SMOOTHING THE LHC DURING LS1

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Abstract

The two-year Long Shut-Down 1 (LS1), triggered by the repair of the splices in the interconnections of the Large Hadron Collider (LHC) cryo-magnets, gave the opportunity to the survey and alignment team to smooth the position of the 27km of the LHC in order to guaranty its best performance for the RUN2 expected between 2015 and 2018. For the first time after the starting of the LHC, the roll angle of the LHC cryo-magnets as well as their position in vertical and in horizontal (transverse) were measured. This large measurements campaign has allowed a realignment of many components and will be an important source of information useful for the analysis of the stability of the LHC, allowing then the survey team to predict the areas where the future movements are going to take place.

This paper gives an overview of the techniques and the software used for the smoothing, the realignment process and a preliminary analysis of the stability of the LHC.

INTRODUCTION

The Large Electron Position (LEP) tunnel, bored in the middle of the 80's, is hosting the LHC magnets from 2007 and their installation and alignment was completed in 2008. The behaviour of this tunnel, in terms of stability, has been studied between 1992 and 2000 at a time the LEP magnets were measured vertically every year. Some areas are known to be quite unstable, in particular the middle of the sector 78 where a yearly sinking of 1.5 mm of the magnets, has been detected. This phenomena is probably due to a geological "fault" and therefore is certainly going to influence the LHC magnets in the future.

The LHC magnets have two cold bore tubes of 50mm diameter to allow the circulation of protons in both directions. The interconnections between magnets are the location of many pipes to ensure the current and helium transition and are consequently very sensitive to roll angle displacement and transversal offsets. From the point of view of mechanics and beam aperture, these magnets are much more demanding in terms of alignment than the LEP ones, while they are installed in the same unstable tunnel.

The final alignment, also called smoothing, of the LHC magnets was realised between 2007 and 2008, then during the shut-down which followed the incident of September 2008, all the magnets were re-measured in the vertical direction and only two sectors over the eight in the horizontal one.

A new rhythm of a run period of three years followed by a long shut-down of two years has being decided in order to optimise physics studies. It doesn't allow any more a measurement of the whole machine every year but only every five years. It is therefore quite important to know precisely the unstable areas where a short intervention to realign the magnets has to be undertaken during the short technical stops, which take place during one month in the winter season.

THE LHC MACHINE

The LHC, a circular collider of 27 km circumference, is composed of more than 2000 "cold" components. It is divided in eight sectors, each one comprising a standard Arc and 2 half Long Straight Sections (LSS) and 2 half Dispersion Suppressor (DS) as shown on Figure 1.[1]

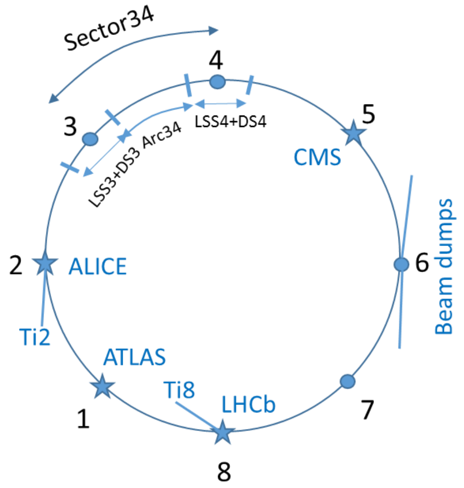


Figure 1: the LHC machine

The Arc magnets

The LHC arcs are like a continuous vacuum pipe, going from Q11 located Right of the IPn to the Q11 located at the Left of the IPn+1. They are composed of only "cold" magnets operating at 1.9K. Each arc hosts 138 dipoles and 45 quadrupoles magnets over a length of 2.5 km.

The LSS and DS components

The LSS and DS are the location of "cold" magnets like the final focus quadrupoles and separator dipoles but also of many resistive quadrupoles, beam instrumentation, collimators, accelerating cavities, etc. Unlike the arcs, this is not a long continuous pipe but a succession of components separated by vacuum chambers and operating at different temperature. They are covering a length of 440 m on each side of the IP. For simplification purpose, I will call these regions LSS in the continuation of the paper.

MEASUREMENT CAMPAIGN STRATEGY

In order to measure the position of the magnets at their "operating" location, it has been decided to smooth the Arcs magnets when their temperature is below 100K and after all the mechanical movements have taken place. This operation was then achieved after the reparation of the interconnections, the magnets being cooled down and ready for run2. It took place from June 2014 to January 2015.

