CHAPTER 11

THE ALIGNMENT OF LHC COMPONENTS

11.1 THE GEODETIC REFERENCE NETWORK

The geodetic reference network provides a three dimensional framework and is needed for the first positioning of components. In addition, it allows the accelerator to be installed correctly with respect to the injection system, particularly with the SPS.

The reference network has to take into account all of the geodetic parameters which are required due to the size and location of the accelerator: geoidal undulations and deviation of the vertical (vertical geodetic reference surface), ellipsoidal reference surface for the earth (horizontal geodetic reference surface), geodetic coordinates, etc. Throughout the work to update the CERN vertical datum (geodetic reference surface) and to establish a geocentric set of horizontal datum position parameters for the CNGS project [1], the topocentric set of datum position parameters established for LEP [2] have been maintained for LHC [3]. The geoid determined for LEP will also be used to determine the height of LHC elements.

Table 11.1: Geodetic Parameters for LHC

XCERN P0	2000.00000
YCERN P0	2097.79265
ZCERN P0	2000.00079
Latitude at P0 (gon)	51.36920
Longitude at P0 (gon)	6.72124
Height of P0 (m)	433.65921
Azimuth of CERN Y-axis: Azyc (gon)	37.77864
GRS80 ellipsoid semi-major axis (m)	6378137.0
GRS80 ellipsoid first eccentricity: e^2	0.0066943800229
GRS80 ellipsoid second eccentricity: $(e')^2$	0.0067394967755
Radius of curvature in the Meridian at P0: RP0 (m)	6368761.40
Radius of curvature in the Prime Vertical at P0: NP0 (m)	6389299.67

11.1.1 Connection with LEP Network

The best reference geometry in the tunnel was provided by the position of the LEP quadrupole alignment targets. These points were accurately positioned from the surface and underground networks during the construction of the LEP machine and their radial and vertical position was checked periodically during the machine lifetime. The absolute shape of the machine as well as the relative position of the quadrupoles was proved by the quality of the beam orbit. In addition, the length of the orbit measured geometrically fitted very well with the RF measurements, within an accuracy of 2×10^{-7}.

The underground geodetic reference network is based on the position of the LEP quadrupoles. Before their removal, a last refinement of their absolute radial position was carried out by injecting accurate gyroscopic measurements into the data set.

11.1.2 The New Reference Points

Layout

The new geodetic reference network is defined by a set of 580 new points sealed in the floor of the tunnel, in the passage area. In the arcs, they are installed at 53.45 m intervals, in front of the middle of the first cryo-dipole of each half-cell. In the LSS, the distance between two consecutive points is shortened, to provide flexibility for component alignment [4].

Derivation

The reference points have been determined by angle, distance, wire-offset and gyroscopic measurements with respect to the LEP quadrupoles and to the reference pillars located at the bottom of each pit (previously linked to the surface network). Both measurements on the new points and those carried out on LEP before its removal (wire offsets and gyroscopic measurements) are fitted together by using least square adjustment assuming, as a basic hypothesis, that the pillars are fixed. They provide a set of co-ordinates in the global CERN co-ordinate system, for the new points as well as for the LEP quadrupole targets.

In the vertical plane, the heights are determined by direct optical levelling. This levelling is also connected to the LEP quadrupoles - which were surveyed and realigned every year since 1992. The accuracy of the measurements is 0.4 mm per km (r.m.s.).

One special levelling reference has been sealed deep under the floor of the enlarged part of the tunnel at Points 2, 3, 4, 6, 7 and 8. Two more of these are also installed around the ATLAS and CMS experimental caverns to enable checking of their stability. All these deep reference points are included in the levelling traverses, and will be considered as fixed, to allow future checks of parts of the machine.

