LONG SHUTDOWN 2 LHC SMOOTHING STATUS AND DATA ANALYSIS

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Abstract

During the two-year Long Shut-Down 2 (LS2), triggered by the LHC Injectors Upgrade (LIU) project, the CERN surveyors took in charge the smoothing of the 27km components of the LHC to guarantee its best beam aperture and energy performance for the RUN3 between 2022 and 2026.

During this large measurement campaign, the roll angle of the LHC components in the Long Straight Section (LSS) as well as their position in vertical and in horizontal directions were measured by direct levelling and stretched wire methods. These initial data were computed by CERN homemade software to define and optimize the workload of the displacement sequence, in order to re-align all the cryo-magnets within a +/- 0.2 mm tolerance.

This LS2 smoothing campaign at cold (> 80K) is the third one after the LHC installation (2008) and LS1 (2013-2014). CERN has now collected an important source of data useful for the analysis of the LHC stability which will allow the survey team to predict the areas where future movements are going to take place.

The paper gives an overview of the methodologies, techniques and software used for the smoothing, the realignment process and an analysis of the stability of the LHC tunnel based on the data collected during the three campaigns.

INTRODUCTION

After the full dismantling of the Large Electron Positron (LEP), the same underground infrastructures bored in the middle of the 80s, have been re-used to host the Large Hadron Collider (LHC) machine. The installation of the LHC magnets started in 2007 and the alignment was fully completed in 2008 [1].

The stability and behaviour of the LEP tunnel have been studied between 1992 and 2000. Some areas are known to be quite unstable, such as the middle of sector 78 where a yearly vertical displacement of 1.5 mm has been detected due to a geological fault.

The LHC cryo-magnets, installed in the same tunnel are much more demanding in terms of alignment than the LEP ones, due to mechanical constraints and beam aperture requests. Additional new experimental caverns and both bump tunnels have been made specifically for the LHC.

The behaviour of the unstable infrastructures bored for the LEP and the new ones added for the LHC have a direct impact on the machine stability.

With the new LHC rhythm defined by a run period of three or four years followed by a long shutdown of two years, it is not possible to organize yearly measurements of the whole LHC machine. On the other hand, the unstable areas should be well known and monitored in order to perform short interventions and smooth the magnets during the winter technical stops.

LHC MACHINE

The Large Hadron Collider (LHC) is a circular collider of 27 km circumference composed of more than 2000 “cold” components. The LHC is divided into eight equal sectors, each one composed of a standard Arc and two half Long Straight Sections (LSS) and two half Dispersion Suppressor (DS) as shown in Figure 1.

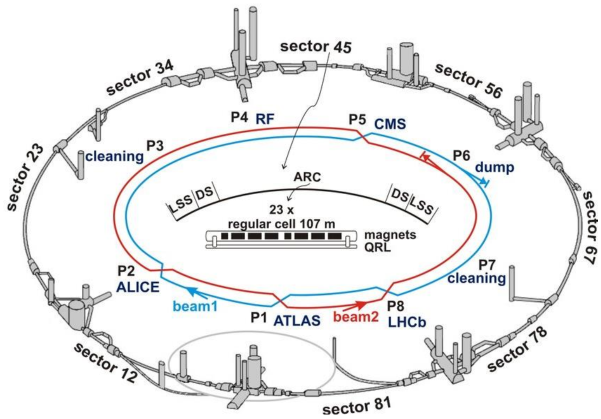

Figure 1: General LHC view

LSS and DS area

Four LSS stand the LHC experiments at the Interaction Point (IP) located in their midst; the four other LSS are equipped with beam instrumentation and a virtual IP is also defined in their middle. The IP is surrounded by the final focus quadrupoles and separator dipoles but also by many resistive quadrupoles, beam instrumentation, collimators and accelerating cavities linked by vacuum chambers and operating at different temperatures (cold/warm).