For the LSS magnets, because of time constraints and as it was not possible to have them all under cold temperature, it was decided to smooth their position at warm temperature, already in 2013.

SMOOTHING THE LSS

The roll angle measurement

The smoothing operation starts with the roll angle measurements of the components and their re-adjustment if necessary.

Table 1 shows the deviations w.r.t the theoretical roll angle values. The average value is for almost all the LSSs lower than 0.1 mrad, which is the limit for the realignment. The quite important standard deviation of LSS4 is due mainly to the movement of the accelerating cavities by more than 1 mrad. For LSS1 and 5, it is due to the movement of the magnets in the areas of the D1 separator dipoles where civil engineering works took place at the end of the 90's to give space to the ATLAS and CMS caverns. For the LSS6, there is also a large standard deviation and a big number of magnets which were realigned, this area was also quite perturbed during the excavation of two beam dumps tunnels. The LSS2, 3 and 7 are the most stable ones.

Table 1 : roll deviations of the LSS magnets

LSS	**Deviation to theoretical roll angle (mrad)**				**Realigned magnets(%)**
	avg	r.m.s	min	max	
1	0.04	0.16	-.48	0.53	34
2	0.04	0.11	-.18	0.34	35
3	-.09	0.08	-.23	0.06	40
4	0.13	0.36	-.49	1.77	44
5	0.09	0.15	-.14	0.45	43
6	0.07	0.30	-.90	1.24	64
7	0.06	0.08	-.21	0.24	29
8	0.07	0.11	-.28	0.33	48

The vertical measurement

Measurements were done using a Na2 optical level taken only on the fiducials of the magnets located between Q11Ln and Q11Rn of the LSSn, the geodetic network is not used any more except the deep references. For each LSS, the calculation is fixed on the altitudes coming from the "quick" levelling [2] of one or two deep references and on the above mentioned quadrupoles.

The results of the measurements show that:

- For LSS1 and 5, there is a positive slope going from the centre of the experiment towards the separators magnets D1 with a maximum offset of about 2 mm (Figure 2), including the final focus low β quadrupoles. This "cat's ears" phenomena is mainly due to civil engineering works as already mentioned in this paper.
- For LSS2, there is an unstable area between the Q10 and Q8 located on the left side, which corresponds to the tunnel excavated at the end of the 90's for the TI2 proton transfer line. Similar situation at LSS8 on the right side, which corresponds to the tunnel of the TI8 proton transfer line. The movements are in the range of +1.5 mm for both LSSs.
- For LSS6, two tunnels have been excavated symmetrically w.r.t the IP6 to locate the beam dumps and this generates some positive vertical movement of more than 1 mm on the right side and surprisingly nothing on the left side as shown on Figure 3.
- The LSS3, 4 and 7 are quite stable.