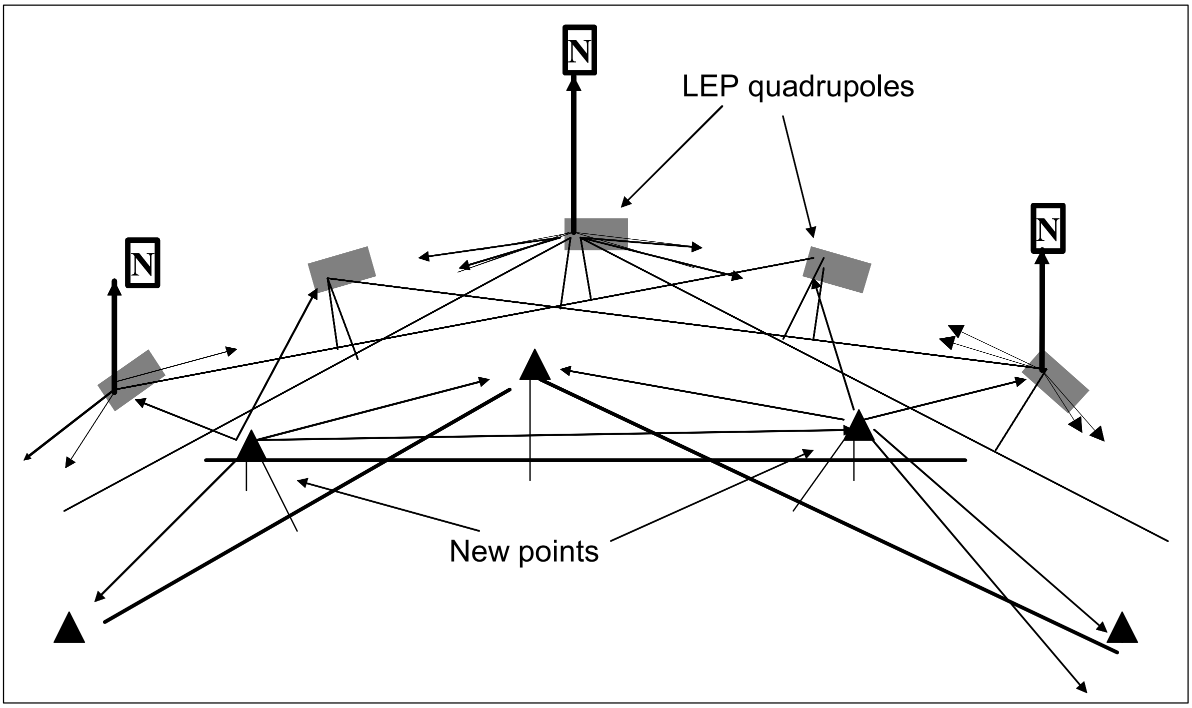


Figure 11.1: Layout of the Measurements

TI2 and TI8

The geometrical link between the SPS and the LHC is made by measuring the reference network of these two lines in a similar way to the LHC and by forcing the orientations in the SPS and the LHC to stay unchanged in the adjustment process.

11.2 THEORETICAL ABSOLUTE POSITION OF THE LHC

The LHC ring is contained in a plane parallel to and 300 mm above, the LEP plane. The interaction points IP1 to IP7 are located on the normal (orthogonal vector) to this plane in each corresponding point of LEP [5].

The co-ordinates of the IP's are defined in the global CERN reference frame, and the parameters of the mean beam line at the origin for MAD input are given in the Tab 11.2, below.