The DS is located at the LSS extremities before the beginning of the Arc area from Q7 to Q11. The LSS and DS are covering a length of 440 m on each side of the IP.

For the sake of simplicity, these both regions are named LSS later in this paper.

Arcs Area

The area starting from Q11 (after the DS) is named Arc and is composed of only cold cryo-magnets operating at

1.9K. As shown in Figure 2, each arc hosts 138 dipoles and 45 quadrupole magnets over a length of 2.5 km.

For example, sector 78 (from Point 7 to Point 8) is composed of the right part of LSS7, named LSS7-R, the arc 78 and the left part of LSS8, named LSS8-L)

Figure 2: LHC Arc view with cry-dipole in bleu and cryo-quadrupoles in white

THE LHC SMOOTHING STRATEGY

Taking into account the human resource limitation during a long shutdown, the Geodic Metrology group workload, the co-activities in the LHC tunnel and the time constraints during an LS, it has been decided to adopt the following strategy:

- The LSS cryo-magnets are smoothed at warm (ambient temperature) before the secondary component alignment campaign,
- The Arc cryo-magnets are smoothed at the end of the LS at cold when their temperature is below 80°K and after all the mechanical internal movements have taken place. [2] [3]

In order to define the component positions, the following measurements are performed:

Roll angle measurements

The smoothing campaign starts with the measurement of the angle around the beam axis with a tilt-meter on a reference surface. The roll angle component is adjusted if out of tolerance (+/- 0.1 mrad).

Vertical measurements

The vertical measurements are done using Na2 optical level and LS15 digital level taking the fiducials of the components and the geodetic deep references (GITL) installed on each LSS. Thus, all the vertical measurements (LSS and Arc) are defined with respect to the absolute reference used in the machine and part of the Cern Coordinates System (CCS). [4]

Radial and polar measurements

Almost all the radial measurements are carried out using the stretched wire method developed at CERN in the 60s: the surveyors measured the offsets between the fiducials of the component and a stretched wire [5].

For the LSS campaigns, angles and distances are also measured with AT4xx laser trackers from Q7Ln to Q7Rn, in the bypass and in the LHC experiment caverns.

Software & Survey Database

All the measurements (polar, levelling, wire, …) are computed with the "Logiciel Général de Compensation" (LGC) that is an in-house surveying data processing software of the Geodetic Metrology group at CERN based on the last square adjustment.

The socket component offsets (radial, vertical and longitudinal) are inserted in the Survey Database in order to compute the beam offsets used by the physicists.

The vertical and radial offsets are used to create the input needed by the Rabot Software to "smooth" an accelerator in the horizontal or vertical direction. The program identifies the beamline elements that do not lie on the smooth curve and the displacements that should be applied to correct the position of the components. [6]

Smoothing workflow

The smoothing activity is an iterative process starting with the initial measurement of the component in order to define the displacements needed to obtain a smooth curve in the vertical and radial directions within the tolerance (+/- 0.2 mm).

After the first displacements, the adjusted components are re-measured with respect to the fixed ones in order to validate the new positions and continue the process with a second or third displacement campaign if needed.

THE LSS SMOOTHING

The campaign is not strictly limited to the LSS area as the measurements are going until Q12 to ensure an overlapping with the smoothing of the LHC Arcs and the displacements are limited in the LSSn area from Q7Ln to Q7Rn.

The LSSs are smoothed in two steps: a first campaign concerning the main components is performed in order to define the vertical and radial geometry of the LSS that will be used as the reference to align in a second step the secondary components.

Main components

A first campaign concerning the "heavy" components such as the cryo-magnets, the dipoles, the RF cavities, …. is performed in the roll angle, vertical and radial direction.

For the experimental LHC points, the LSSs are smoothed with respect to the position of the interaction points defined by the detector pixel positions. The main component smoothing is finalized when all the offsets are inside of +/- 0.2 mm tolerance in vertical and in radial directions.