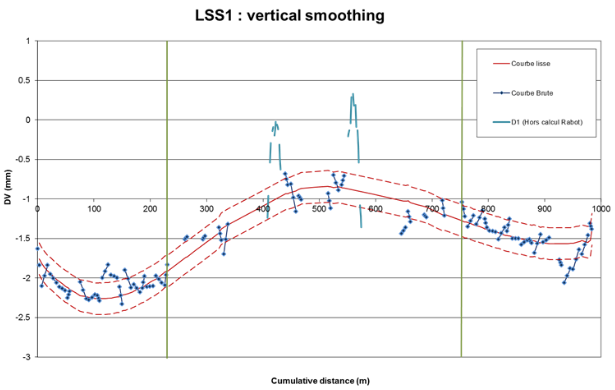


Figure 2: the LSS1 vertical profile

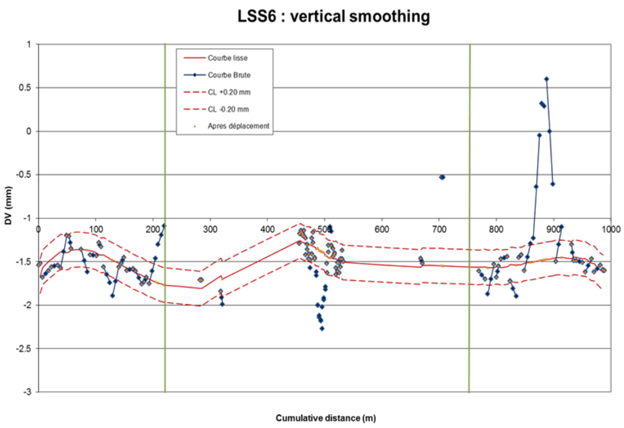


Figure 3 : the LSS6 vertical profile

The horizontal measurement

The measurements are done with offsets w.r.t a stretched wire taken only on the fiducials of the magnets located between Q12Ln and Q12Rn of the LSS n. Angles and distances were measured with the AT401 around the experiments in LSS1, 2, 5 and 8. For each LSS, the calculation is fixed on the theoretical coordinates of the Q2L and Q2R and a radial constraint of 1mm is imposed on the magnets between Q8 and Q12 on each side of the LSSs. This technique is applied in order to have a perfect adjustment between the measurements taken during this phase and the same measurements taken during the arc smoothing phase.

The results of the measurements show that:

- For LSS1 and 5, a “cat’s ears” phenomena is also present, the magnets moving towards the outside of the LHC ring with probably the same origin as the one explained for the vertical direction (Figure 4).
- In LSS2, the magnets between Q10 and Q8 on the Left side are also quite unstable with a movement of maximum 1.5 mm toward the exterior of the LHC centre. These are the same magnets as the ones which were unstable in the vertical direction.
- In LSS8, many magnets seem to have moved in particular the D1 separators dipoles and the ones at the arrival of the TI8 tunnel in the LHC.
- For LSS6, the magnets unstable in the vertical plane have moved by a maximum of 3 mm towards the centre of the LHC as shown on Figure 5
- In horizontal also, the magnets of the LSS3, 4 and 7 are quite stable

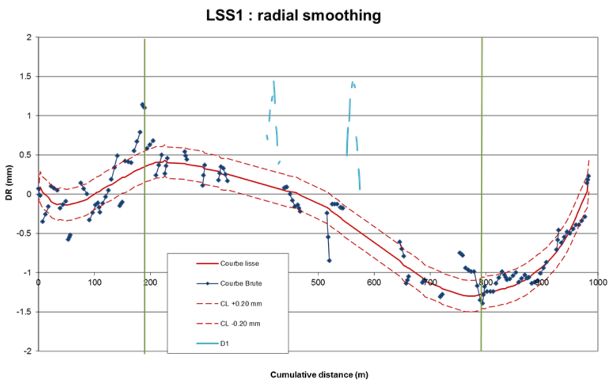


Figure 4 : the horizontal profile of LSS1

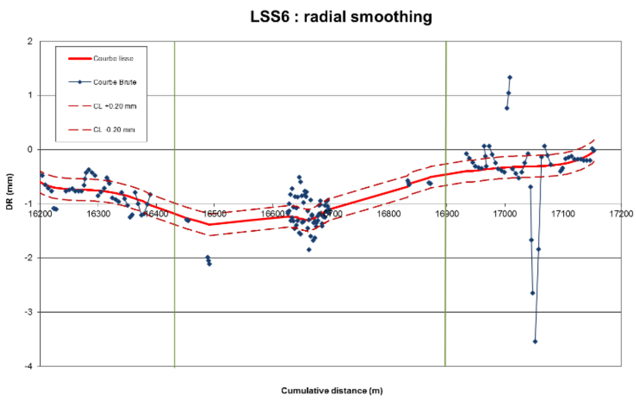


Figure 5 : the LSS6 horizontal profile

The civil engineering works that took place for the LHC at the end of the 90’s are still generating quite important movements of the tunnel floors in the vertical and horizontal directions. The unstable areas are quite well identified and have to be followed up carefully in the future.

SMOOTHING THE ARCS

The roll measurement

Like for the LSS magnets, the smoothing operation starts with the roll measurements of the components and their re-adjustment if necessary.

Table 2: roll deviation of the Arc magnets

Sector	Deviation to theoretical roll angle (mrad)				Realigned magnets	
	avg	r.m.s	min	max	%	Nb>1 mrad
12	0.06	.12	-.38	0.57	26	0
23	0.02	0.14	-.76	0.69	20	0
34	-.05	0.22	-1.5	0.77	33	3
45	.07	0.15	-.83	0.72	46	0
56	.01	0.17	-.91	0.64	23	0
67	.06	0.16	-1.12	0.43	39	1
78	.06	0.15	-.90	1.19	33	1
81	.07	0.22	-.65	1.16	48	1
all					34	

Table 2 shows that all the sectors, except 34, have an average trend to sink towards the outside of the LHC ring, the sectors 45 and 81 are the most unstable from the point of view of magnets to be realigned, the sectors 34 has the biggest offsets from the point of view of the standard deviation and min and max values.

