# A STRATEGY FOR THE ALIGNMENT OF THE LHC

*Jean-Pierre QUESNEL, CERN*, 1211 Geneva 23, Switzerland*

## 1. INTRODUCTION

The Large Hadron Collider (LHC) is the new accelerator being constructed on the CERN site. It is installed in the 27 km circumference tunnel that previously housed the Large Electron Positron Collider (LEP).

The LHC design is based on super conducting twin-aperture magnets, which operate in a super fluid helium bath at 1.9 K, and in this complex project, all the techniques – magnets, cryogenics, vacuum, installation, alignment…etc- are deeply interdependent. This last point makes essential that survey and positioning aspects are studied in parallel since the beginning of the project, and a good understanding of the construction of the elements and of their use is also fundamental for aligning them correctly. For the installation, no room is left for improvisation, and a precise analysis of all the needs and the methodologies to be applied have to be defined well in advance with respect to the installation constraints and the mechanical design.

The experience gained from the other machines built at CERN or elsewhere has been fully taken into consideration, and two main specific aspects very different from the other machines have been identified. For these points, dedicated studies have been performed. For the other aspects, the "classical" methods can be improved and applied. Improvements have been brought particularly in the quality aspects and the efficiency of the methods. All the survey activities for the LHC project have been defined in work packages, described in detail, and are fully integrated in the project baseline. After a review of the geometrical aspects to be considered, this paper presents the organisation of the works done or to be done.

## 2. THE SPECIFIC ASPECTS

This project presents two main characteristics, from the alignment and positioning point of view, which are different from the usual accelerators: the magnets are cryomagnets, and the focussing elements around the experiments have to be aligned within a very high accuracy.

### 2.1. Preparation of the magnets

The cryomagnets have this particularity that they are housed in a cryostat and so are not physically accessible once the magnets are connected. They are long (17 m for the dipoles), and the cold masses as well as the cryostats are subjects to deformations due to mechanical constraints during transport, cryostating operations, vacuum and thermal effects. In addition, the responsibility of the production of the cryo-magnets and of their preparation prior to their installation is splitted into four groups. Since the beginning of the project, the Survey group has brought its expertise in the techniques of measurement for recommending and defining the methods and equipments to be applied for all metrological measurements at each stage of the construction of the magnets: assembly of the cold masses, assembly of the elements, fiducialisation. It has been and it is still particularly involved in the studies performed on the geometrical stability of these cryo-magnets, and in the evaluation of the error budget for their construction and alignment [1].

The choices of the techniques and methods to be applied which have been made are based on the criterion of accuracy, but also reliability and quality [2]. The methods based on laser tracker techniques used for the assembly are as accurate and safe as they are for quality controls. Besides the very high accuracy, the necessary redundancy of the measurements allows a recalculation of the measurement files at any moment.

The role of the Survey group in the production is now specially centred on the determination of the position of the alignment targets with respect the cold masses.

### 2.2. The alignment of the inner triplets

The method chosen is based on the experience gained from the previous machines at CERN, the ISR, the SPS (p-$p^-$ collider) and the LEP.

In particular, in the LEP, the repeated surveys of the underground reference networks, in a recent and consequently not yet stable tunnel, with no link to the experiments, made difficult to have a good geometrical relationship between the machine and the experiment. It was also impossible to align the low beta sections within the requested accuracy with classical methods, and the subsequent monitoring of the magnets with very accurate hydrostatic levelling systems was very effective in improving the orbit quality.

Preliminary studied performed very early allowed taking a positive decision for the construction of dedicated galleries around the experimental areas of ATLAS and CMS. These studies have been continued to make all the measuring systems compatible with the elements to be aligned in their environment, and now the installation of the measuring equipments – hydrostatic levelling and wire positioning systems (HLS and WPS)- is under way [3] and [4].

## 3. THE POSITIONING OF THE MAGNETS

### 3.1. The theoretical definition of the machine

The two ends of each element of the LHC and the transfer lines as well as the orientation parameters of its axis are defined in the 3D global CERN co-ordinates system. The calculation is performed by running the MAD software. A MAD-X application replaces now the more traditional BEATCH program which was used up to now for the calculation of the transfer lines.