Secondary components

A second campaign concerning all the secondary components such as the collimators, masks and beam instrumentation equipment is needed to complete the LSS smoothing. These "light" components are aligned with respect to the "heavy" ones previously well aligned on the smooth curves. As shown in Figure 3, the secondary components are mostly aligned in 3D with the AT4xx laser tracker using the survey sockets as references on the main magnets or a specific network previously installed in the area and computed with respect to the main component positions.

During the LS2, the LHC vault has been equipped with magnetic nests to link temporally the 3D network with the LHC machine and increase the reference points in order to perform laser tracker alignment method.

Figure 3: Laser tracker measurement on a CERN nest

If the 3D method, voluntarily limited to a +/- 25 m volume, cannot be applied: the 2D+1 method is used for long=distance configuration or to measure "hidden" components with stretched wire.

The LSS smoothing is finished when the main and secondary components are well aligned with respect to the LSS smooth curve tolerances in the vertical and radial directions.

This paper will focus on the main component offsets obtained after the LSS and ARC smoothing.

LSS: LS2 RESULTS

LSS roll angle

The main magnets of the 8 LSS have been smoothed during the first part of the LS2 at ambient temperature. Table 1 shows the deviations w.r.t the theoretical roll angle values:

- The average value for all the LSS is lower than 0.1mrad, which is the limit for the realignment. About 30 % of the components were out of tolerance and have been taken into consideration for the roll adjustment.
- As observed during the LS1 [7], the quite important standard deviation of LSS4 is due mainly to the offsets out of tolerance (up to 1.6 mrad) of the four cylindrical refrigerator cryomodules. These complex components housing the 16 radiofrequency (RF) cavities stand on a hyperstatic supporting system.
- The standard deviation of LSS6 is explained by the 30 MSD magnets installed in LSS6, half of them were out of tolerance with a value up to 0.6 mrad. In addition, a large number of magnets were realigned in both areas perturbed during the excavation of two LHC beam dumps tunnels. Moreover, an important offset was measured on the LELJ connexion cryostat with a 1.25 mrad offset. This "empty" and "light" cryostat does not stand well on its jacks and is under the influence of the forces generated by the adjacent components. A dedicated alignment method was implemented under vacuum for the LEBL.11L4 and LEAR.11R6.

Table 1: LSS Roll angle deviation (mrad)

LSS	Avg.	RMS	MIN	MAX	%
LSS1	0.01	0.17	-1.04	0.21	35%
LSS2	0.04	0.11	-0.28	0.31	34%
LSS3	-0.03	0.13	-0.39	0.28	33%
LSS4	0.06	0.30	-0.59	1.58	30%
LSS5	0.02	0.06	-0.17	0.15	9%
LSS6	0.01	0.26	-0.68	1.25	21%
LSS7	0.08	0.09	-0.25	0.31	34%
LSS8	0.05	0.10	-0.19	0.31	27%

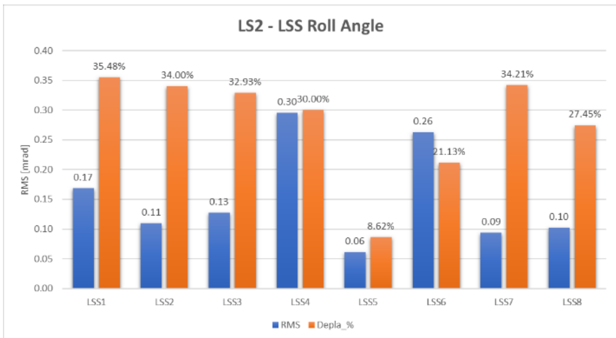

Figure 4: Roll deviation of the LSS magnets

LSS Vertical smoothing

The direct levelling is performed from Q12Ln to Q12Rn by using Na2 optical and LS15 digital levels by measuring:

- The E (Entrée,) M (Middle) and S (Sortie) sockets on the components,
- The GGPSO (Ground reference pillars) located in the LHC concrete floor in order to perform a new altimetric determination of the network and collect data for any future studies such as floor monitoring.
- The Hydraulic Levelling System sensors (HLS) on the lowbeta magnets crossing the experimental caverns to link the vertical measurements, [7]
- The deep reference GITL giving the reference altitude.

