Status report on the Survey and Alignment of the accelerators at CERN

M. Jones, H. Mainaud Durand, D. Missiaen, J.-P. Quesnel
CERN, 1211, Geneva 23, Switzerland

This paper describes the major survey and alignment activities of the accelerators at CERN since 2004. During the last two years, the existing machines have been heavily consolidated, the beam line for sending neutrinos to Gran Sasso has been built, and the LHC project has seen a lot of progress. The paper will review the situation of the PS and SPS accelerators, as well as the status of the CNGS and LHC projects. Finally, it will give an overview of the experience gained from the LHC project for future large projects.

1. INTRODUCTION

CERN is the European Organization for Nuclear Research. It is located at Geneva, across the border between Switzerland and France.

During the last two years, CERN has intensively prepared its accelerators for the future commissioning and runs of the LHC. At the same time, it has built the beam line to send Neutrinos to Italy, in the frame of the CNGS. The LHC project has also seen a lot of progress, and special milestones have been reached.

This paper will review the mains aspects of the consolidation of the existing machines from the alignment point of view, describe briefly the key points of the CNGS project for surveyors, and review the progress of the LHC project as well as the experience gained by the Survey group from such a large project.

2. THE EXISTING MACHINES, THEIR CONSOLIDATION, AND ASSOCIATED MACHINES

The Proton Synchrotron and the Super proton Synchrotron machines, built in the sixties and seventies respectively, are part of the injector of the LHC. They have been stopped for a one year long maintenance shutdown. This time has been devoted to a global realignment of the two machines.

2.1. PS

A quarter of the PS magnets have been removed and reinstalled, and a global survey of the ring has been performed with all the magnets replaced at their theoretical position. The metrology of this machine is still based on a quasi regular octagonal network which guaranties the shape of the ring, with additional smoothing measurements. At the start-up of the machine, a beam based alignment has been made by the physicists by running MICADO with the input of the orbit measurements and taking into account the real position of the Beam Position Monitors (BPM). It was decided to displace 3 magnets horizontally and 3 magnets vertically by up to 1 mm (10 were displaced in each direction prior to the re-alignment) and a perfect correlation was found between the magnets moved, the expected improvement of the orbit and the final orbit. The results are shown in Table I.

	Min peak H [mm]	Max peak H [mm]	Min peak V [mm]	Max peak V [mm]	P to P H [mm]	P to P V [mm]	rms H [mm]	rms V [mm]
26/04/06	-7.2	6.2	-2.6	2.6	13.4	5.2	3.5	1.1
PU number	45	5	23	60				
Expected	-3.3	3.3	-1.6	1.3	6.6	2.9	1.7	0.7
PU number	87	10	23	95				
27/04/06	-3.3	3.0	-1.7	1.5	6.3	3.2	1.7	0.8
PU number	45	10	23	95				
Error 27 vs. Exp. [%]	0.7	9.7	6.1	15.6	4.5	10.4	0.9	5.5

2.2. SPS

During the last four years, a continued degradation of the vertical alignment was detected. This was found to be due to a degradation of the polyurethane inserts of the jacks which had already been changed for the first time in 2000. The quality of the new inserts was not good and the polyurethane was not incompressible as required. Studies showed that due to safety rules, the chemical components had changed, inducing changes in the mechanical characteristics of the material [1]. As a results all the jacks of the 216 quadrupoles of the SPS have been changed and as the quadrupoles are themselves the geometrical reference of this 6.6km long ring, the technique of “1 in 2” has been applied in order not to loose the geometry of the machine. The quadrupoles were then smoothed along the whole ring as usual, using stretched wires for the radial position and direct leveling for the vertical. As for the PS machine, the beam base alignment procedure has been applied in order to correct the effects of the errors in the fiducialisation, alignment and/or magnetic fields. This procedure reduced the orbit distortions to +/- 1.2mm in the V and +/- 1.8mm in the H planes after having moved 9 and 6 elements in the vertical and horizontal planes respectively.