The machine lies in a plane parallel to the plane of LEP. So it is tilted by 1.4% with respect to the horizontal, and the interaction points are deduced from those of the LEP machine by a translation of 300mm perpendicular to this plane.

## 3.2. The alignment process

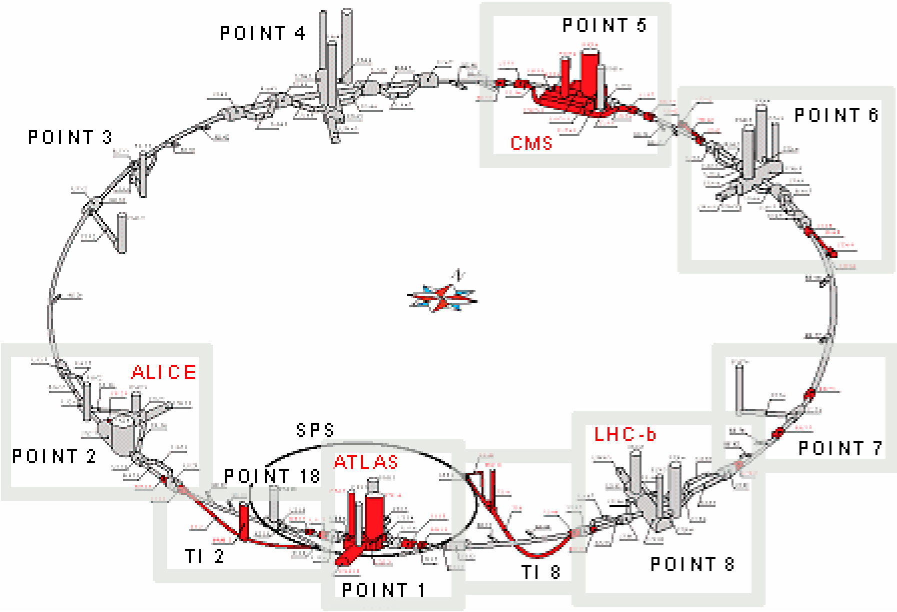


**Figure 1: layout of the LHC**

The geodetic reference network has been established and measured before the dismantling of the LEP machine, in order to take the full benefit of the very good geometry of the LEP quadrupoles. No new connection with the outside geodetic network has been performed. Now, the network is maintained and controlled, with periodic levelling and gyroscopic measurements of the ring and around the experiments respectively. A particular attention is paid to the zones which have been affected by civil engineering works, mainly the ATLAS and CMS experimental areas, the connections with the transfer lines, and the beam dump tunnels (see figure 1). The figure 2 shows the deformation of the network around the ATLAS cavern due to the convergence effects. Detailed analysis of the data measurements collected at each step of the installation can give a confidence on the stability of the points in the arcs. New levelling references anchored deeply under the floor of the tunnel have been installed at the extremity of each arc and are included in the network.

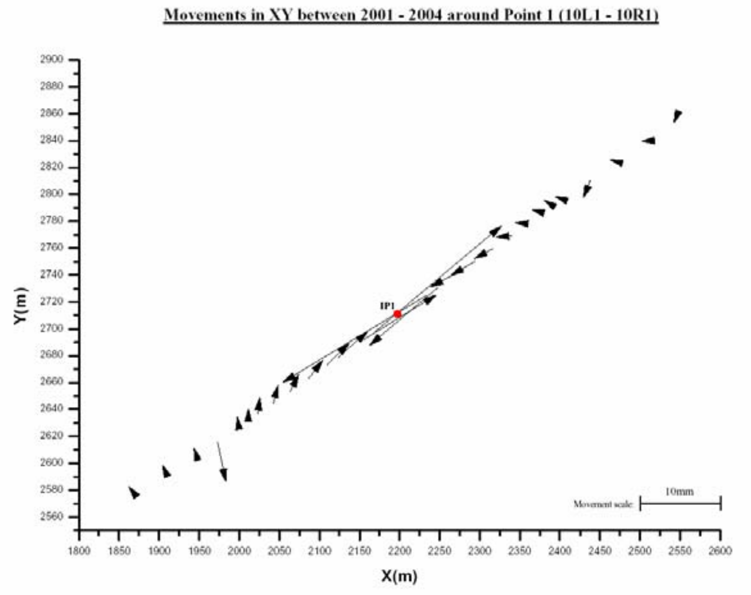


**Figure 2: movement of the network around ATLAS cavern**

A particular attention has been paid to the jacks which support the magnets and are used for the adjustment positioning. Their position with respect to the fiducials eliminate any lever arms effect at the level of the fiducials during the alignment, and a such layout makes significantly easier and faster the alignment process. In the flexibility of the bellows of the interconnects, a one mm offset has been preserved in addition to the alignment errors budget between consecutive cryomagnets for the lever arm effects in the interconnects in order to be able to move a magnet when cold.