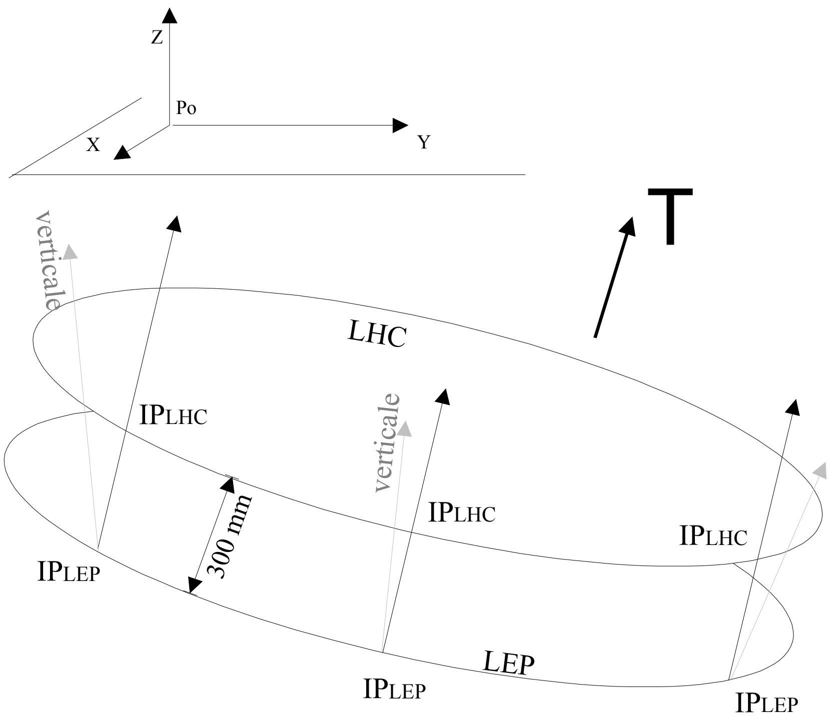


Figure 11.2 : Position of LHC with respect to LEP

Table 11.2 : Parameters for MAD SURVEY

X0	-2202.21027
Z0	2710.63882
Y0	2359.00656
THETA0	-4.315508007
PHI0	0.0124279564
PSI0	-0.0065309236

11.3 INTERNAL METROLOGY OF THE CRYO-MAGNETS

11.3.1 The Cryo-Dipoles of the Arcs

Layout of the Fiducials

Each element to be aligned in the tunnel is equipped with (at least) two reference alignment targets and a reference for the control of the transverse tilt. These references are called fiducials [6].

These are located on the cryostat in a very favourable position with respect to the adjustment jacks, in order to minimise the lever arm effects and so facilitate the alignment process of the magnets.

The cryo-magnets of the arcs and DS are equipped with four fiducials. Two transverse fiducials S and T are used to control the tilt. Due to the possible thermal vertical deformations of the cryostat, a dedicated central jack is needed to adjust the vertical sag. The central fiducial M is used to control this sag [7].

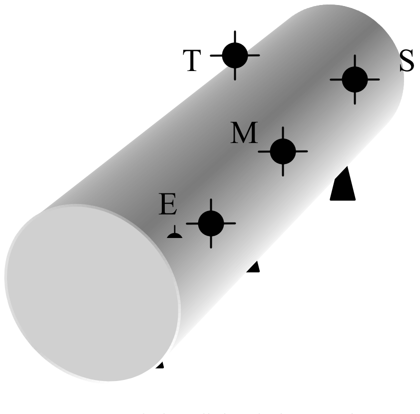


Figure 11.3: Layout of the fiducials on the cryo-dipole

The design of the fiducials allows instruments to be set up for the direct measurements carried out on them during the smoothing phases (see Sec. 11.6.2).

Determination of the Fiducials

The determination of the fiducials with respect to the mechanical plane and geometric axis is performed after the cold tests of the cryo-magnet. In this process, the geometric axis is defined as the best fit of a series of points located in the centre of each cold bore tube (with an auto-centring device going through it) and measured with a laser tracker from the two ends, assuming that the mean axis has the theoretical radius.

This operation, called "Fiducialisation", gives an accuracy of the position of the fiducials to better than 0.1 mm at 1σ [8].

As the measurements are performed at room temperature, a correlation factor is established during the cold tests in order to validate the position of the fiducials with respect to the cold mass, thus ensuring that warm magnets positioned in the tunnel reach their theoretical position when cold. In the same process, the central cold post is adjusted and blocked in order to force the shape of the cold mass to that measured in industry.

The oval deformation of the cryostat under vacuum in the sections containing the fiducials has been checked on prototypes and since it is always below 0.05 mm, it can be considered as negligible [9].