2.3. LEIR

In the framework of the PS complex during the same period, the new LEIR machine has been built. This small machine will be used as part of the injection chain of the ions into the LHC. It is the result of a transformation of the LEAR machine used few years ago for the cooling of the pbars. The four large composite dipole magnets at each corner of the ring remained in place, with the straight sections reconfigured and a new injection/extraction line installed to bring the ions from the Linac3 and to send them on to the PS. The metrology of the ring is based on a square of 4 pillars installed in the center of the ring and traditional methods were used to align and smooth the elements. The beam circulated at the first attempt.

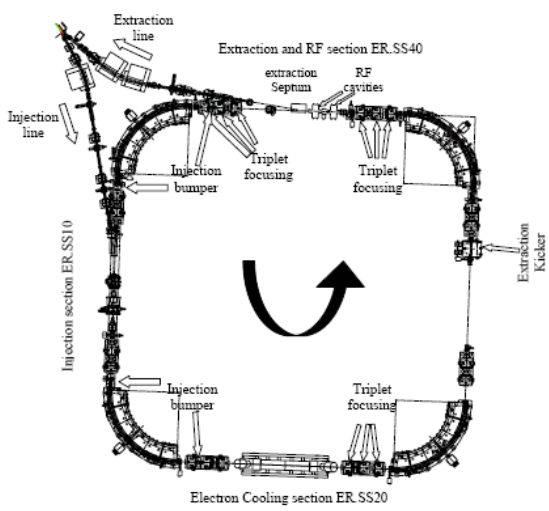

Figure 1: The LEIR layout

2.4. CTF3

Another small complex, the CTF3, is under construction for studying the feasibility of CLIC. This facility is composed of a small Linac, a delay loop, a combiner ring, associated transfer lines, and an experimental zone (CLEX) for testing the efficiency of the RF cavities for this project. This set of beam lines is housed in the last Linac and Electron and Proton Accumulator building used for LEP. The metrology of these machines is performed with the total station TDA5005, the direct leveling, and additional specific measurements with the laser tracker. The Combiner Ring is currently being installed and aligned, and the CLEX is due to be installed in the second half of 2007. It is envisaged to install in CLEX the system of real time "pre"-alignment requested for CLIC, with an accuracy of a few microns, using HLS, WPS and Rasnik systems, as was done previously on the first CLIC mock up [2].

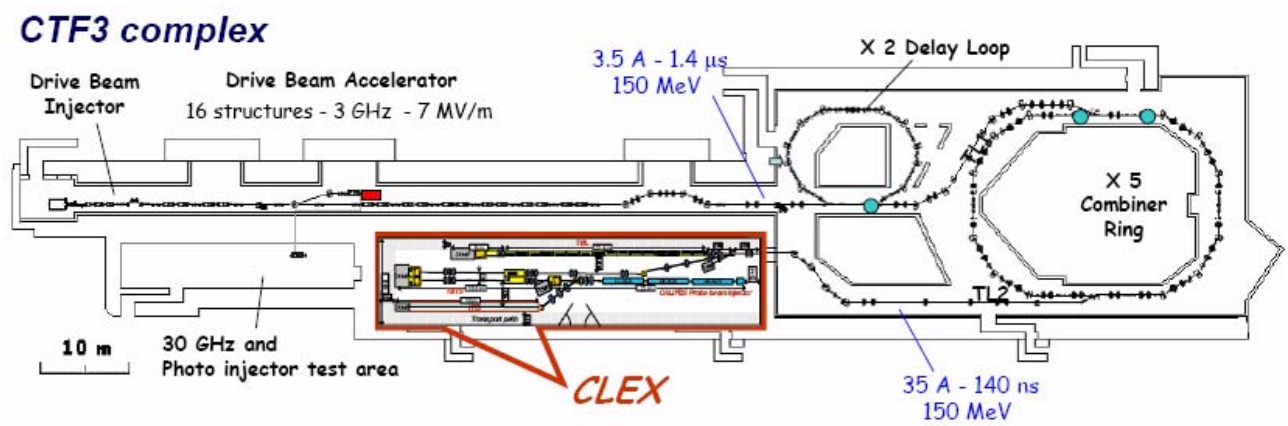

Figure 2: The CTF3 layout

3. CNGS

3.1. General description

The CERN Neutrino To Gran Sasso is a line composed of 400 magnets along 800m, installed with a slope of 5.66%. After having reached the target and the horn, the SPS extracted beam is composed of ions and kaons which then decay to give muons neutrinos which continue their way through the earth up to the Gran Sasso Lab in Italy, 730 km away from CERN, where a huge detector will study the oscillation of the neutrinos.