The average number of magnets realigned for the whole LHC is 34% with a big difference between quadrupoles and dipoles (Figure 6), almost 60% of quadrupoles were realigned and only 26% of dipoles.

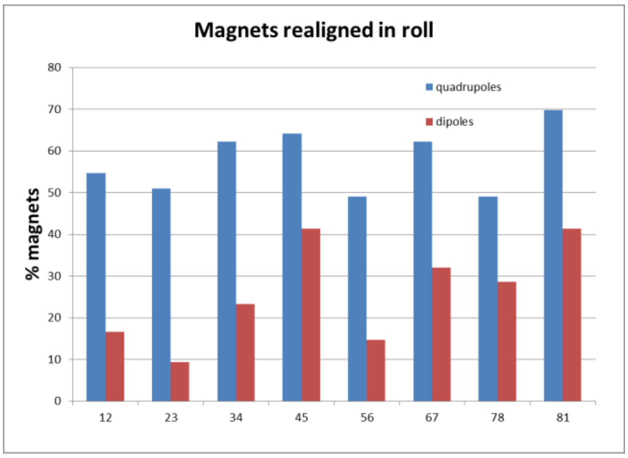


Figure 6 : dipoles and quadrupoles

The vertical measurement

Measurements were done using a DNA03 digital level taken only on the magnets located between Q1Rn and

Q1Ln+1 of the Arcn_n+1, the geodetic network is not used any longer except the deep references. The measurements were done using the Cholevsky method and with "outward" and "return" measurements taken the same day. Two fiducials were measured for the quadrupoles while a third one to check the sag was taken on the dipoles.

For each sector, the calculation is fixed on the altitudes coming from the "quick" levelling [2] of the deep references located at both extremities of the sector.

Then a smooth curve, which is the most probable trajectory followed by the particles beam, was calculated with the PLANE [1] software and the magnets which were more than 0.20 mm away from this curve were considered to be to realign.

Table 3: vertical offsets w.r.t. the smooth curve

Sector	Deviation to the smooth curve (mm)			Realigned magnets	
	r.m.s	min	max	%	Nb > 1mm
12	0.15	-.74	0.55	31	0
23	0.16	-.46	0.52	39	0
34	0.16	-.55	0.68	36	0
45	0.15	-.65	0.47	31	0
56	0.13	-.55	0.55	24	0
67	0.12	-.37	0.38	29	0
78	0.13	-.76	1.03	39	1
81	0.21	-.89	1.38	45	1
all				34	2

Table 3 shows that 34% of the magnets were realigned, mainly in the sector 81, which is the most unstable from the point of view of the spread of the deviations. As the standard deviations of the offsets w.r.t the smooth curve at the end of the shut-down 2008-2009 was between 0.09 and 0.11 mm [3], it can be seen, from column 2, that there is no important degradation in the alignment in a period of almost five years, except for sector 81.

Figure 7 shows that a little bit more of quadrupoles than dipoles have to be realigned.

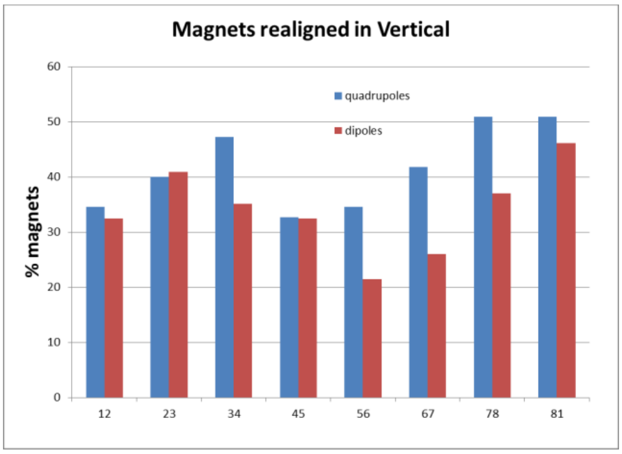


Figure 7: magnets realigned in vertical direction

The horizontal measurement

Measurements were done using offsets w.r.t a stretched wire, taken on two fiducials of the magnets located between Q8Rn and Q8Ln+1 of the Arcn_n+1 with the sequence shown on Figure 8. As a matter of fact, the part between Q8 and Q12 on each side of the Arc, already measured during the smoothing of the LSS, is re-measured in order to have a good overlap between both measurement campaigns. No distances were measured, no link to the geodetic network.