Additional Measurements

At the hand-over of the dipole cold masses at CERN, the shape of the magnet is checked by measuring a set of points inside the cold bore tubes using a laser tracker. This shape is compared to the theoretical one. The operation will be done on 10% of the dipole magnets.

The cartography of the tubes at the ends of each cryo-dipole is performed at the same time as the fiducialisation process. It consists of measuring the position of the flanges of several pipes and critical elements, in order to control the feasibility of the interconnection between two consecutive magnets. When the beam screen is inserted in the cold bore tube just before going down in the tunnel, the position of the end of the beam screen is also verified.

11.3.2 The SSS

The Fiducials

Three fiducials are installed on the cryostat of the SSS, similar to those of the cryo-dipoles. As no central jack is needed, no central fiducial is required.

The fiducials are determined by the survey group with respect to the magnetic axis of the cold mass, during the magnetic measurements under ambient conditions.

Additional Measurements

The mechanical position of the BPM is measured with the laser tracker with respect to the fiducials, in the same process as the adjustment of the extremity of the drift tubes for the lines V1 and V2 and the cartography of the ends. This gives good knowledge of the real position of the BPMs when the SSS is aligned in the tunnel and facilitates the interconnection between magnets.

11.3.3 Other Magnets

The separation magnets are equipped with six fiducials and the fiducialisation is done at BNL. On arrival at CERN, the position of the magnet with respect to its fiducials is checked, as well as the position of several tubes at the ends. For the inner triplets, the same kind of measurements will be done.

11.4 MEASUREMENTS FOR INSTALLATION

In order to facilitate the integration of the equipment in the tunnels, the real shape and position of the tunnel in the CERN global reference frame are used. The information is provided by the civil engineering department for the new caverns and tunnels.

The profiles of the LEP tunnel measured every 10m during the construction have been re-calculated with the new geometry for the existing tunnels. In addition, new measurements have been carried out at critical points, on the floor and the ceiling, mainly for the cryo-line and the transport vehicle passage.

Due to the lack of space in the tunnels, 'as built' measurements will be done at different steps of the installation of the machine to prevent topological problems between the various components. These are carried out using a laser scanner, which is the most efficient tool for collecting the data, reconstructing 3D models and studying their compatibility with the theoretical CAD models for integration.

A typical example of as built measurements is the check of the position of the jumpers of the QRL after their installation [10].

11.5 PREPARATORY WORKS

A series of tasks are performed prior to the alignment of the magnets in order to help during the final installation.

11.5.1 Marking on the Floor

This work consists of marking the vertical projection of the geometrical mean of the dual beam line, the position of the elements in the long straight sections (LSS), the interconnection points and the vertical projection of the head of the jacks in the arcs on the floor. In the transfer lines, the beam line is drawn in the straight parts of the lines, as well as the position of all the elements defined by BEATCH file, completed with the position of their supports. This work provides clear positioning for anybody working in the tunnels and is performed prior to the installation of the general services. The accuracy of the marks is ± 2 mm (r.m.s.) [11].

11.5.2 Positioning of the Jacks

The jacks of the magnets have an adjustment range of ±10 mm in radial and ±20 mm in vertical position. This is needed for compensating the errors of the floor, the errors in their own positioning, cryostat construction errors and ground motion during the life of LHC [12]. Because of this very limited range, the heads of the jacks are positioned within ±2 mm before the installation of the cryomagnets, with the adjustment screws in their mid position. 5 mm of the range of the vertical screw can be used to compensate the errors of the floor but for larger deviations of the floor, shimming or grinding is needed. After their accurate positioning, the jacks are sealed and fixed on the floor and then their position is checked again [13].

11.6 ALIGNMENT OF THE MAGNETS

The alignment of the magnets is performed in two phases: the first positioning and the final one, called smoothing.

11.6.1 First Positioning

This phase takes place once the magnets are installed on their jacks. It consists of independently aligning each magnet with the reference geodetic network and a magnet is considered to be aligned once its fiducials have reached their theoretical position. At the same time, a small local smoothing from magnet to magnet is done in order to obtain a relative alignment precision of ± 0.25 mm (r.m.s.) in radial and vertical for each magnet, and 0.5 mm (r.m.s.) axially, over a distance of 110 m. This smoothing decreases the influence of the small relative errors between the points of the reference network. The transverse tilt is adjusted within 0.15 mrad (r.m.s.) and the absolute precision in radial and vertical can be considered equivalent to that of the reference network.