Due to the very limited range of the jacks (+/- 10mm in radial, +/- 20mm in vertical), the magnets have to be unloaded within +/- 3mm with respect to their theoretical position. It is why an accurate marking of the position of the elements on the floor of the tunnel has been performed, as well as a measurement of the altitude of the floor under each jack. Then each jack will be aligned to its theoretical position, prior the installation of the cryo-magnets.

The first alignment is performed when a series of magnets is installed. Each magnet is aligned with respect to the reference geodetic network using the classical total stations for distances, and levelling and wire offset measuring instruments. In addition, a local radial smoothing is performed with wire offset measurements, prior to the interconnection works can start. Direct levelling methods are preferred to the 3D methods with the total stations for the alignment in the vertical direction. This more accurate method makes that there is no need for a smoothing in the vertical plane.

The final alignment will take place once the magnets are cooled down, in order to take into consideration all the external forces due to thermal and vacuum effects. The smoothing is done individually in the two planes, with wire offsets and direct levelling measurements in the horizontal and vertical plane respectively, sector per sector of the machine. All the measurements are carried out directly on the fiducials of the magnets, without any reference to geodetic reference network, except to the deep levelling references located at the extremities of each arc.

The connection to these levelling references, which are considered as fixed points, allow also a better absolute determination of the machine.

### 3.3. The integration aspects

In parallel to the design of the elements to be installed, their integration in the tunnel is studied carefully. To do this, the theoretical position of each component is defined in the CERN 3D reference co-ordinates system, and a theoretical model of each element is built. The CAD software (EUCLID and CATIA) are used to verify the possibility for all the equipment to be installed in the tunnel or not. All the algorithms and the parameters allowing taking the local shape of the Geoid into consideration have been provided by the surveyors to the designers [5] and [6].

This integration is done not only for the elements to be installed, but also for the space to be reserved for some activities, and in particular for the alignment process. In a so small tunnel for a so large machine, space is very expensive, and free space is immediately jeopardised by somebody. For survey, necessary space around the targets, above the magnets as well as around the jacks is defined on all the integration drawings and the surveyors take also benefit of the space dedicated for the transport of the equipments which is always kept free. In the arcs, a volume for the measurements above the magnets can be reserved for the measurements. In the long strait sections where are all sorts of equipments are installed it is very difficult to preserve a such area, and it is much more efficient and flexible to base the alignment methods on offset measurements carried out in the passage area.

## 4. THE TOOLS

### 4.1. Survey equipments

The SPS type targets have been adopted as a standard for all the elements to be aligned in the LHC and the transfer lines. These targets can appear to be rather large compared to the small spheres which can be used now with laser trackers, but they allow the forced centring of the measuring equipments, and this point is essential for the final alignment of the elements and the maintenance.

The use of the laser tracker is limited to the internal metrology of the magnets. For the positioning, motorized total stations, digital levels and home made wire offset measurements devices are preferred to the laser tracker. The use of laser trackers for the alignment would have implied to increase a lot the number of points of the reference network, with accurate points installed on the vault which is far to be the most stable part of the tunnel. Such method would have induced additional costs for the maintenance of the network it self. At the inverse, the classical instruments are much cheaper, do not need a dense reference network, allowing significant savings, and procure in the same time a very high precision of the alignments in a short time.

Accessories – centring system for the instruments and the targets, jigs for tilt measurements- have been also developed for the LHC with a particular attention paid to the ergonomic aspects in their concept.

### 4.2. Positioning equipments

An auxiliary jack has been developed for the vertical adjustment of the cryomagnets. It is inserted in the column support of the main jack during the alignment process, and allows a precise and smooth vertical displacement of the magnet.