Layout of the tunnels

3.2. Geodetic considerations

As it was to be installed at CERN, the CNGS line had to be calculated in the CERN Co-ordinate System using the MAD-X software. The starting point is well known since it is the same as that of the TI8 (see chapter 4.1). The azimuth and slope angles, two other input parameters mandatory for MAD-X, were more difficult to obtain since the target for the particle beam is not located at CERN but in Italy, 120 kms away from Rome and 730 km from the origin. The idea was therefore to determine the position of the Gran Sasso detector point in the CERN system. This was done using GPS measurements taken in Italy and then several transformations were to be applied to derive the co-ordinates in the CERN Co-ordinate System.

On the CERN side, a new geoid was also defined in order to ensure an accurate alignment w.r.t local gravity (XYH system) whilst the theoretical definition was made in a Cartesian (XYZ) co-ordinate system. This was done with the help of the"Office Federal de Topographie" in Bern, Switzerland.

3.3. Alignment

3.3.1. Geodetic network

A geodetic network similar to the one installed for the LHC injection lines (see chapter 4.1) has been used. It has been determined using the same instrumentation and techniques.

3.3.2. Main components

The magnets have been aligned in this new tunnel from the network using total station measurements for the horizontal plane and optical levelling for the vertical, and then smoothed in the horizontal plane with wire offset measurements.

3.3.3. The target

The target station is composed of a "gun barrel" containing 5 target units. Each target unit is made of a Carbon-Carbon tube containing target rods and surrounded by an Aluminium tube. Each step of the assembly of the target units has been checked using a laser tracker. The final fiducialisation of the "gun barrel" was also made using the same technology.

As the target station is installed in the tunnel completely buried in a protective shielding, it is barely accessible by standard alignment techniques. Its alignment has therefore been realised using 3 alignment bars equipped with fiducials, the target station fiducials being determined as "hidden points". The target was also aligned with respect to the geodetic network

The line has been tested in summer 2006. The extraction process having already been tested for the TI8 line, the particle beam was detected well centered by the BPMs located upstream to the target without any correctors activated. (see figure 3). Moreover, a good muon profile was visible at the level of the 1st and 2nd muon detectors which are installed at the end of the 1 km long decay tube (figure 4). The installation is now ready and has already delivered its first neutrinos to the huge detector in the NGS Laboratory.