This operation is performed when the magnets are not yet connected and the interconnection can only start at the end of this process [14, 15].

11.6.2 Smoothing of the Magnets

This phase is the final alignment of the magnets. Unlike LEP or the SPS, for the LHC the final alignment must be applied to all quadrupoles and dipoles - which have nearly the same sensitivity to misalignments. The process can only start once the magnets are connected, under vacuum and are cooled down, so that all the mechanical forces are taken into account.

The objective is to obtain a relative radial and vertical accuracy of 0.15 mm over a distance of 150 m [16]. As with the first alignment, the accuracy mentioned is applied at the fiducials. The vertical smoothing is performed with direct optical levelling measurements whilst the radial one is done by wire offset measurements. For this latter operation, access to the tunnel is required with the ventilation system adjusted to give minimum air-flow and certainly not exceeding 8000 $m^3 h^{-1}$.

This smoothing process initially corrects both residual errors in the pre-alignment and ground motion. As various geo-mechanical and structural forces are acting on the tunnel, the reference network mainly tends to move vertically, but magnets may also become tilted by a transverse component of this motion and by the deformation of the floor - thus also generating a radial displacement. Repeated measurements of the network are very expensive and in fact useless if, on the other hand, tilt, radial and vertical measurements are made directly on the magnets and then processed with respect to a local trend curve within a sliding window along the machine [17]. This efficient method allows an optimal and minimal detection of the magnets which need to be realigned.

At the end of the process, the misaligned magnets are moved, while keeping a contingency for relative movement (within the tolerance) at interconnection level [18].

An additional 1 mm offset can be made in the interconnections during the realignment process. This value is included in the maximum offset acceptable for the bellows of the interconnects.

11.7 ALIGNMENT OF THE INSERTION ELEMENTS

11.7.1 The Inner Triplets and TAS

Three points can be mentioned from the experience of 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 it difficult to have a good geometrical relationship between the machine and the experiments;
- It was impossible to align the low-beta sections within the requested accuracy with classical methods, and that generated many demands for re-alignments;
- The subsequent monitoring of low-beta magnets with very accurate (a few µm r.m.s.) hydrostatic levelling systems was very effective in improving the orbit quality.

Table 11.3 : Requested Alignment Accuracy

Functionality	Function	Accuracy (r.m.s.)
Alignment of one triplet w.r.t. the other magnets of the same arc.	F1	0.1 mm
Alignment of the experiment w.r.t. the machine.	F2	See § 11.7.2
Alignment of one triplet w.r.t. the other triplet (left vs. right)	F3	0.3 mm
Alignment of Q1 vs. Q2 vs. Q3 for one triplet	F4	0.1 mm Few µm for short term stability
Alignment of the TAS	F5	0.33 mm

The requirements on the accuracy for the alignment of the inner triplets are given in Tab. 11.3 [19]. The situation for LHC is very different to that of LEP. The tunnel was finished sixteen years ago, the experiments at points 2 and 8 have been dismantled, no major civil engineering works have been undertaken there, and dedicated UPS galleries have been built for the geometry around ATLAS and CMS. The LHC geometry can be better related to the experimental caverns, thus minimizing the changes with respect to the experiment during the construction [20].

Each cryo-magnet Q1 or Q3 is equipped with 6 targets for the alignment F1. Three targets would have been sufficient but due to the symmetry of the installation with respect to the IP, the number of fiducials has been doubled to allow the installation anywhere. The Q2 has two additional targets in its centre, due to the additional central jack. The alignment F1 is performed with classical methods: optical levelling and wire offset measurements.

Each cryo-magnet is also equipped with additional targets dedicated to the permanent monitoring of their position. For the radial alignment, the equipment is as follows:

- A wire stretched along each triplet allows the function F4;
- A wire stretched through the two UPS galleries and the UX cavern allows the function F2, and F3.