Due to the very limited space under the magnets, the access to the jacks is quite difficult. It is why the hydraulic auxiliary jacks to be used for the vertical adjustment are manipulated with a dedicated arm in order to facilitate their installation in the body of the main jacks. The precise vertical movement is obtained by inserting or removing a piston in the hydraulic circuit, providing a very slow movement mainly when going down, and an integrated linear sensor allows the control of the vertical movement. This sensor will make the realignments for the maintenance very easy and fast.

## 5. DEFINITION OF THE WORK

Once the alignment works are identified, they are defined as work-packages. The global view of the work-packages is given on the figure 3. It can be seen, as an example, that the alignment works in the arcs are split into 6 parts: the measurement and maintenance of the geodetic network, the marking works on the floor, the controls of the position of the cryogenic line (QRL), the positioning of the jacks, the first alignment of the cryo-magnets, and then the smoothing of these elements.

Each work-package is described by two documents. An engineering specification describes the work to be done, the accuracy, the data and the drawings to be used. It also defines the goal of the work to be done, the conditions for doing the work (tunnel clean, lights up, other workers in the tunnel…etc), the situation in the tunnel before, during and after the work, as well as the responsibilities of all the groups concerned. This document is subject to approbation by all the persons concerned by the work.

In addition, a procedure gives information on the professional skills required for performing the work, the resources needed from the hardware point of view, the preparation of the work, the methodology to be applied, and all the quality aspects. This document defines the work to be performed by the Contractor and by CERN, and the responsibilities of each party. In particular, attention is paid to the possibility for the Contractor to validate by himself his work whatever the hypothesis of calculation to be chosen, and all aspects concerning the storage of the data are defined.

And additional workflow diagram can complete these two documents for the most complex work packages. It shows in a graphical manner the order of the operations to be performed as well as the resources needed and the responsibilities for everyone.

All these documents are integrated in the official baseline of the project and can be accessed by anybody concerned.