The LSS1 and LSS5 have similar behaviour, see Figure 5 for LSS1 as an example:

- They were both impacted by the Civil Engineering activities generated by the High-Luminosity Large Hadron Collider (HL-LHC) project. New adjacent galleries, close to the LHC tunnel have been excavated since April 2018 at PT1 and PT5. The LSS1 and LSS5 are monitored with 3D profiles and vertical measurements on the ground reference points. Vertical displacement up to 3.0 mm have been observed in the LSS5-L side in October 2019.
- The D1 magnets named MBXW in the areas of the separator dipoles where civil engineering works took place at the end of the 90s are still unstable and request regular vertical re-alignment.

In addition, in LSS5, a -3 mm vertical displacement campaign was performed in order to re-align the centre of the straight section with respect to the CMS pixel detector position. The area from Q10L5 to Q10R5 was impacted by this request that was performed in 4 steps to avoid large offsets on the vacuum bellows.

LSS2 and LSS8 are connected with Ti2 / Ti8 tunnels coming from SPS: these areas with new tunnels excavated at the end of the 90s for the proton transfer line are also unstable. The smoothing of these straight sections had to be done in accordance with the smoothing of both injection beam lines coming from the Super Proton Synchrotron (SPS) in order to keep the beam aperture at the connexion point. The displacements stay in the range of 1 mm maximum.

In the LSS7, a dozen of components along 200 m on the right side have been moved down 1mm in order to erase a bump and optimize the smoothed curve.

The LSS3 and LSS4 are quite stable with vertical displacement of a few components measured outside the +/- 0.2 mm tolerance.

LSS Radial smoothing

The measurements combine offsets w.r.t a stretched wire taking the fiducials of the magnets located between Q12Ln and Q12Rn of the LSSn and 3D tracker measurements with additional points fixed on the vault ensuring the link between all the stations and the reference network for the 3D displacements.

For LSS1, 2, 5 and 8 with lowbeta magnets and experiments constraints the calculation is fixed on the Q2Ln and Q2Rn magnets and a radial constraint of 1mm is added on the magnets between Q9 and Q12 on each side of the LSS.

For LSS3, 4, 6 and 7 without IP, a free calculation is done with a radial constraint of 1mm between Q9 and Q12 on each side of the LSSs

For LSS1 and LSS5 the divergence area is also impacted with a radial displacement of the magnets towards the outside of the LHC ring with probably the same origin as the one explained for the vertical direction.

In LSS2 and LSS8, the magnets between Q9 and Q11 have some random disturbances of a few tenths of mm around both injection tunnels coming from the SPS.

No significant displacement for LSS3 and LSS7, only a few tenths of mm have been corrected.

As observed for the roll angle, the RF cavities in LSS4 are unstable in the horizontal plane and have moved by a maximum of 2 mm towards the centre of the LHC.

For LSS6, the MSD magnets unstable in the radial direction have been realigned by a maximum of 1 mm.