The positions of the elements are detected with wire positioning sensors (WPS). The resolution of such sensors is 5 μm. For ALICE and LHC-b, where the stability is not altered by new heavy civil engineering works, no UPS gallery has been designed, and no stretched wire will be installed through the experiment. The radial link between left to right is made using the reference network of the tunnel, determined directly where the experiments do not obscure the lines of sight.

The vertical positioning is performed with hydrostatic levelling systems (HLS) installed from one triplet to the other one, through the UPS galleries and the UX cavern. These systems allow the functions F2 to F4 to be satisfied.

At the four intersection points, the cryostats are installed on motorised jacks to allow initial and maintenance alignments in these confined and (later on) radioactive areas.

Due to the high level of radiation which is expected, all the electronics are installed in less critical areas, UPS galleries at points 1 and 5 and UL galleries at point 2 and 8.

The TAS will be aligned from the network of the experiment.

Table 11.4: Installations for the Four Experiments

Function	ATLAS and CMS	ALICE and LHC-b
F3	Left to right vertical link (HLS)	Left to right vertical link (HLS)
F1	Two permanent levelling reference	One permanent levelling reference
F3	Left to right radial link (WPS) via UPS galleries	Left to right radial link via network
F4	Radial and vertical control of one triplet (WPS and HLS)	Radial control of one triplet (WPS)
F1	Link with the machine network	Link with the machine network
F2	Radial link with the experience (WPS via UPS galleries)	Radial link with the experience via network
F2	Vertical link with the experience (HLS)	Vertical link with the experience (HLS)

11.7.2 The Experiments

The Geometrical Links with the Machine

Each LHC experiment will be surrounded by a reference network that will be linked to the machine geometry either via the UPS galleries for ATLAS and CMS or via direct views for ALICE and LHC-b since there are no WPS systems traversing these two experiments. The reference networks are in the form of plug-in and foldable brackets on walls and metallic structures and the configuration is adapted to the needs for the detectors.

Two hydrostatic stations are installed in the four experimental caverns for the vertical link with the machine.

Accuracy

An error budget at 1 σ has been estimated for the ATLAS and CMS configurations from the machine itself to the reference network in the cavern and then to any other detector points.

That exercise has to be divided into the different steps of the geometrical process to link the machine geometry to any fiducial mark on the detector and to the locations of the reference points in the cavern, namely:

- Survey galleries reference line (UPS geometry) versus machine geometry : radial 0.1/0.2 mm, levelling 0.1/0.3 mm.
- Cavern reference points directly linked to the UPS geometry versus that geometry : radial 0.2/0.4 mm, levelling 0.1/0.2 mm. This is also the error budget of any fiducial mark directly measured from those reference points.
- Cavern reference points NOT directly linked to the UPS geometry versus cavern reference points directly linked to the UPS geometry: 0.5 mm in the three directions.
- Any detector fiducial mark versus cavern reference points NOT directly linked to the UPS geometry: 0.3 / 0.7 mm in the three directions.

Thus the global range of the three dimensional uncertainty at 1σ of any reference point in the cavern versus the nominal beam line is from 0.3 mm up to 0.6 mm, the global range of the three dimensional uncertainty at 1σ of any fiducial mark versus the nominal beam line being from 0.5 mm up to 1.2 mm.

The Stability of ATLAS

Due to very limited possibilities for vertical mechanical re-adjustments, tracing the vertical movements is critical [20].

Estimations for the ATLAS cavern floor stability show the following:

- Initial settlement due to cement contraction : about -2 mm from the time the concrete is poured to the time ATLAS gets possession of the cavern (4 to 5 months);
- Experiment weight : an additional adiabatic move over about 6 months of -5.5 mm due to the weight of ATLAS;
- Heave to hydrostatic pressure : about +1 mm per year, up to 20 mm over 20 years in the worse case.

