MANAGING THE SURVEY ACTIVITIES DURING LS1

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Abstract

The Long Shut-Down 1 (LS1), has been triggered by the repair of the splices in the interconnections of the Large Hadron Collider (LHC) cryo-magnets. The "weakness" of these splices needed to be repaired in order to run the LHC at its ultimate energy of 14TeV to accumulate more luminosity and events to improve the knowledge of the parameters of the Higgs's boson discovered at CERN in 2012. This long shut down of CERN accelerators gave the opportunity to the survey and alignment team to measure and realign the 27km of LHC magnets but also most of the injector chain components. The Proton Synchrotron (PS), the first accelerator at CERN, its booster (PSB) and transfer lines were not realigned since years. Some parts of the Super Proton Synchrotron (SPS) and the transfer lines to the LHC are known to be geologically unstable since their construction. All these are very good reasons to review the alignment of almost all the components of the CERN complex. The LHC big detectors were also considerably modified and this work was done under the control of the survey team, using the cavern network as a reference. This network was re-measured and linked to the machine network.

This paper gives an overview of the survey activities done during the two years of shut-down, especially from the management and organisation point of view, taking into account the enormous amount of work to be done with tight schedules and by personnel which has considerably changed since the previous measurements campaign in 2008.

INTRODUCTION

The LS1 which has been triggered by the repair of the splices in the interconnections of the LHC cryo-magnets has been prepared during several years. The survey team has decided to take advantage of this long period of access in the tunnels to organize an intensive campaign of measurements in the LHC in order to finalise the smooth position of the cryo-magnets but also in the other machines. Smoothing the accelerator components and anticipating future misalignment were the main goals of this measurement campaign. The survey is also deeply involved in important upgrades of the LHC experiments as well as in the assembly and alignment work for non-LHC experiments being built or reshuffled during the LS1 period. An intensive maintenance and consolidation work has been carried out on the LHC low beta magnets monitoring system as well as on annexed monitoring systems in ATLAS and CMS. Hence the systems these future high radiation areas have been controlled and remote qualification equipment has been installed additionally [1]. Definition and justification of the work proposed, procedures and resources as well as preliminary results are presented in this paper.

THE CERN ACCELERATOR COMPLEX AND THE DETECTORS

The flagship of CERN, the LHC is a circular proton-proton collider of 27 km of circumference. Prior to their injection into the LHC, the particles are generated and accelerated in the CERN injector complex (Figure **1**) composed of a source, a linear accelerator LINAC2, the Proton Synchrotron Booster (PSB), the Proton Synchrotron (PS), the Super Proton Synchrotron (SPS) and two transfer lines called TI2 and TI8. The proton-proton collisions are observed by four main experimental detectors located at four places along the LHC: ATLAS, CMS, ALICE and LHCb.

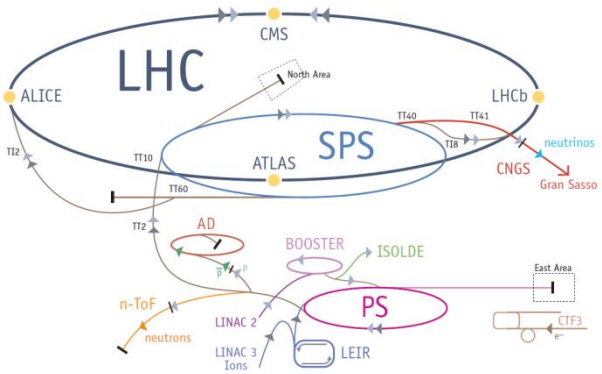


Figure 1 : the LHC and the Injectors complex

WHY A SO HEAVY MEASUREMENT CAMPAIGN ?

Most of the lines constituting the injectors have not been measured since years and a refreshment of the alignment was necessary. The LHC itself was not measured completely since its first alignment in 2007 and it was always foreseen that the smoothing process would take several years after its installation.