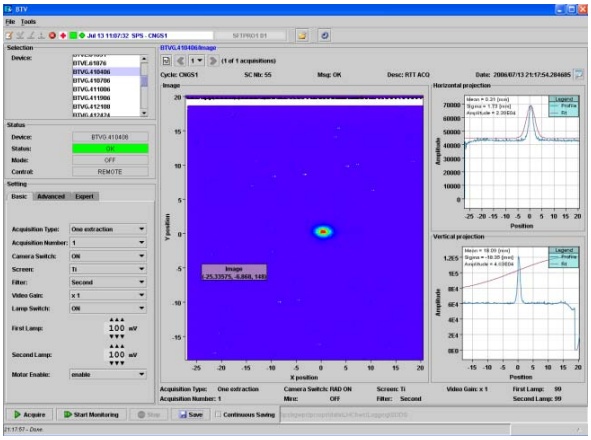

Figure 3: First beam

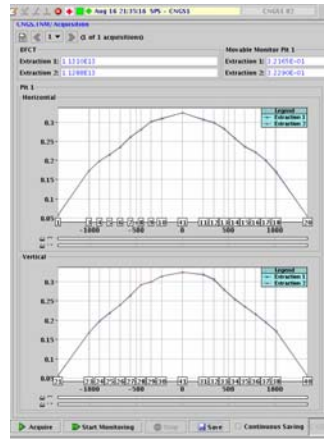

Figure 4: muon beam profile

4. LHC

4.1. The injection lines

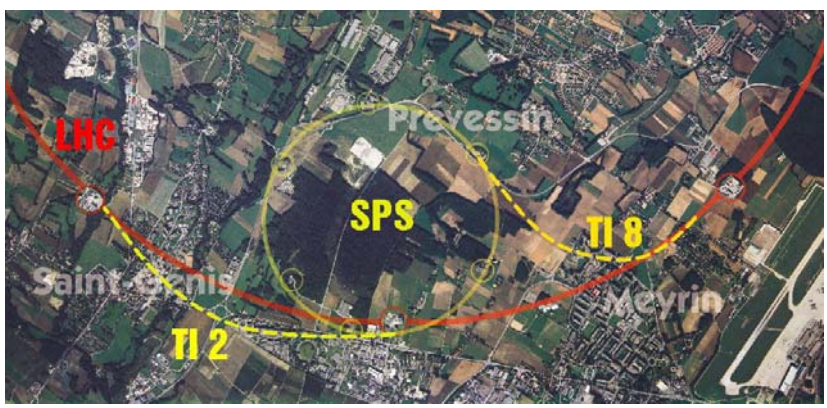

Figure 5: the injection system

The first injection line TI8 consists of about 400 magnets aligned on a 2km long circular arc with a 3.5% slope. It is housed in a 3m diameter section tunnel, which does not give much room for all the equipment and the passage.

The theoretical geometry has been designed in the CERN coordinates system by the new MAD-X software. This software allows the possibility of tilting transversally the magnets of transfer lines in order to be able to inject a beam in the LHC machine with the correct inclination of the ellipse w.r.t. the plane of the LHC.

A forced centering network has been installed in the floor of the tunnel, measured with classical techniques: TDA5005 total stations for angles and distances, digital leveling, with the addition of gyroscopic orientations every 120m, distances measured with the Mekometer and wire offset measurements all along the traverse. The magnets have been aligned in this new tunnel from the network using the total stations for the horizontal plane and optical leveling for the vertical, and then smoothed in the horizontal plane with wire offset measurements.

The line was tested in autumn 2004. After having tested independently the extraction process and calibrated accurately the energy of the beam in the SPS, the physicists sent the beam into the line. At the first shot the beam reached the target without any corrector activated. (See picture)

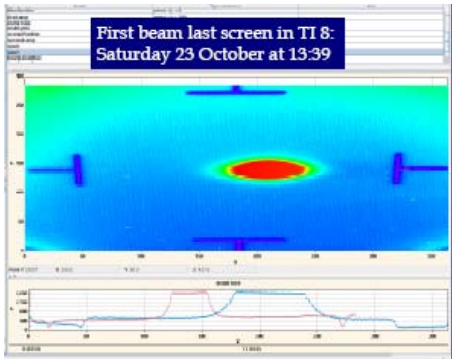

Figure 6: first beam in TI8

In the TI2 tunnel, which is the second injection line, the geodetic reference network is established and periodically maintained. Half of the line as well as the connection with the SPS machine is already installed and aligned. The last half will be installed after the end of the transport of the cryodipoles of the machine, as the transport is made through this small tunnel. The transport would be possible but more difficult with the beam line installed.

4.2. Cryogenic line

The super fluid helium used for cooling down the cryomagnets is distributed by an independent line which runs all around the LHC tunnel. The implantation of this line is globally not critical as long as enough room is left for the installation of the magnets, except for about 200 services modules which link the line to the magnet cryostat with a jumper connection and for specific regions where the two lines are very close. A lot of delay in the installation of this line had been generated by not having considered seriously enough the positioning aspects. The Survey Group was asked to find a solution to help the contractor to install the line. The solution consisted first to define the theoretical position of all the elements in the XYZ CERN coordinates system, similar to a classical beam line, and second to mark on the floor the position of the elements and measure the height of the floor at that point. At the same time, the Survey group proposed to modify the supports and to develop simple movable adjustment devices to allow the contractor to align the elements correctly with a simple plumb line and tape measure. Fiducials have been welded on the service modules on which significant geometrical non conformities have been found. They have been measured with the laser tracker, and the theoretical position of these elements has been calculated taking into account the real shape of the jumpers. To speed up the installation, CERN decided to install the first sector itself. Classical 3D alignment methods where used in this sector without any marking out phase.

Figure 9: The QRL line with the jumper connection

4.3. Metrology of the magnets

The LHC is composed principally of 1232 dipole magnets, and 474 SSSs containing quadrupole magnets.