According to the results of a-priori analysis, it would seem that stable conditions in ATLAS cavern within less than 1 mm per year might not happen in the first 15 years of its lifetime.

The main problem for ATLAS is the ability to precisely monitor and react to any movement in the floor level relative to the LHC beam. A permanent hydrostatic levelling system will be installed on the detector and linked to the main network specifically in order to monitor the relative movements of the feet at better than 50 μm.

Possibilities of beam adjustments have been studied for ATLAS in order to compensate the vertical motion of the cavern and its detector. An 'immediate' adjustment of less than 1 mm could be achieved by changing the magnetic field in the last magnet in the LSS, a 'short term' adjustment of about 1 mm could be achieved by adjusting jacks under the last triplet and a 'long term' adjustment of several mm's will imply a re-alignment of a string of magnets in the tunnel.

The Stability of CMS

Even if the mechanical configuration of CMS permits easier re-adjustments, a hydrostatic system has been also proposed to monitor the central wheel (YB0) of the CMS yoke. The layout and its integration enable it to be linked directly and easily to the hydrostatic tube traversing the CMS cavern in such a way that YB0, containing the barrel and the central detectors, can be inspected vertically via the entire machine hydrostatic system in the UPS and the radial tubes in the tunnel up to the inner triplets. An uncertainty of less than 0.5 mm with respect to the inner triplets is estimated.

The Stability of ALICE and LHC-b

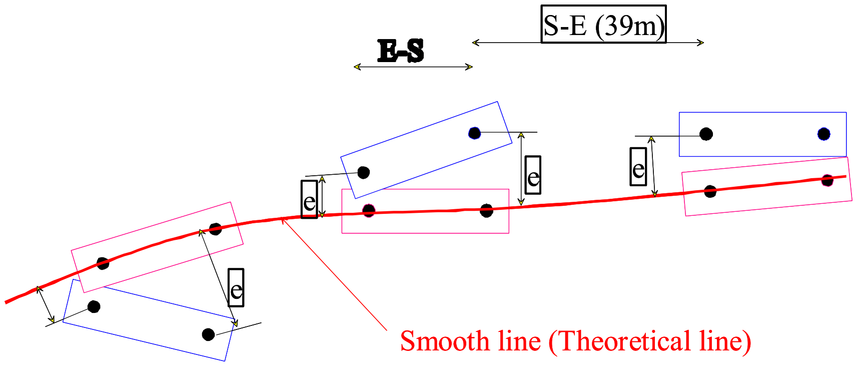
No direct links via WPS or HLS on any detectors in ALICE and LHC-b have been proposed yet. Only the periodic checks of the reference network and links with the machine will provide information about the stability of the detector.

11.8 ALIGNMENT OF THE TRANSFER LINES

As for the ring, the elements of the transfer lines are aligned with respect to the reference geodetic network and then smoothed into the SPS and the LHC through the elements concerned at the ends of the lines. The accuracy of the final alignment of the quadrupoles is 0.15 mm. The BPMs fixed on the quadrupoles are aligned in the workshop with respect to these quadrupoles, and only surveyed when installed in the tunnel [21].

11.9 MAINTENANCE OF THE ALIGNMENT

From 1992 to 2000, the vertical position of all LEP quadrupoles was surveyed annually. These measurements gave a very good knowledge of the tunnel stability and the hypothesis of the degradation of the alignment of the LHC was based on the results of these measurements [22]. Fig. 11.4 gives average statistics of misalignment around the trend curve of the smoothing process.



Polynome	92	93	94	95	96	97	98	99
max	0.00408	0.00105	0.0013	0.0008	0.0007	0.00067	0.0007	0.0007
min	-0.00216	-0.00145	-0.00073	-0.0009	-0.00068	-0.0009	-0.0008	-0.0008
rms	0.00060	0.00031	0.00019	0.00020	0.00020	0.00018	0.00018	0.00024

E-S (3 m)	92	93	94	95	96	97	98	99
max	0.0006	0.0006	0.0004	0.0004	0.0006	0.0006	0.0005	0.0005
min	-0.0008	-0.0004	-0.0004	-0.0006	-0.0004	-0.0004	-0.0003	-0.0003
rms	0.00017	0.00014	0.00014	0.00014	0.00014	0.00014	0.00012	0.00011

Figure 11.4: Deformation of LEP between 1992 and 1999

The table shows that after the first three years which were needed to recover correct alignment, the accuracy of successive alignments stabilised around 0.2 mm (r.m.s.) per year.