The *Proton Synchrotron and its Booster*

The PS was measured in the vertical and horizontal direction in 2005 while the PSB was measured in 2008. For these two rings, there was a strong request from the Operation team for a realignment of the main components, quadrupoles and dipoles, especially because a new linac, the LINAC4, will be connected to the injector complex in 2018 and the increase of energy will require a more accurate alignment of the components.

The Super Proton Synchrotron

The quadrupoles magnets of this 6.9 km circumference accelerator are measured in the vertical direction every year.

The last vertical measurements realised in 2011 showed that the tunnel ground movements, located at the two

crossing points with the LHC tunnel (40 m lower), have generated such a significant misalignment that it requires a realignment of the areas (Figure **2**)[2]. In the horizontal direction, the last measurements were done in 2005. On top of that, the Operation team has problems to run properly the machine.

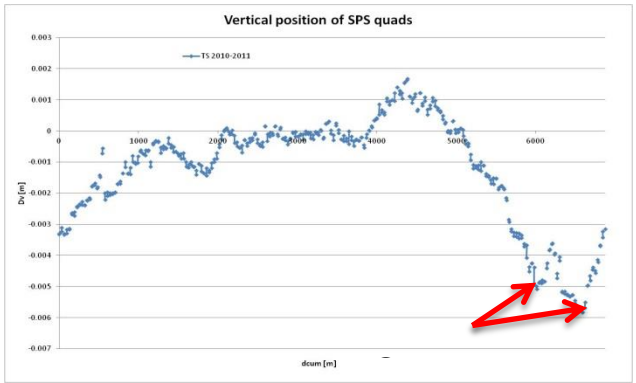


Figure 2 : vertical deviation of SPS quadrupoles magnets

The TI2 and TI8 transfer lines

These two transfer lines, linking the SPS to the LHC, were built in the beginning of the 2000's and are still considered as "new and unstable" from the civil engineering point of view. As a matter of fact the TI8 was re-measured in the winter shut-down 2011-2012 and 80% of the quadrupoles magnets requested a realignment in the vertical direction and roll angle. The TI2 which was known to be more stable was measured during the same shut-down, only 20% of magnets were realigned in the vertical direction, but the beginning of the line is linked to the SPS at the location where an important realignment has to be realised. Therefore this portion of the line has to be realigned accordingly. Figure **3** shows the vertical TI2 profile.

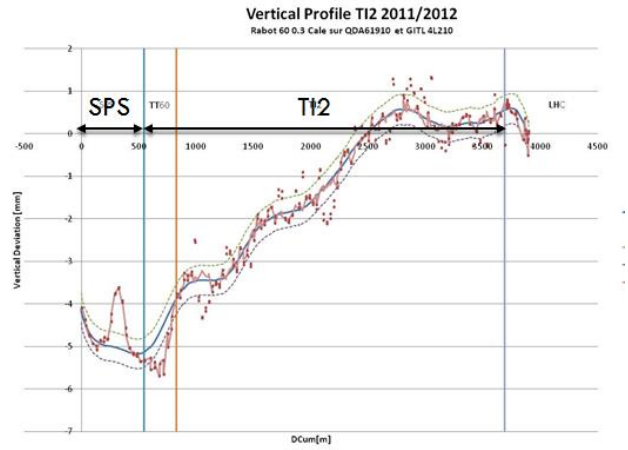


Figure 3 : vertical deviation of TI2 quadrupoles magnets

The Large Hadron Collider

The LHC main magnets were measured in the vertical direction during the shut-down 2008-2009. In the horizontal direction the last measurements were realised during the smoothing campaign which took place between beginning 2007 and middle 2008. The only exceptions are:

- The sector 78, in which an unstable area has been observed since two decades. Measurements in the horizontal direction have been made during the winter shut-down 2011-2012.
- The sector 34, where an accident took place in September 2008 and a big number of magnets were exchanged. A horizontal measurement was done in 2009.