The fact that these magnets require a good geometry for physics and beam aperture as well as for the interconnect ability between them has led to the decision to undertake metrological measurements at different steps of the assembly. These measurements are made using the laser tracker technology.

The dipoles, 15 m long curved cylinders, are measured during the assembly of their cold mass in industry and, once they are in their cryostat at CERN their curve is adjusted during the operation of fiducialisation.

The SSSs, a 5 to 11 m long straight object, are fiducialised using mechanical and magnetic measurements. The position of the Beam Positioning Monitor is also measured w.r.t the reference axis

For both types of magnets, the position of all the tubes at the extremities are measured and adjusted to be within the tolerances given by the interconnection specifications. All the measurements are processed by dedicated Visual Basic software and are stored on the Internet and in an Oracle database.

According to the geometry criteria, the Magnet Evaluation Board makes a classification of all the magnets, allocates each magnet to a specific slot along the accelerator and determines the shifts and rotation with respect to a nominal position.

With all the information being available in different databases, an automatic process has been developed which takes into account the theoretical position of a magnet in the CERN Co-ordinate System (CCS), the allocation of a magnet to this position, the fiducialisation parameters and the shifts and then calculates the co-ordinates of the fiducials (in the CCS) to be used during it’s alignment in the tunnel.

4.4. Alignment of the ring

The magnets are installed in the arcs and the long straight sections as described in [3]. All the adjustment jacks are aligned at their theoretical position using a total station TDA5005, and then are sealed in place. This is necessary due to the limited range of the jacks, but the fact that the heads of the jacks are well known in position also helps for installing the cryomagnets with an automatic handling machine. A total station is used to measure the initial position, relative to the final installed position, of the cryomagnet on its carriage in the passage area before unloading it onto the jacks. This allows the calculations of the 3D trajectories of the translation tables during the unloading process.

A first alignment is then performed with a TDA5005 in the horizontal plane and with an optical level in the vertical plane, the total station measurements in the vertical plane having not been found to be accurate enough. The tilt is controlled with a jig equipped with an electronic tiltmeter. At the end of the process, a series of ~110m long wire offset measurements is performed for the smoothing of the magnets and the magnets are adjusted radially if necessary to obtain a relative initial alignment within 0.2mm at 1 sigma prior to their interconnection.

Before the installation of the magnets, the reference network is controlled in radial with wire offset measurements, and with direct digital leveling in vertical. The measurements show clearly that the 600m long part of the tunnel between the points 7 and 8 is still moving down with a speed of ~2mm per year, and confirm what was already known from LEP. In this area the jacks have been displaced in order to anticipate this floor motion.

The regulation of the ventilation in the tunnels is one of the main problems for obtaining good measurements. This is why a 100 m tube will be used for protecting the wire from the wind. The 500mm diameter tube will be suspended from the monorail which is installed all around the ring. The completed system is assembled from 6m long accordion sections of soft plastic ventilation ducts. Presently, the system is only used in the Long Straight Sections (LSS).

Figure 10 and 11: wire offset measurement system

Presently all the magnets are aligned in 2 sectors, and globally 40% of the ring is aligned.

4.5. Low beta magnets around the LHC-b and ATLAS experiments.

The long straight sections are under installation. In particular, the injection from the TI8 line is being connected to the machine. Also, the low beta sections have been installed around the LHC-b experiment at point 8. A process similar to that of the arcs is applied to the LSS and the low beta quadrupoles but due to environmental constraints, the smoothing of these special magnets is performed with the laser tracker. The first HLS and WPS equipment used for monitoring the position of the low beta quadrupoles are under installation at the point 8. All the sensors are tested, the specific supports have been calibrated in our calibration base, and specific studies on the effects of radiation on the measurements of these sensors have been performed [4].

Around ATLAS, a specific network installed in dedicated galleries links the 2 triplets of quadrupoles. [5] Two HLS networks have been installed in these galleries as well as on the bedplates of the ATLAS detector. A carbon peek wire is stretched through the 2 galleries and the ATLAS experimental cavern, parallel to the beam line. Another wire is stretched along each triplet and connected to each quadrupole. The invar rods which allow the link between the main wire and the 2 others have been built, calibrated, and installed in their shafts. The readings of these HLS and WPS networks have been disturbed by the earthquake at the origin of the Tsunami in Indonesia at Christmas 2004 [6]. Asimilar installation in under way at point 5, around the CMS detector. The data acquisition system is ready to be tested at point 8, in conjunction with the Control group of the machine.