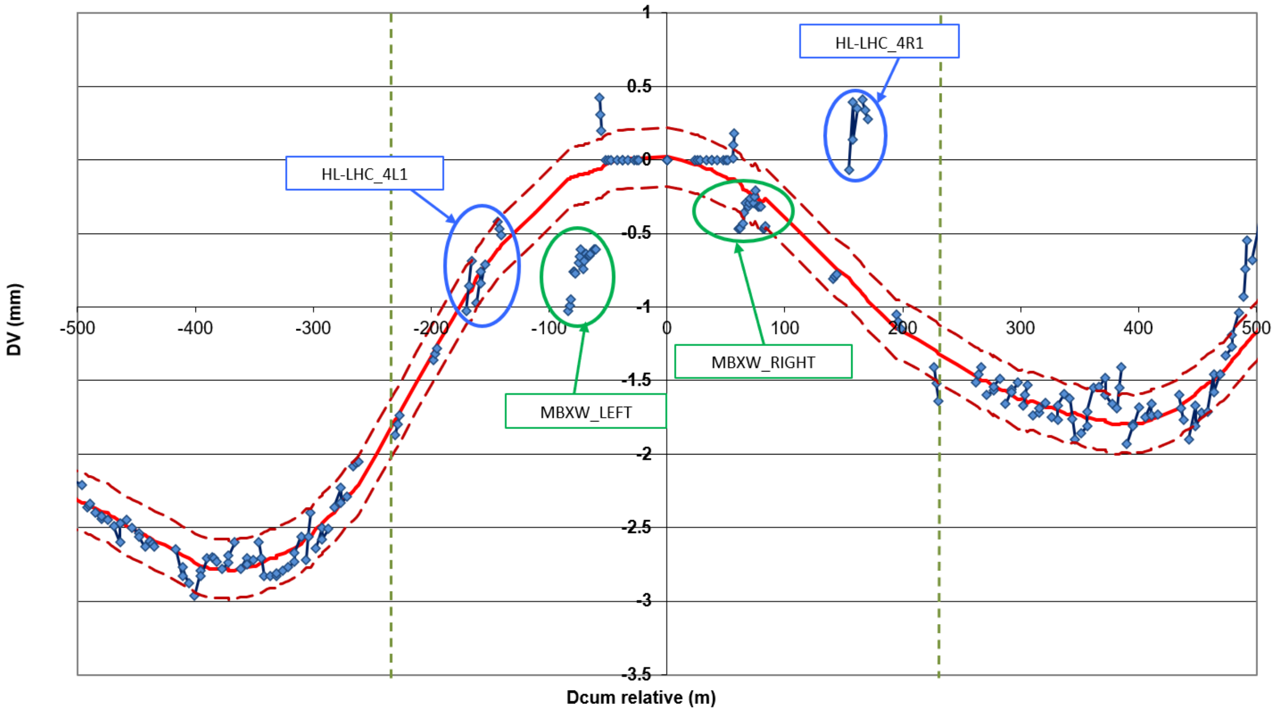

Figure 5: LSS1 vertical smooth curve before realignment

THE ARC SMOOTHING STRATEGY

The Arc smoothing (roll, direct levelling and wire measurements) is done at less than 80K, the magnets should be first cooled down and ready for the next run. The survey campaigns are scheduled with all the powering tests with a lot of access constraints.

- For the vertical measurement, two fiducials are measured for the quadrupoles while a third one to check the sag was taken on the dipoles. The measurements were performed using the Cholevsky method and with “outward” and “return” measurements were taken on the same day. The calculation is fixed on the GITL taking also into account the vertical position of the Q8 magnets determined during the LSS campaigns.
- For the radial calculation, the area between Q8 and Q12 on each side of the Arc, already measured during the LSS smoothing, is re-measured in order to have a large overlap between both campaigns. In addition, the LSS offsets are re-used to create virtual wire offset measurements in LGC and are combined with the measurements done from Q8Rn to Q8Ln+1. No distances are measured, and no link to the geodetic network. The calculation is fixed on one extremity with an additional radial constraint on the LSS main components (few tenths of mm) and 5 mm on the arc cryo-magnets.

ARC: LS2 RESULTS

ARC roll angle

As done for the LSS components, the ARC smoothing operation starts with the roll measurements of the components and their readjustment if necessary.

In total, 388 cryo-magnets with a majority of quadrupole have been realigned. Figure 6 shows that the LS2 standard deviation is about 30% better than the LS1 results.