About 100 quadrupoles where re-aligned using the smoothing method each year in order to recover an alignment within 0.15 mm (r.m.s.).

Therefore, the precision of the alignment will be as follows:

- After one year 0.2 mm in vertical, 0.2 mm in radial, mainly due to tilt deviations, so 0.28 mm transversally to the beam,
- 0.50 mm in the interconnection plane due to lever arm effects and amplification errors.

About 350 cryo-magnets will therefore have to be re-aligned annually.

At the lowest point, a subsidence of about 2 mm per year is still active and affects 600 m of tunnel in a gradual way (Fig. 11.5).

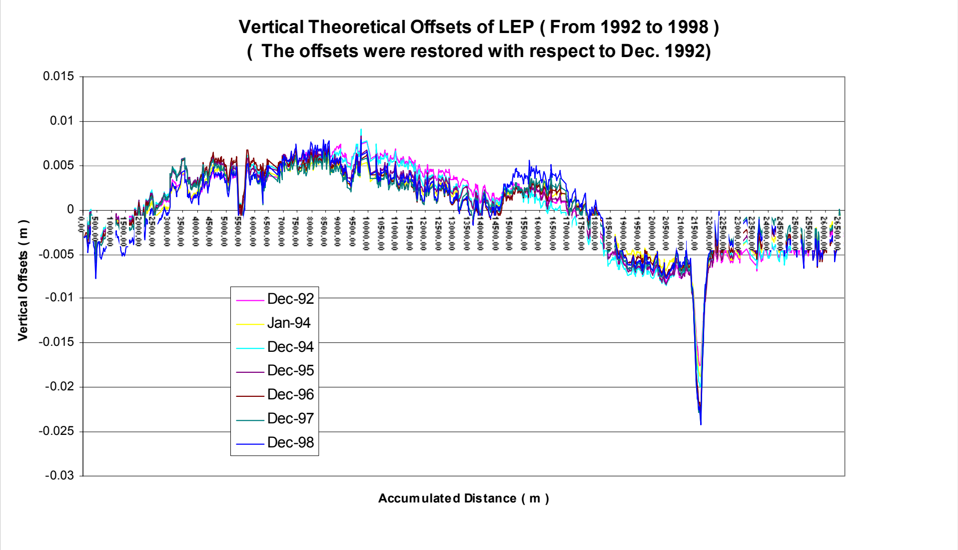


Figure 11.5: Vertical theoretical offsets of LEP from 92 to 98

This will have a serious impact on the range of the jacks of the cryo-magnets and the jumper connections with the QRL in this area. In order to delay the effect on these elements, an anticipation of the motion over four years will be taken into account for the installation of the jacks and the QRL.

In order to prevent movements beyond tolerances for bellows, a permanent geometric control of the interconnections will be set up. A sensor will send a warning to the control room when the critical limit in the relative movement of two consecutive magnets is reached. Initially, half of the interconnections will be equipped – these have been chosen according after analysis of movements observed on LEP.

11.10 QUALITY ASSURANCE

The successive phases of the alignment process are describes in detail [23], including the conditions needed for performing the work, and the procedures determine the role of the contractors and CERN in the quality control process.

All the geometrical data are stored in a dedicated database [24]. This database manages the following data:

- The theoretical 3D positions of all the elements, the orbit points provided by MAD and the fiducials,
- The measurements carried out for the metrological works (networks control, alignments, smoothing),
- The calibration parameters of the instruments,
- The results of the works, the real position of the elements.

For elements such as BPMs and correctors which are parts of the cryo-magnets, their real position is deduced from the position of the main components taking the assembly errors contained in the MTF into account.

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