In parallel, the actuators for the low beta quadrupoles adjustment jacks have been developed in collaboration with the RRCAT laboratory in India. [7]. Three prototypes based on the SPS polyurethane jacks technique have been tested successfully at CERN and the series has been delivered. They allow a displacement of the heavy, more than 10T, cryomagnets within an accuracy of few microns. We are now waiting for the motors and their drivers.

4.6. As-built measurements

A large and complex accelerator like LHC machine needs to integrate several thousand different components in a limited amount of space. During the installation, those components are installed in successive phases, always with the goal to leave the necessary space available for the equipment which will follow. To help ensure the correct conditions for the installation, the Survey Group have been using a laser scanner to provide as-built measurements of specific areas.

In response to increasing demand for measurements of this type, the group purchased a Leica HDS3000 in 2004 and have now undertaken a large number of independent scans, lasting from less than one day to more that a week. These represent more than 8 km of tunnel with a point approximately every 20 mm both horizontally and vertically. The kit purchased with the scanner has been adapted to the CERN survey standards, and scripts written to reduce scan times in the tunnel whilst maintaining a homogeneous density of points along the tunnel surfaces [8].

The work has mainly concentrated on the long straight sections LSS of the LHC, where the equipment is specific to each section and is often densely packed. The data has successfully been used for quality control of installations and enabled problematic installations to be changed before the contractor moved off site. Some areas have now been scanned 3 or 4 times following successive installations of equipment.

Typically the scans for a given zone are carried out in the tunnel, and once back in the office they are merged together and geo-referenced in the CERN Coordinate System. The final database might vary in size between 30 and 700 MB , and due to limits in CATIA the point cloud is broken down into short segments and each segment is exported as a text file of less than 35 MB. These text files are imported into CATIA and a surface mesh fitted over the point cloud. This mesh is stored as a new object and subsequently compared to the 3D design model [9]. At this stage the original data in Cyclone is often consulted since the colour coding provides a clearer view of the scene.

The integration team are charged to provide documentation of the LHC installations, and with the proven success of the as-built information provided by the Laser Scanner received the support to make a more systematic as-built record of the LSS, together with the tunnels and caverns around the access shafts. Our own role in this increased too, is to include the initial work in CATIA in order to hand over the point cloud mesh objects to the integration team and not just the point clouds as before. To be able to carry out this additional work, several staff and a team from our sub-contractor have been trained in the use of scanner and the necessary aspects of CATIA. A team now works nearly full time on these projects.

5. WHAT WE HAVE LEARNT FROM LHC

5.1. Technical aspects

5.1.1. Needs for metrology for the elements

Due to the complexity of the elements to be built, their size, and the high accuracy requested, the Survey group has been involved in the construction of the cryomagnets more than ever before. The very limited aperture for the beams, as well as the limited flexibility of the interconnections from magnet to magnet generated very strict constraints on the position and shape of the beam pipes in the cryomagnets. Since the beginning, the Survey group was convinced that traditional methods would not be applicable for such magnets. Against (at the beginning) the opinion of the groups in charge of the production of the magnets, we tried to define a procedure for measuring the shape of the magnets (curvature, cartography of the ends). To obtain the best shape of the magnets, the methodology should be applicable in industry during the construction, and not only at a late quality control stage at CERN, where finding errors is too late. The laser tracker technique has been retained against other classical optical tooling methods. The laser tracker, when correctly used, allows redundancy in the measurements, the files can be recalculated at CERN, and this allows the possibility of controls at any moment. This strategy revealed itself to be very efficient. In addition to the accuracy which could be reached, it has brought a real confidence in the measurements and the possibility to prove that the work was done correctly or not, at each step. Several movements of the cold masses inside their cryostat have been detected with a high degree of confidence even though these movements were declared impossible.