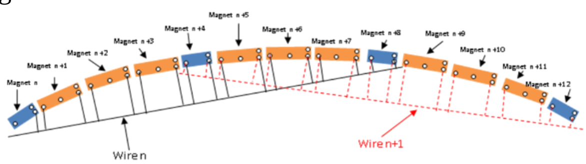


Figure 8: ecartometry sequence

For each sector, the calculation is fixed on the real coordinates of the Q8Rn and the Q8Ln+1 coming from the smoothing of the LSS.

Like for the vertical measurements, a smooth curve was calculated with a threshold of realignment between 0.2 and 0.25 mm.

Table 4: horizontal offsets w.r.t. the smooth curve

Sector	Deviation to the smooth curve (mm)			Realigned magnets	
	r.m.s	min	max	%	Nb > 1mm
12	0.21	-.86	1.01	26	1
23	0.28	-1.88	1.20	37	5
34	0.35	-2.09	1.39	45	8
45	0.26	-1.71	0.96	46	2
56	0.25	-1.39	1.12	24	4
67	0.23	-1.53	0.78	29	3
78	0.27	-2.04	1.22	34	4
81	0.38	-.1.61	1.65	45	9
all				36	36

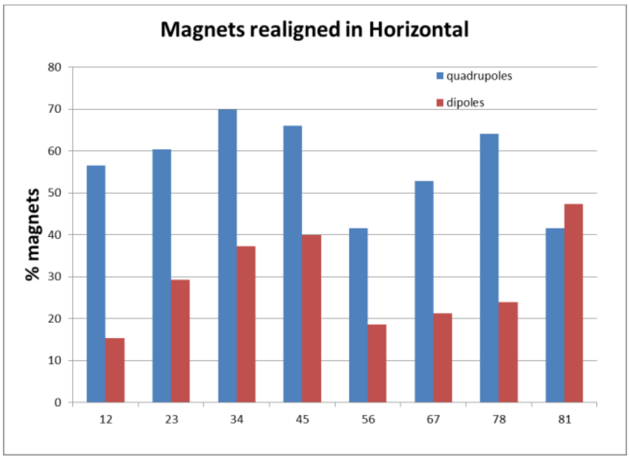


Figure 9: magnets realigned in horizontal direction

Table 4 shows that 36% of the magnets were realigned, 36 of them by more than 1mm, 3 of them by more than 2 mm. Sector 34 and 81 are the most unstable, 8 and 9 magnets respectively realigned by more than 1 mm, and with a wide spread of deviations. It shows also that the standard deviation of the offsets w.r.t the smooth curve, which was between 0.10 and 0.20 mm after the initial smoothing in 2008, has increased drastically in all the sectors.

Figure 9 shows that two times more quadrupoles than dipoles have to be realigned.

PREDICTIONS FOR LS2

After the horizontal measurements done on sector 34 and 78 during the shut-down 2008-2009, an extrapolation, based on statistics of two measurements campaigns only, showed that two magnets per sector might have an offset of more than one mm after 10 years. Indeed, the number of magnets with an offset bigger than one mm was much bigger (average of 4.5 magnets per sector for a period of only five years) as shown in Table 4. The predictions were not so pessimistic.

With the data measured during LS1, simulations taking into account the situation after the realignment done and the degradation measured during five years will hopefully give us the number of magnets to realigned during LS2 in each sector.

COMPARISON WITH PREVIOUS MEASUREMENTS

The comparison of the data of several measurements campaign, in particular of one LHC sector of 3.3 km, is quite complicated because of its length and the errors done during the measurements which could be bigger than the displacements observed.

Even in the case of the vertical measurements, which are referred to the local gravity, the shape of the vertical deviations w.r.t the theoretical position of consecutive measurements could be quite different.