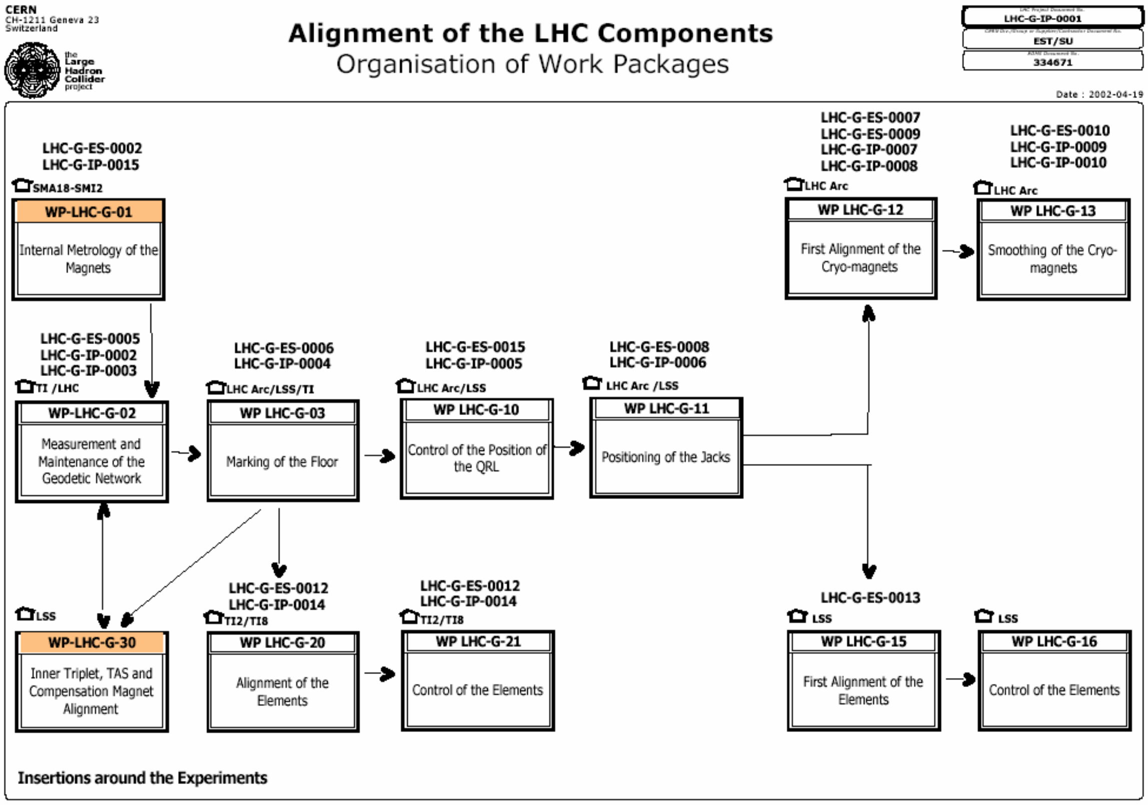


**Figure 3: work packages for LHC alignment**

# 6. QUALITY ASPECTS

## 6.1. The SURVEY database

CERN has a global approach for the quality, through the Quality Assurance Plan for the project. Besides the documentation, all data relevant to the manufacture of the equipments are stored in the Manufacturing Traveller Facility, so called MTF, and the “Reference LHC database” which is designed to store all data pertaining to the collider, its components, and their layout. [7].

As the SU group manages for nineteen years a relational database SURVEY based on ORACLE™ concerning all the geometrical data for all the other machines at CERN, it have been decided to upgrade this database for the LHC, mainly in setting up connections to the MTF, the reference LHC database, and the database for the magnets.

The SURVEY database is used to store the theoretical 3D definition of the machine issued from MAD calculations. It contains also the theoretical co-ordinates of all the alignment targets of the magnets, the co-ordinates of the reference networks, all the geometrical measurements performed in the tunnels with their attributes, the calibration parameters of the instruments, the results of the processing of the measurements, and the real position of the components aligned or surveyed [8]. Archiving possibilities allow statistics computations on the evolution of the position of the elements.

An associated software GEODE provides to the user interactive access to the data and to a set of calculation algorithms.

In parallel, all the documents and files are managed with an Electronic Data Management System (EDMS). The documents are submitted for approval to the concerned persons, and the system can manage for the comments if any. The status of the documents (in work, engineering check, released or cancelled) informs on the validity of the document.

## 6.2. Analysis of the data

A detailed analysis of the measurement data is performed at each step of the alignment works, in order to detection of the mistakes. As far as the reference networks are concerned, it also allows a permanent detection of the systematic errors of the instruments or eventual ground motion and slow deformations of the reference network, and can generate needs for recalibrations, or re-measurements of reference points.

The figure 4 gives an example of the analysis of the wire offset measurement data compared to the angular measurements made on the reference network in the sector 4. This set of measurements had been measured at different periods and the comparison shows a good global quality of the integration of the new kind of measurements in the network. A more detailed analysis area per area can also show that no deformation has been detected. These kind of analysis is very useful, it can have an influence on the planning of the installation and it allows an anticipation of the problems.

