerator tunnel and to cavern references. In any case it was possible to link both side of the experiments with "standard" measurements. The calculation was fixed on the deep reference(s).

Table 2: Vertical position (mm) of low beta quadrupoles

IP	Stability tunnel-cavern	Q3L	Q2L	Q1L	Q1R	Q2R	Q3R
1	.12	-.04	-.25	-.36	-.55	-.36	-.14
2	.43	.51	.14	.05	-.04	-.04	-.06
5	.41	.51	.29	-.04	-.24	.17	.13
8	.02	.13	.36	.19	-.35	-.49	-.03

Table 2 shows in column 2 that the stability between the deep references of the tunnel and the cavern references is very good for IP1 and 8, but for IP2 and 5, it seems that there is a movement between the tunnel and the cavern. Either the tunnel is going downwards or the cavern upwards. The first hypothesis seems more plausible even though, these references are anchored 25 m below the surface of the tunnel in very stable rocks.

Concerning the position of the magnets, it has to be mentioned that for:

- IP1: the magnets have a tendency to go down as they are closer to the IP. This was already detected during the previous survey;
- IP2 : same remark than for IP1 on the Left side, very good alignment on the Right side;
- IP5 : same remark than for IP1 on both sides;
- IP8 : the magnets are a bit too high on the left side and a bit low on the Right side. The same tendency was detected during the previous survey.

All the low beta quadrupoles magnets have been realigned remotely to their theoretical position with a deviation lower than 0.1 mm at 1 σ.

Horizontal smoothing of the LSS

The LSS are the Long Straight Sections of about 500m located on each side of the Interaction Points and containing various equipment, such as separator magnets, stand-alone quadrupoles, low beta quadrupoles, accelerating cavities, collimators, dumps, etc.

It was decided to realise a major survey in these areas to improve the relative position of these critical equipment before they become highly radioactive.

As already explained [1], the horizontal smoothing in the "standard" LHC arcs is done with respect to a stretched wire, the length of this wire being limited to 120 m because of the curvature of the tunnel and the size of our instrumentation. In the LSSs, this limitation doesn't exist and longer stretched wires of 160 m, made of "Vectran", were used with an overlap between the wires of 100 m to strengthen the geometry. The measurements were done for all the IPs between the Q8 on the left side (Q8Ln) to the Q8 of the right side (Q8Rn).

Two types of LSS have to be considered:

- These containing an LHC experiment around IP1, 2, 5 and 8 (Figure 1).
- These without experiment where the geometrical link is always possible as it is the case for IP3, 4, 6 and 7 (Figure 1).

For the LSS with experiment, as a direct metrology to link both sides is not possible, the following measurements were performed and added to the calculation:

- the permanent monitoring systems (WPS) linking one side to the other through the Survey galleries for points 1 and 5 [4];
- the position of the "fiducials" used for the permanent monitoring with respect to the ones used for the "standard" measurements;
- a "standard" metrological survey through the Alice experiment in IP2;

The calculations were done taking as a fixed point the Q2Ln and as an orientation the Q2Rn. Radial constraints of 1mm were added around the Q8Ln and Q8Rn in order to have a smoothed shape at the junction between the standard arc and the LSS.

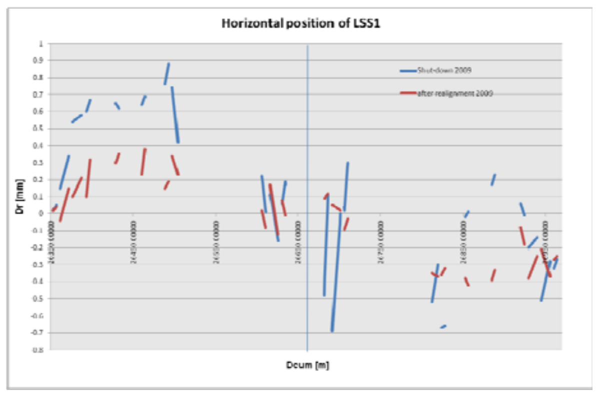

Figure 7 : Horizontal position of LSS1

In LSS1, Figure 7 shows that the smoothed shape was improved by realigning a significant number of magnets on both sides and the low betas quads mainly on the Right side.

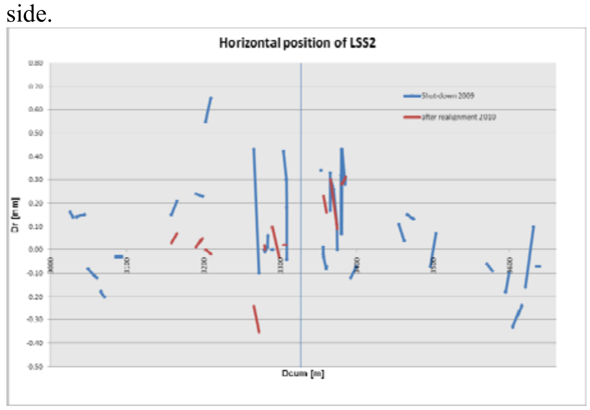

Figure 8 : Horizontal position of LSS2

In LSS2, it can be seen that the displacements done of the low beta on the right side were not done properly, instead of moving Q1, it would have been preferable to move Q2 and Q3.