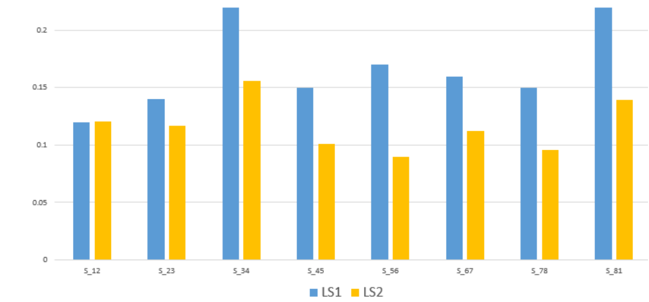

Figure 6: Roll deviation of the ARC magnets

Table 2 shows that all the sectors, except 34, have an average trend to sink towards the outside of the LHC ring.

Sector 34 is the most unstable with 93 magnets (about 50 % of the sector) out of tolerance and the biggest offsets from the point of view of the standard deviation. Sector 34 goes through an area of limestone at the foot of the Jura mountain range which is considered geotechnically very challenging and is very porous. Since the LEP construction, this area has been facing substantial migrations of groundwater and sand causing excesses of hydraulic pressure building up on the tunnel surface.

Sectors 23 and 56 are the most stable with less than 20% of the components aligned in roll angle direction.

Table 2: ARC Roll angle deviation (mrad)

	LS2_2020-2021					
	SOCKETS				COMPONENT	
Sector	RMS	MIN	MAX	AVG	Depla_NB	Depla_%
S_12	0.12	-0.64	0.44	0.03	45	23.56
S_23	0.12	-0.57	0.91	0.04	31	16.23
S_34	**0.16**	**-0.66**	**0.84**	**-0.10**	93	**48.69**
S_45	0.10	-0.46	0.62	0.05	38	19.90
S_56	0.09	-0.31	0.40	0.02	33	17.28
S_67	0.11	-0.37	0.49	0.05	55	28.50
S_78	0.10	-0.40	0.29	0.01	43	22.51
S_81	0.14	-0.32	0.68	0.08	50	26.18

ARC Vertical smoothing

483 cryo-magnets have been vertically realigned, about 31% of the arc components.

Table 3: ARC vertical deviations (mm)

	LS2_2020-2021					
	SOCKETS				COMPONENT	
Sector	RMS	MIN	MAX	ABS.MAX	Depla_NB	Depla_%
S_12	0.14	-0.61	0.87	0.87	49	25.65
S_23	0.14	**-1.10**	0.45	1.10	56	29.32
S_34	**0.17**	-0.53	0.68	0.68	94	**49.21**
S_45	**0.17**	-0.80	0.37	0.80	65	**34.03**
S_56	0.10	-0.25	0.31	0.31	39	20.42
S_67	0.14	-0.40	0.85	0.85	50	26.18
S_78	0.14	-0.49	0.34	0.49	69	**36.13**
S_81	**0.16**	-0.33	**1.00**	1.00	61	**31.94**

Table 3 shows that sector 34 is the most unstable with more than 49% of the cryo-magnets out of the tolerance in the vertical direction.

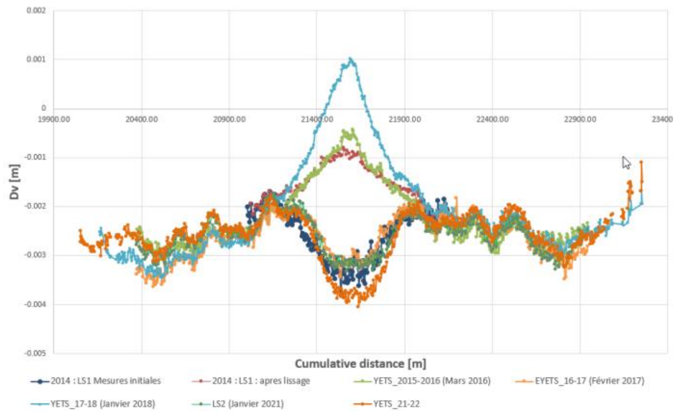

Figure 7: S78 vertical smooth curves since LS1

Sectors 78 and 81, identified as unstable during the two previous campaigns (installation and LS1) are again relevant with more than 30% of the components smoothed.