A new problem rose with these kinds of instruments. The tendency of the manufacturer to promote their instruments by arguing that they were easy to use by “anybody”, made it very difficult to convince the people responsible for the magnets to have a good level of redundancy in their procedures. This was judged to be time consuming and too expensive. Finally they accepted our procedures for a correct use of the instruments for each dedicated application.

5.1.2. Tolerances, accuracy…etc

When speaking about error budget, the vocabulary had to be redefined. By tradition, mechanical people consider the maximum error when assembling mechanical pieces. When a dimension is over, the piece is rejected, if not it is good. For the LHC, the simple addition of the maximum deviations (tolerance) could not be applied when considering the alignment errors table, simply because too many parameters had to be taken into account. It was proposed to consider the standard deviations, defined at 1 sigma, and to combine them quadratically, even if the method is not conservative, to reach acceptable values. With elements coming from everywhere around the world and people using their own vocabulary and customs in this domain, the need for a redefinition of the errors and a clarification of the counting methodology was very strong.

5.1.3. CAD and geodesy

The LHC project covers a surface of ~100 km^2. Typically CAD software has been used on much smaller areas for numerical precision reasons. In addition, the coordinates provided by CAD are referred to a Cartesian coordinate system appropriate for a particular service. For the LHC it was essential to integrate numerous different services together and perform interference checks and other controls in 3D. Fortunately CAD software had evolved and the numerical precision had been increased sufficiently to be able to handle coordinates in the global CERN coordinates system (CCS). An application was developed, integrating transformation modules from the Survey Group's own software, to enable CAD data to be transformed from one local model system to another, by passing through the CCS. This improvement allowed the 3D integration study of all the components in the real tunnel and the experiment caverns, as well as the theoretical calculation of the new long injection tunnel axes.

The clouds of points of the as-built installations determined by laser scanning are geo-referenced in the CCS. Using the same transformation modules, they can now be introduced directly into the CAD application, and compared quickly to the theoretical model. Linking the different CAD models in a given zone by means of the CCS has been a great improvement for the design of the project, as well as for the integration and as-built control of the installations.

5.2. Installation process

Survey people have a very important role to play all along the installation process. They are the first to work in the tunnels to provide the basic reference marks necessary for the first installation of the services. They are the last ones to work in the tunnel for finalizing the alignment of the components. What is new is that in order to organize the work as accurately as possible, all the work has been defined in advance through engineering specifications and procedures. Nevertheless, the installation process is something which is subject to many changes, for a lot of reasons (problems somewhere, changed schedules, delays, additional elements, cabling forgotten…etc). Our activities do not suffer too much from changes such as these because we have based the methods of alignment on a minimum of constraints. For example, usually, some space is kept free all along the ring for survey measurements above the magnets. For the LSSs where many sorts of elements are installed, a method of alignment which uses the space reserved for the transport of the elements –and so kept free- has been preferred to the more conventional ones to avoid any conflict somewhere with larger elements, additional cables or shielding. In addition, this kind of choice allows a maximum of flexibility when applying the stretched wire techniques with offset measurement devices up to 1.5m long. It allows also the up to 130m

long wires to be very simply protected against the wind in these areas thanks to long flexible venting ducts supported by the monorail, increasing significantly the precision of alignment.

5.2.1. Database

The Survey database had been designed 20 years ago. About 400 measurements and 5000 pieces of information are daily inserted into this database. Upgrades have been necessary to adapt its structure to make it compatible with the databases of the other groups. This tool is fundamental for the integrity of the data. Due to the use of data which are located in other databases, a software "spy" has been written in order to detect any late changes which have not been announced to any data which would have been used for the alignment. This software has revealed itself to be very efficient and is an absolute necessity.

5.2.2. Choice of the alignment methods

In order to standardize the alignment of the machine, it has been necessary to be involved in the design of the project since the first studies. We contributed to the design of each element to be aligned, considering the alignment targets, the adjustment supports, and the access to the elements in the tunnel.

5.3. Management

5.3.1. Use of contracts

For aligning the LHC, the Survey group has been asked to use result oriented contracts. This was a major change for the Survey group, and it has been very challenging to find a solution which would preserve the quality of the work and satisfy the commercial rules at the same time. The risk was very big of becoming much more concerned by mercantile considerations rather than technical ones.