Table 1 : horizontal deviation w.r.t a smooth curve at 1σ for each LHC sector

	Horizontal (mm)		**Vertical (mm)**	
Sec.	After 1st smoothing (2007-2008)	Before 2nd smoothing (2009)	After 1st smoothing (2007)	Before 2nd smoothing (2009)
12	0.11		0.10	0.16
23	0.11		0.12	0.16
34	0.11	0.23	0.11	0.17
45	0.19		0.11	0.13
56	0.20		0.10	0.13
67	0.20		0.10	0.14
78	0.11	0.21	0.11	0.15
81	0.10		0.11	0.14

The analysis of these (few) measurements is shown in Table **1**. It shows that in the horizontal direction, the deviation to the smooth curve at 1 σ goes from 0.11 mm to 0.23 mm and 0.21mm (for sector 34 and 78) over a year time. In the vertical direction, the degradation goes (in average for all sectors) from 0.11 mm to 0.15 mm over the same period of time. It means that, in the case of the horizontal direction, if no realignment is done during the LS1, in 2018, after a period of 10 years, the deviations to the smooth curve will be 0.35 mm at 1 σ ($0.11mm \times \sqrt{10}$). Therefore there is a probability of 1% to have a magnet whose deviation to the smooth curve is bigger than 1 mm, for the whole LHC it is equivalent to 20 magnets. This justifies a measurement and a realignment campaign for these magnets.

The experimental detectors

The geodetic network of the four experimental caverns housing the main LHC detectors was re-measured during the last big shut-down of 2008-2009 and partially updated during each Technical Stop, showing important movements due to the fact that the caverns housing ATLAS and CMS are relatively new civil engineering structures. The geometrical link between these networks and the accelerator components, including the low β quadrupoles, was also done at the same period.

SURVEY ACTIVITIES PLANNED FOR THE LS1

The survey activities to be accomplished during LS1 can be divided into three main categories:

- the maintenance and preventive survey whose goal is to anticipate any degradation of the alignment in order to ensure a good alignment during the next run of the machine. The next access to the machine will be in 2018 for LS2. This activity is mainly triggered by the Survey team or the Operation one.
- the alignment of new installed accelerator or detector components and the monitoring of the opening and closure of the LHC experiments. This activity is realised upon request of the equipment owners and frequently with a very short notice
- the maintenance of the monitoring systems

Maintenance Survey

Taking into account the date of the last measurements, the "known stability" of the areas and the requests of the Operation team, the following activities were scheduled:

- the full survey and realignment of the PS main magnets
- the full survey and alignment of the PSB quadrupoles and dipoles
- the full survey and alignment of the SPS quadrupoles, dipoles and pick-ups including the realignment of the "hole"
- the full survey and alignment of the quadrupoles of the TI2 transfer line
- the full survey and alignment of all the components of TI8
- a "fast levelling" of the LHC in order to re-determine an absolute altimetric network over the whole LHC machine
- the full survey and alignment of all the LHC components
- the determination of the geodetic network of the four LHC caverns

Alignment and Monitoring

The LS1 was also the opportunity for many equipment owners to install new components or to replace damaged ones. In this case, an alignment or a re-alignment will be requested. The main operation where alignment operation are foreseen are the followings :

- the exchange of 18 cryo-magnets in the LHC and two half-cells of dipoles and quadrupoles in the SPS
- the installation of 20 new LHC collimators and an important number of Beam Position Monitors (BPM)
- the reinstallation of 12 Roman Pots
- the installation of new pick-ups on the PSB injection line
- insertion of new experimental detectors
- opening and closure of the experimental detectors

Maintenance of Monitoring Systems

LS1 is widely considered to be the "last chance" to carry out extensive work in the vicinity of the low beta magnets, before radiation levels will rise to a level where only short interventions will be allowed. The twelve different worksites (8 triplets and 4 experiments) were revised for the following aspects:

- validation of the monitoring systems for data consistency after the run and validation before the restart.
- design, integration, mechanical on site modification, validation and installation of remote qualification systems, such as an automated filling / purging station for the hydrostatic levelling system, a wire displacer system for the control of the stretched wire reference and a wire break sensor.
- installation of load sensors in the jacks of the triplets in order to have an additional control parameter during remote positioning [3].
- In addition, longitudinal displacements of the cryostats have been carried out on one triplet in order bring an inclined jack back into operational position. A temporary longitudinal monitoring system has been developed for this purpose.