Sector 78, with 36% of the component re-aligned, is an area with extremely complicated geotechnical features as a fault line runs directly across the sector. This sector was identified as an issue dating back to the construction of the

LEP and identified as a problematic area in the FCC high-risk study.

Figure 7 shows the movement over the years since the LS1 with the elastic vertical movement along 800 m from MQ.29R7 to MQ.29L8. It has been decided to let the tunnel move with regular survey campaigns. The vertical offsets are confirmed by the beam operation corrector settings.

Sector 45 is also significantly affected by the vertical displacement with 34 % of the cryo-magnets realigned.

Sectors 12, 23, 56, and 67 can be considered as less disturbed even if a 1 mm vertical displacement has been performed on the dipole LHC.MB.A17R2 in sector 23.

Compared to the results obtained during the installation and LS1 campaign, the LS2 standard deviations mean value of the offsets w.r.t the vertical smooth curve is 0.15 mm.

ARC Radial smoothing

507 cryo-magnets have been radially realigned during LS2, about 33% of the arc components.

Table 4: ARC radial deviations (mm)

	LS2_2020-2021						
	SOCKETS					COMPONENT	
Sector	RMS	MIN	MAX	ABS.MAX	> +/- 1 mm	Depla_NB	Depla_%
S_12	0.23	-1.27	0.73	1.27	3	67	35.08
S_23	0.22	-0.99	1.77	1.77	2	57	29.84
S_34	0.18	-0.89	0.74	0.89	0	61	31.94
S_45	0.17	-0.89	0.69	0.89	0	60	31.41
S_56	0.15	-0.84	0.86	0.86	0	43	22.51
S_67	0.20	-0.79	0.83	0.83	0	61	31.61
S_78	0.19	-1.22	0.49	1.22	2	64	33.51
S_81	0.23	-0.50	0.86	0.86	0	94	**49.21**

Table 4 shows that sector 81 is the most unstable with more than 49% of the cryo-magnets out of the tolerance in the radial direction.

Less than 35% of the magnets have been affected in sectors 12, 23, 34, 45, 67 and 78. During LS2, only seven cryo-magnets with displacements higher than 1 mm, up to 1.7 mm, have been corrected compared with LS1 where 36 magnets were concerned covering all the LHC sectors. Sector 56 is the most stable with less than 25 % of displacements.

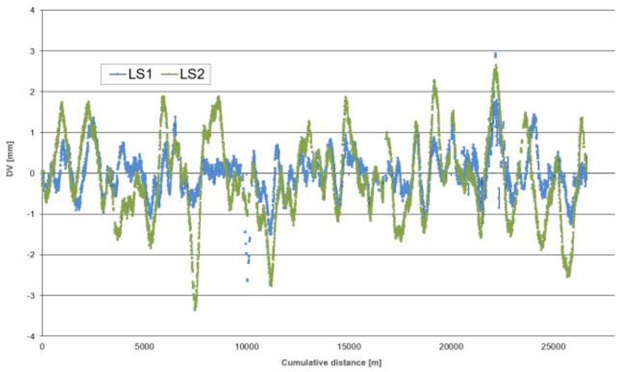

Figure 8: LS1 and LS2 radial smooth curves

A full view of the LS1 and LS2 radial smooth curve is given in Figure 8: even if the radial measurements are not directly linked with the CCS, the relative position of both curves is globally homogeneous with local amplifications and a significant difference from 15R3 to 20L4 where is located the sector 34.