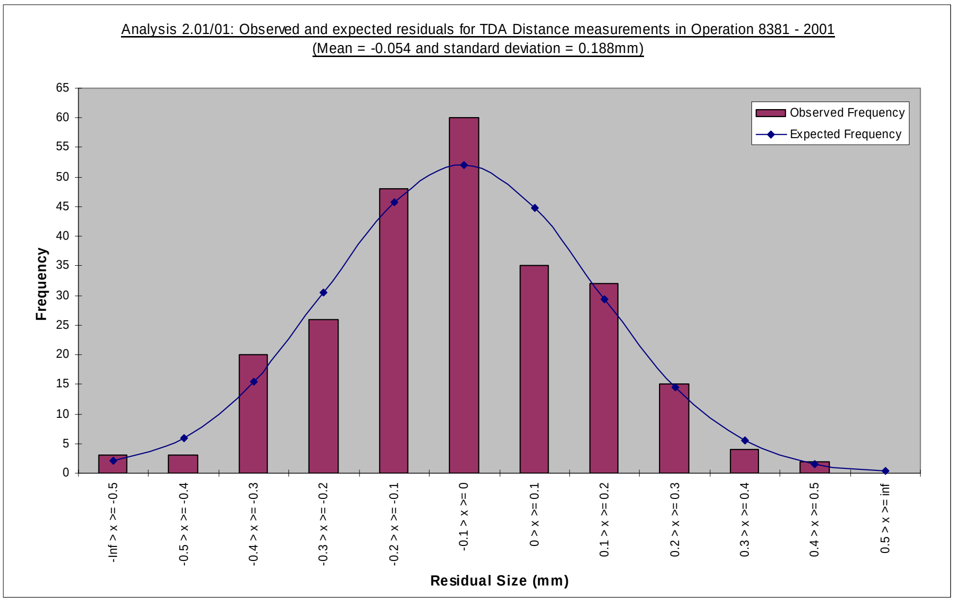


**Figure 4: analysis of wire measurements**

### 6.3. As built measurements

At each step of the installation, as built measurements are carried out with a laser scanner in the most critical parts of the tunnels. The shape and the position of the equipments measured can be compared to the CAD digital mock-up, in order to prevent any topological conflict and to keep the documentation up to date [9].

## 7. CONCLUSION

The role of the persons in charge of the alignment of a machine is not limited to the positioning. It essential to be involved also very early in the design of the elements, in terms of mechanical stability, assembly, quality and controls, targets and supports. In particular, for the metrology of the long LHC magnets, the surveying techniques are very efficient, as far as they are used correctly. It is also important to check that all the elements to be aligned are equipped with fiducials a correct supporting system.

The preparation of the installation includes also our participation to the construction of a digital mock-up of the machine. Survey The control on site of the real shape and position of the tunnel and the already installed most critical elements with the laser scanner make possible to detect any non-conformity on the position or shape, and to prevent any future topological conflict during the installation.

Emphasis has been put on the quality aspects. Of course, surveyors have a long tradition of the controls, particularly through the redundancy of the measurements, and the quality is not a new aspect for them. For this project, the visibility of the quality has been improved, helping all the actors for the access to the information, and the SURVEY database contributes a lot to this. The description of each work package in document files constitutes a good documentation for the future, as far as it is maintained up to date, and for all the persons concerned by the installation, with in particular the sharing of the responsibilities.

For the positioning of the elements, the classical methods intensively used at CERN on the other machines will be also used for the alignment of the LHC. They are tested, efficient, accurate and safe. It why it can be said that we will align the LHC with a wire.

## 8. ACKOWLEDGMENT

I would like to acknowledge all the members of the Working Group on Alignment for their contribution to the studies on the stability of the cryo-magnets, the colleagues from the other laboratories involved in this project, particularly from Fermilab and BNL for the insertion elements and from CAT (India) for the adjustment jacks, the members of the CERN Survey group and the contractors GEOTOP-HALLER-HYPARC and SETIS for all the alignment works done.

**References**

[1] J.B. Jeanneret, J.-P. Quesnel, w. Scandale, A. Verdier , “Report on the mini workshop on the alignment”, LHC project note 247, CERN, 16 Feb 2001

[2] D. Missiaen, Measuring huge electro-magnets using laser tracker technology, Optical3D, Zurich, September 2003

[3] W. Coosemans, H. Mainaud Durand, A. Marin and J.-P. Quesnel, The alignment of the LHC low beta triplets : instrumentation and methods, Proceedings of the 7th International Workshop on Accelerator Alignment, 2002, spring 8, Japan.

[4] H. Mainaud Durand, Micrometric alignment metrology: means, developments and applications, TS Workshop, CERN, May 2004.

[5] Mark Jones, "Transformations between the geodetic and astronomical reference & coordinate system", internal note, CERN, EDMS n° 107907, Feb. 2000

[6] Mark Jones, "Geodetic definition (datum parameters) of the CERN coordinate system", internal note, CERN, EDMS n°107981, Nov. 1999

[7] Samy Chemli, "databases and configuration management", LHC performance workshop, Chamonix XII, CERN-AB-2003-008ADM, march 2003

[8] C. Podevin, M. Jones, D. Missiaen, "The CERN SURVEY database and its interface GEODE", Proceedings of the 8th International Workshop on Accelerator Alignment, CERN, 2004.

[9] T. Dobers, M. Jones, Y. Muttoni, "Using a Laser Scanner for the control of accelerator Infrastructure and Machine Integration", Proceedings of the 8th International Workshop on Accelerator Alignment, CERN, 2004