MANPOWER

The alignment strategy consists in splitting the work between the Survey manpower contractor and CERN member staff. The contractor will be attributed the activities that are repetitive and can be described precisely inside procedures, the contractor being fully responsible of the quality of the work. They concerned mainly accelerator components. The CERN staff members are in charge of the coordination, the supervision of all the activities and the alignment of non-standard equipment. For the experiments, the situation is a bit different as in some cases there is a possibility of getting staff to participate to alignment works as a contribution of the external collaboration toward CERN. In this case, these persons are directly integrated into teams with CERN staff members.

Table 2 : missing manpower for LS1

Areas	Time needed (man/months)	Period (months)	Man
PS and PSB	26	11	2.3
SPS and TLs	53	15	3.5
LHC	99	21	4.7
Experiments	210	21	10

total	**20.5**

An estimate of the manpower necessary to realise all these activities, taking into account the time needed, the planning and co-activities constraints, was elaborated. The activities were decomposed into four main areas and Table **2** shows for each of them the manpower needed but not available at CERN.

To fulfil these needs, a maximum of 13 persons were requested to the contractor, four persons were made available by the experimental collaborations and two projects associates from a polish university joined the team. Moreover, two mechanical technicians were available to give a hand for some specific measurements of detectors and the maintenance of the monitoring systems.

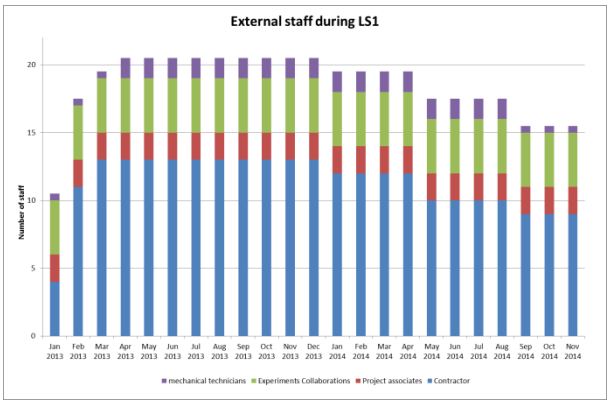


Figure 4 : repartition of external staff

Figure 4 shows the repartition of the external staff during the LS1.

The main problem is that at the beginning of the LS1, most of the external staff has never worked at CERN before and is not familiar with the specific metrological techniques and instruments used at CERN to achieve the accuracy requested by the beam particles, 0.1 mm at 1 σ between consecutive magnets. CERN staff members have trained the CERN permanently based team of the contractor (3 persons) during several years, the contractor being responsible to train the new comers at their arrival at CERN.

PLANNING

For technical constraints, it was rapidly clear that the year 2013 will be dedicated to the PS, PSR, and SPS measurements campaign as well as the warm Long Straight Sections of the LHC while the year 2014 will be devoted to the measurements of the magnets in the LHC arcs after their cool-down.

The main difficulty was that, even the main initial goal of LS1 was the LHC magnets splice repair, every equipment owner wanted to realise as much work as possible not only in the LHC but also in the injector complex, the consequence being that the amount of work became tremendous while the length of the LS1 was not extended. It appeared then that, in some cases, the co-activities were very difficult to manage. At a certain time, especially in the LHC, the changes of the planning were almost taking place every day, a staff of the survey team being obliged to update the activity of the field teams almost every day.

On top of that, the survey main activity for the LHC, which is the smoothing of the cryo-magnets under cold temperature, has to take place at an imposed period and during a very short duration for the above mentioned reasons.