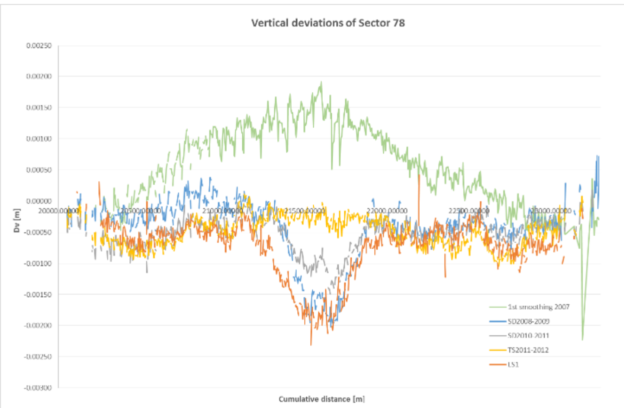


Figure 10: vertical deviations of sector 78

On Figure 10, the global shape of the sector 78 of the 1st smoothing in 2007 (in green) is completely different than the shape of 2009 (blue) even if they are processed with the same software, the altitudes of the same fixed points at each extremity and the measurements done under the same conditions.

But it doesn't mean that all the magnets have moved by such a difference. Even if the global shape is not a relevant criteria to study, some "patterns" visible on most of the shapes indicates that a local analysis might be bore relevant.

For horizontal measurements, this is even worse as the measurements are linked to the neighbouring ones, therefore with a propagation of errors quite important. They are processed with only two fixed points, one at each extremity and a radial corridor of 5 mm w.r.t their theoretical position. This corridor has been defined, by simulations and measurements, to be the maximum transverse error of the geodetic network and impose to the magnets not to be outside these value from their absolute position. Any change of parameters of the data processing may give a completely different shape of the position of the magnets. Again, the difference of the deviations is not the best criteria to study.

An alternative could be to use the deviations w.r.t the smooth curve determined for each measurement campaign. The smooth curve will be different but the deviations are more "locally relative" and could be more relevant. A study has been done and was not very satisfying as, even if it seems that the magnets have a tendency to be on the same side of the smooth curve, there was not systematism concerning the fact they have to be realigned or not. Some of them were realigned once and never again, others were realigned in one direction after one measurement and in the opposite way during the next campaign.[4]

There is also the possibility to eliminate the propagation of the uncertainties of the measurements and the reference datum by using the technique of inclinations and deformations. [5]

We have chosen to study two types of vertical inclinations:

- The ES inclination (InES), which is the deviation w.r.t the theoretical slope between the fiducials Entry (E) and Exit (S) of the same quadrupole over a distance of 3m.
- The SE inclination (InSE), which is the deviation w.r.t the theoretical slope between the fiducial Exit (S) of the quadrupole Qn and the fiducial Entry (E) of the quadrupole Qn+1, located 50 m downstream.

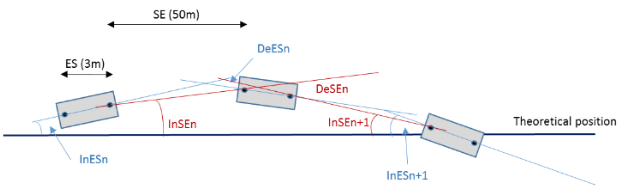


Figure 11 : Inclination and Deformation concept

Then, the deformation is the difference between two consecutive inclinations along the beam. There is a deformation for each type of inclination, DeES and DeSE as shown on Figure 11.

Figure 12 shows the average of the InES per sector and at three different dates. For all sectors except 56, there is an increase of the inclination of the quads ES by an average of +0.003 mrad/year and a change of the speed of the inclination in 2009, which is slower than before. This is perhaps due to the fact that the E fiducial is the location of the unique jack and therefore systematically sinking w.r.t the other extremity. During the same period, the inclination between two consecutive quads (SE) is changing in the opposite direction by an average of -0.0002 mrad/year. At the epoch of the LEP, the evolution was respectively 0.008 and 0.001 mrad/year. It seems that the tunnel is more stable than 20 years ago.

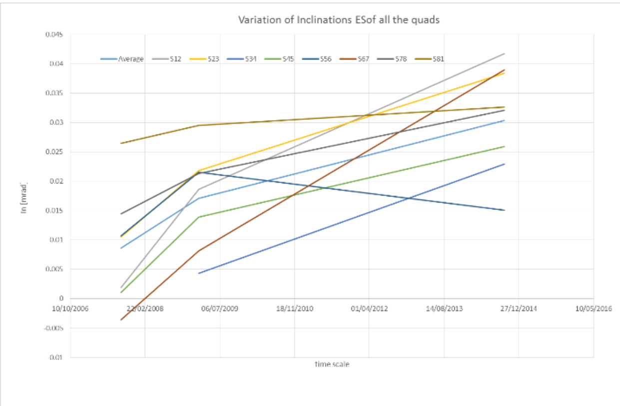


Figure 12: Inclination of quads ES

The inclination InSE over 50 m shows (Figure 13) clearly the “hole” of the sector 78 and a perturbation in Sector 81.