The engineering specifications and detailed procedures have been joined for each survey task to the technical specification of the call for tender. As the alignment of the accelerators is a very specific and specialized job, only the repetitive tasks have been defined as result oriented. In addition, all the survey and computing equipment as well as software are provided by CERN. The CERN staff is also responsible for some parts of each task at different stages of the process.

Thanks to the very positive attitude of our contractors, and despite the frequent changes of schedules and conditions for working in the tunnel (limited space, ventilation, unforeseen co-activities …etc), it was possible to preserve the necessary flexibility in our organization.

5.3.2. Collaboration with other labs

The survey group has been involved in two collaborations with other labs. The first one concerns the delivery of the insertion elements by FERMILAB –US-. Even if some definitions of the alignment or construction errors are not completely clear to my point of view, the discussions on this topic where very positive.

A second collaboration has been set up with RRCAT –India- for the supply of the actuators the low beta quadrupoles Q1 to Q3 located around the four LHC experiments [7].

In the two cases, these collaborations gave us an opportunity to work with people working with different methods and traditions, and the results were very positive.

5.3.3. Management tools

For managing the cost estimate, a Working Baseline Structure (WBS) has been created for the project. The Survey is considered as a system in this WBS. The WBS is periodically updated with the evaluation of the work done and the work still pending or delayed. Our WBS is divided into four main parts, related to independent budget codes: the alignment of the machine, including computing and software, the metrological controls of the elements, included their fiducialisation, the alignment of the low beta sections, which require very high precision, and the metrology of the experiments. This tool revealed itself to be very efficient for managing our activities, probably due to a maximum of flexibility left to the users.

6. CONCLUSION

Although all attention at CERN is focused on the LHC project, a lot of work has also been done for all the other machines. Thanks to a standardization of the methods and an efficient data management system it is possible to perform all the work efficiently. The various success obtained at each step of the tests have been very encouraging for us. Due to the LHC project, a certain number of developments/improvements in the domains of the measurement techniques and computing have been temporarily put on hold. Time will be dedicated to developing automatic techniques for measuring the machines and to improve our alignment techniques and software functionality as soon as the activities linked to the project decrease in intensity.

Acknowledgment

The authors thank all their colleagues from the CERN TS-SU group for their contribution to the work done. They thank also their colleagues from the US labs and CAT with whom it was very nice to work. Special thanks go to the contractors for their technical involvement in the very specific alignment works.

References

[1] G.A. Izquierdo, J.P. Bacher, L. Hominal, S.D. Ilie, S. Sgobba, C. Podevin, J.P. Quesnel, “The SPS quadrupole jacks”, Technical note, CERN, EST-SU-ME-2003/02, EDMS 402303.

[2] H. Mainaud Durand, T. Touzé, “The active pre-alignment of the CLIC elements”, IWAA2006, SLAC, September 2006.

[3] J.P. Quesnel, “ A strategy for the alignment of the LHC”, IWAA2004, CERN, October 2004.

[4] H. Mainaud Durand, A. Herty, E. Dimovasili, A. Marin, F. Ossart, T. Wijnands, “Radiation Induced Effects on the HLS Sensors”, IWAA2006, SLAC, September 2006.

[5] W. Coosemans, H. Mainaud, A. Marin, “The alignment of the LHC Low Beta Triplets: Review of instrumentation and methods”, IWAA2002, Spring 8.

[6] F. Gabriels, “Dans quelles mesures les systèmes de positionnement utilisés par le CERN sont-ils sensibles aux séismes” , Mémoire d’ingénieur INSA, CERN, EDMS 549458, June 2006.

[7] J. Dwivedi, J.P. Quesnel, M. Acar, A. Marin, S.G. Goswami, V. Madhumurthy, H. Mainaud Durand, “The Motorized Alignment Jacks for the LHC Low Beta Quadrupoles”, IWAA2006, SLAC, September 2006.

[8] T. Dobers, M. Jones, Y. Muttoni, "Using a Laser Scanner for the Control of Installations at CERN", Optical 3D Measurement Techniques, Vienna, Austria, October 2005.

[9] J.P. Corso, M. Jones, Y. Muttoni, "Control of the geometrical conformity of the LHC Installation with a Single Laser Source", EPAC2006, Edinburgh, UK, June 2006.