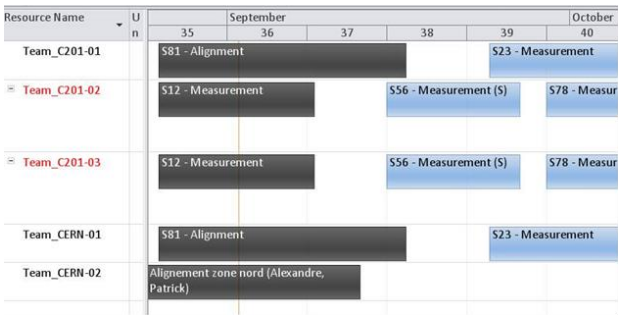


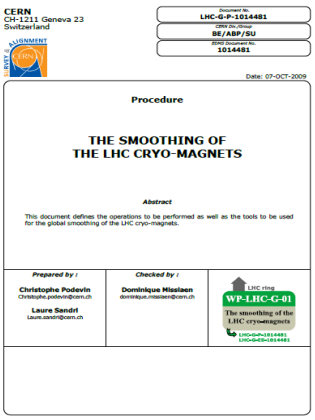
Figure 5 : planning of the LHC smoothing

As an example, several sectors of the LHC had to be measured at the same time (Figure 5) in vertical and horizontal direction, imposing an important number of experienced contractor staff and the availability of additional calibrated instruments.

On the Experiment side, due to the complexity of the installation of the detectors, the requests for alignment interventions can arrive late and the changes in the planning were frequent and the repartition of the activity between the field teams was updated almost every day.

QUALITY CONTROL

The work realised by the contractor was fully described in procedures through engineering specifications and technical procedures as shown on Figure **6**. These documents indicates the work to be done, the way to realise it in order to achieve the required accuracy, the instruments and the software to be used as well as the conditions (temperature of the magnets, environmental, co-activities, etc) encountered during the activity.



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Document No.
LHC-G-P-1014481
Date (Rev. Group)
BE/ABP/SU
EDMS Document No.
1014481

Date: 07-OCT-2009

Procedure

THE SMOOTHING OF THE LHC CRYO-MAGNETS

Abstract

This document defines the operations to be performed as well as the tools to be used for the global smoothing of the LHC cryo-magnets.

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Figure 6 : procedure description

The documents were written prior to the attribution of the contract to the contractor so that the works can be carefully estimated and paid on a lump sum basis.

The contractor, once the measurements are realised, has the responsibility to insert them into the survey database (GEODE) and to realise an initial post-processing of the data, with a minimum of constraints, in order to check the quality of the measurements. The CERN staff members are responsible for the final post-processing including the adaptation on well-known points and the insertion of the final results in the database. They decide also on the components that have to be realigned.

Meetings between CERN and the contractor took place every week to review the work done, the planning for the future activities, safety aspects, instruments problems, staff availability. If the procedures cannot be respected or the measurements conditions are different than what was specified in the procedure, it is notified through a non-conformity which can have a financial impact.

RESULTS

The LS1 started in March 2013 and most of the measurements and realignments have been realised with the main results as follows:

The PS and the PSB

The PSR was measured in the vertical plane showing almost the same shape as in 2005 but in the horizontal direction, surprisingly, it shows that its radius is smaller by 4mm w.r.t its nominal shape and w.r.t the previous measurement.

Following the initial measurement and a careful analysis by the Beam Physics team, the PSB has been strongly realigned, twenty magnets in the vertical direction and roll angle, twenty also in the horizontal plane, some of the quadrupoles being put at their nominal position, the dipoles on a smooth curve, the offset generated was not considered to be critical as the aperture is big in these magnets. A total of 40 magnets were consequently realigned in two iterations.

The TT10 line, which links the PS to the SPS was also completely surveyed and all the magnets located in the area where civil engineering works took place to reinforce the tunnel vault were realigned.

The SPS and the transfer lines

The SPS was completely measured and realigned in the vertical and horizontal plane, including the “hole” as shown on Figure **7**. The first 500 m of the TI2 transfer line, at the junction with the SPS, were completely realigned but for the rest of the line, only the quadrupoles were realigned, 27% in the vertical plane and 30% in the horizontal one. All the components of the TI8 were measured, 38% of the quads were realigned in the vertical and 35% in the horizontal, which is a little bit less than what was expected.