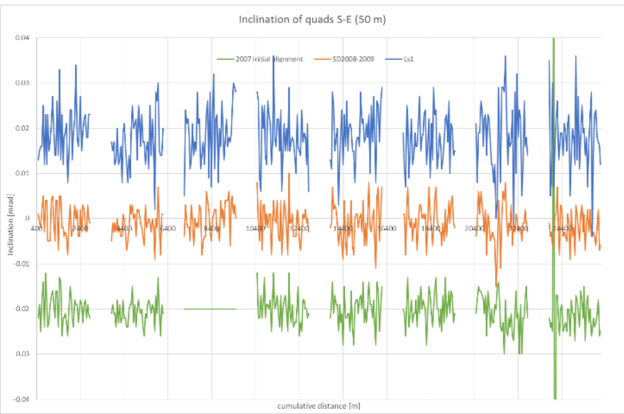


Figure 13: Inclination SE

The analysis of the deformations shows on Figure 14 that from 2007 to 2009 it was positive and after this date it became negative, both for the ES and SE deformation. Concerning the ES deformation, the sectors 78 and 81 are the most active, immediately followed by the sector 34 as shown on Figure 15.

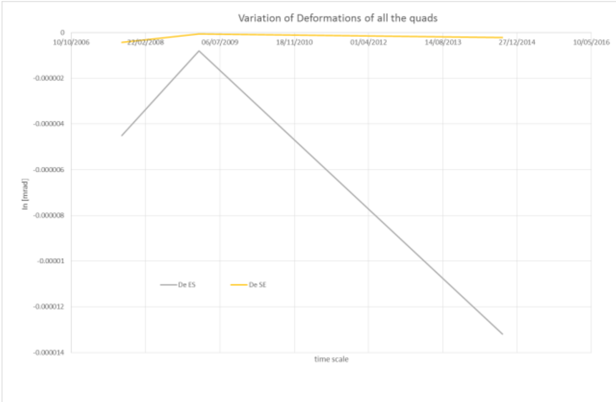
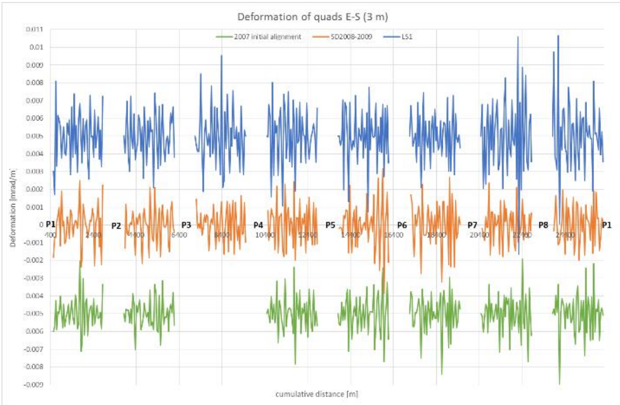


Figure 14 : Deformation



A similar study will also be done in the horizontal direction

Figure 15 : Deformation ES

CONCLUSIONS

During the LS1, the LHC has been completely measured and about 35% of magnets were re-aligned. All the data were analysed using different methods. The most unstable areas have been identified. The LSS1, 2, 5, 6 and 8 are the places of important movements due mainly to the influence of civil engineering works done for the LHC.

Concerning the arcs, the statistical analysis has shown that the LHC is much more stable in the vertical plane than in the horizontal one with 36 magnets having to be realigned by more than one mm, the sectors 81 and 34 being the most unstable ones. The sector 78 is continuing to sink vertically by 1mm per year in its middle part. The statistical analysis shows that the movements of the magnets in the vertical direction are much smaller than during the LEP era and that the sectors 78, 81 and 34 are the much unstable.

The run2 of the LHC has started at an energy of 13 TeV, centre of mass, in spring 2015 and the accumulation of luminosity for 2016 has already exceed the expected value of 25fb-1. This run will last up to the Long Shutdown 2 (LS2), which will take place in 2019-2020. Before the LS2, we will check the unstable areas during the technical stops.

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