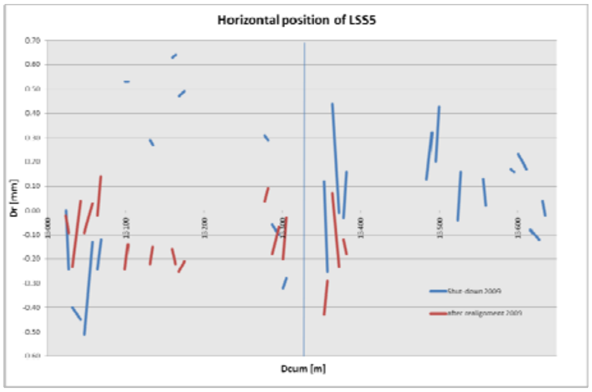

Figure 9 : Horizontal position of LSS5

In LSS5, the situation was almost the same as in IP1. Many magnets were displaced of the left side, included Q1 and Q3 which were displaced by about +0.3 and -0.3 mm respectively. On the right side, after displacement, the Q1 didn't reach its expected position because of inconsistency between standard and WPS measurements which were available six months later than the standard ones.

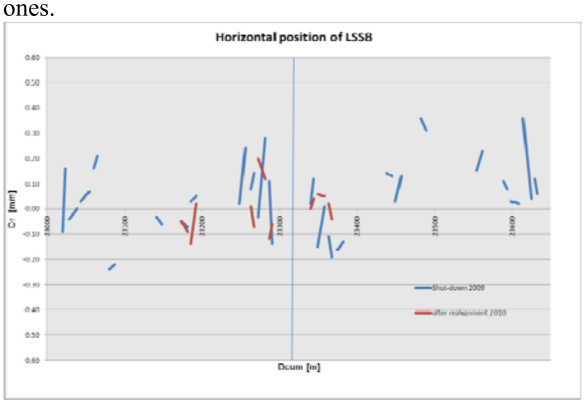

Figure 10 : Horizontal position of LSS8

In LSS8, the calculation was done independently for each side, the Q2 been taken as a fixed point and the Q8 as an orientation. Very small realignments were realised, these area was always very well smoothed.

The main difficulties of these realignments were:

- The fact the WPS data were available in some case very late because of some maintenance on the permanent sensors system.
- Some inconsistent measurements between the standard and WPS "fiducials", these last ones being foreseen at the origin only to measure relative movements.

Nevertheless, the smooth position of the cryo-magnets located in these LSS was significantly improved as well as the link between the LSS and the low betas quads.

For the LSS without experiment, the long wires were stretched all along the LSS between Q8L and Q8R without any interruption. Table 3 shows that with a small number of wires, the residuals of the measurements after adjustment were not bigger than 0.07 mm at 1 σ. A limited number of magnets were realigned.

Table 3 : Horizontal smoothing of LSS3, 4, 6 and 7

LSS	**Residuals** (mm)	**Wires measured**	**Magnets realigned** (%)
3	0.06	10	15
4	0.07	13	25
6	0.04	14	15
7	0.03	8	28

CONCLUSIONS

The unforeseen shut-down of the LHC was firstly devoted to the realignment of the damaged area in the sector 34. It also permitted to detect or confirm some unstable areas with the roll angle and the levelling measurements. The vertical smoothing has improved significantly the relative position of adjacent magnets and the deviations to a smooth curve has reach a value 0.1 mm at 1 σ but has not shown any big misalignment. In the horizontal direction, for the first time, stretched wires of 160 m have been successfully used in the LSS with a precision never reached before. This technique has proved once again its efficiency to improve accurate relative alignment.

The LHC has started to run in November 2009. The first closed orbit has been captured and the deviations were 1.33 mm in H and 0.93 mm in V at 1 σ without any correctors activated. Very quickly some collisions were realised at an energy of 3.5 TeV by beam. The LHC will continue to run until the end of 2011, hoping that the quality of the alignment will not degrade too much during these two years of run. In the mean time, the position of the low beta will be monitored permanently and re-alignments realised remotely, if needed. In 2012, another long shut-down of one and a half year will be used to smooth again the whole LHC in both planes as well as its transfer lines.

REFERENCES

[1] D. Missiaen and al, "The final alignment of the LHC", IWAA08, Tsukuba, February 2008.

[2] D. Missiaen, J.P. Quesnel, "Fiducialisation of LHC Dipole Magnets", LHC-G-ES-0002, EDMS 110632, March 2000.

[3] P. Bestmann, D. Missiaen, J.P. Quesnel, "Final Geo-magnetic fiducialisation of the LHC Short Straight Sections", LHC-G-TP-0006, EDMS 790018, October 2006.

[4] H. Mainaud and al, "The remote positioning of the LHC inner triplets", IWAA08, Tsukuba, February 2008.