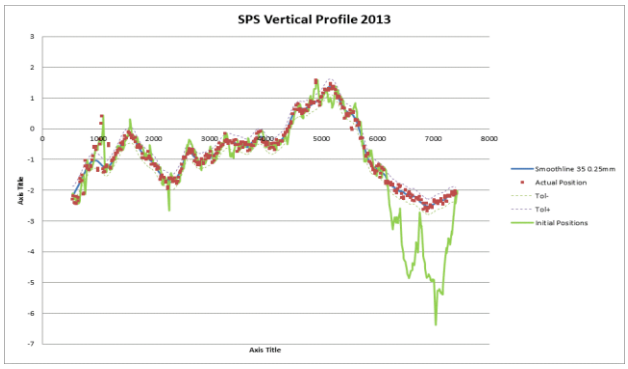


Figure 7 : the SPS vertical profile after realignment

The LHC

The fast levelling was done on every two magnets at the beginning of the LS1, the closure over the 27 km was just below 5mm. A new vertical position of the deep references was then determined and the shape of the LHC machine after a run of three and a half years and before huge repair works was obtained as shown on

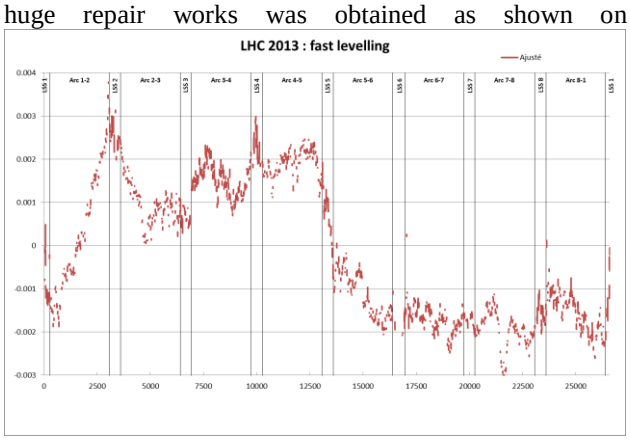


Figure **8**.

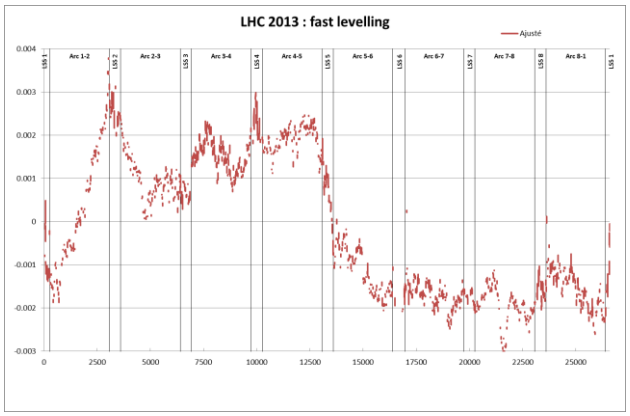


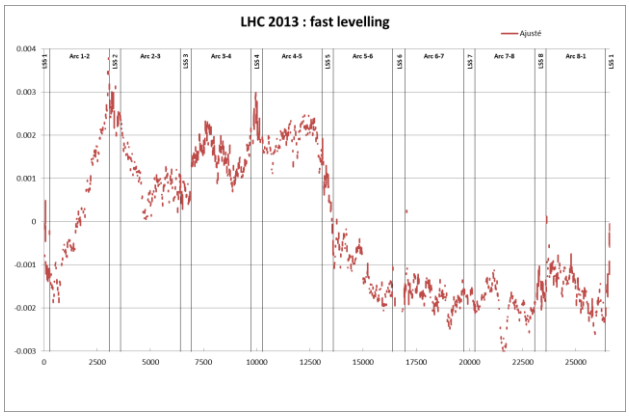
Figure 8 : the LHC vertical profile

All the magnets in the Long Straight Sections of the LHC have been measured and realigned in horizontal and vertical. The smoothing process of the magnets in the arcs has started during summer 2014, two sectors have already been measured and completely realigned while two others have been measured only.