All the radial offsets are contained within +/- 3 mm along the 27 km.

The LS2 standard deviations of the radial offsets are 30% better (0.20) compared to the installation and LS1 campaign (0.28). This improvement of the radial stability should be confirmed after LS3.

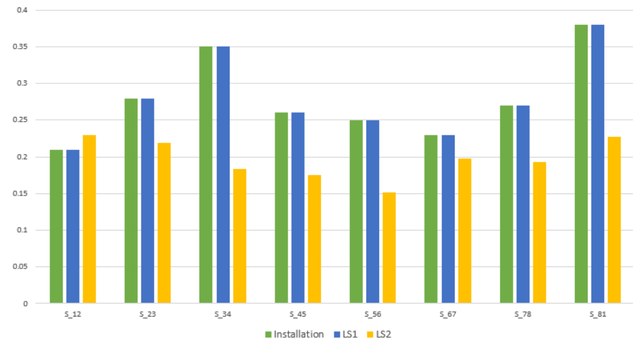

Figure 9: Radial RMS by sector since installation

CONCLUSIONS

Large feedback has been collected during the LS2 with the improvement of GM methodology and process.

- For example, even if direct levelling is still used and well adapted for long traverses: laser trackers are now the common survey tools in the tunnels for short-range 3D activities: the methodology has been updated in the field including the computing process.
- On the other hand, the GM Group has shared its LS2 feedback with the CERN Equipment Owners as they are a key point of the Quality Assurance process. A new engineering note named the "Survey guidelines and requirements" has been published and presents all the survey standards and the requirements from the initial design to the installation and alignment of new accelerator equipment on a beamline at CERN.

The LHC tunnel is still impacted by the civil engineering works that took place at the end of the 90s. Some areas correctly identified as problematic are still generating important movements in the vertical and horizontal directions.

New excavations done in 2018 for the HL-LHC project have been a source of vertical displacements of the LHC floor. These areas will be considered until the LS3 new beamline installation in LSS1 and LSS5.

The LHC underground areas subject to ground movement that require machine realignment are quite well identified. In addition to sector 78, sectors 34 and 81 will get all our attention until LS3. These areas have to be followed up carefully in the future with additional input coming from the Site and Civil Engineering (SCE) department and the beam operators in order to optimize the beam aperture for the LHC machine.

REFERENCES

[1] D. Missiaen, J.P. Quesnel: « The final alignment of the LHC », 10th International Workshop on Accelerator Alignment, IWAA2008, KEK, Japan, February 2008.

[2] D. Missiaen: « The alignment of the LHC during the shut-down 2008-2009 », 11th International Workshop on Accelerator Alignment, IWAA2010, DESY, Hamburg, Germany, 13-17 September 2010

[3] D. Missiaen and al, "Managing the survey activities during the LS1", IWAA2014, IHEP, Beijing, China, 13-17 October 2014.

[4] J. Gervaise, M. Mayoud, E.Menant : « Système tridimensionnel de coordonnées utilisé au CERN », Genève, 1976

[5] J.P. Quesnel: « Stretched Wire Offset Measurements: 40 Years of Practice of this Technique at CERN for Aligning the Accelerators of Particules », 10th International Workshop on Accelerator Alignment, IWAA2008, KEK, Japan, February 2008.

[6] P.A. Sanglier – « First experience on Python development for Survey Software, advantages & drawbacks », 10th International Workshop on Accelerator Alignment, IWAA2008, KEK, Japan, February 2008.

[7] H. Mainaud Durand – « Permanent monitoring of the LHC low beta triplets: latest results and perspectives », 11th International Workshop on Accelerator Alignment, IWAA2010, DESY, Hamburg, Germany, 13-17 September 2010

[8] D. Missiaen, JF. Fuchs – « Smoothing the LHC during LS1 », 14th International Workshop on Accelerator Alignment, ESRF, France, October 2016.