The LHC Experiments

The geodetic networks have been fully re-measured in all the LHC experimental areas improving the geometrical link with the LHC machine. These updates, needed to allow the survey of the detectors and the precise adjustment of the experiment upgrades, have been performed through a coordinated common effort between experiment and machine survey teams. It led to the enhancement of the procedures assuring the coherence between the nominal beam line define by the Low β quadrupoles surrounding the experimental areas and the coordinate frames of the experiments. The survey team has been involved in a large number of tasks related to the opening, the maintenance, the upgrades and the closure of the detectors. Among them:

- the extraction of the beam pipes of the four experiments;
- their re-installation in ALICE and in CMS;
- their replacement by new ones in ATLAS and in LHCb;
- the addition of new detectors modules in ALICE;
- the important upgrade of the ATLAS central part, see



- **Figure 8,** comprising the insertion of the new IBL central detector;
- the construction and positioning off the new YE4 endcap disks of CMS;
- the LHCb dipole magnet consolidation

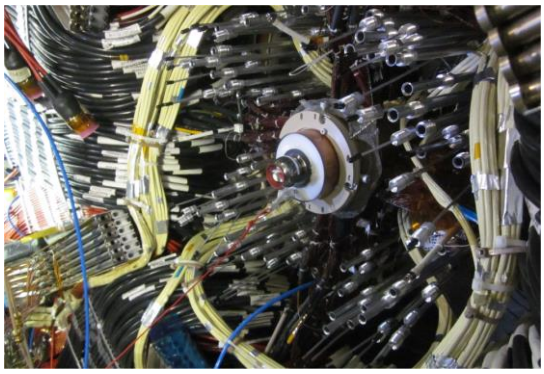


Figure 9 : the ATLAS central detector upgrade

The survey team was also deeply involved in the development of two alignment and monitoring systems based on BCAM cameras [4]. In ATLAS, the ADEPO (Atlas DEtector POsitioning) system will be used to accelerate the closure process allowing the repositioning of more than 1000 tons heavy pieces with a precision of some tenth of mm. It is now installed and the commissioning is going on. In LHCb, a monitoring system of the Inner Trackers has been developed to follow their closure and to survey their movements during the run. This project is in the installation phase.

The Non-LHC Experiments

The survey work for Non-LHC Experiments was mainly done in the SPS North Area for NA62 and COMPASS experiments. The NA62 installation has been completed. All the detectors and experimental equipment have been assembled and are now aligned. The experiment is ready to start the data acquisition.

The upstream part of the COMPASS experiment has been reshuffled. The Drell-Yan configuration is now in place. The check of the positions of the detectors is going on.

CONCLUSIONS

The LS1 was very ambitious from the point of view of survey activities. Most of the machines of the injector's complex were measured and realigned, as the last of survey of some of these machines were quite old and "unstable areas" requested an important realignment, as it was the case for the SPS. The LHC will be completely measured and re-aligned, the work for the Long Straight Sections is already finished while the smoothing of the Arcs is still on-going. All the data gathered during this busy period will be carefully analysed later, allowing the identification of "unstable areas" where the survey team will particularly focus its maintenance activity on these areas in the future.

Many components from accelerators and experiments were exchanged or installed, requiring either a monitoring or an alignment which was always done even in a tight planning.

The main challenge of the survey team during LS1 was the realisation of a huge amount of work during a rather short period of time with very tight schedule and with a lot of inexperienced staff, from CERN or the contractor, which had never work at CERN before and not knowing the specific techniques and instruments used at CERN.

The LHC, the complex of injectors and the experimental detectors have been successfully realigned and will be very soon ready to operate at an energy of 14 TeV, centre of mass, allowing an accumulation of luminosity. More accurate parameters of the Higgs's boson might be determined.

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