Chapter II.11

Survey and alignment of accelerators

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The present chapter summarizes the survey and alignment processes of accelerators and transfer lines. The major geodetic principles governing the survey and alignment measurement space are revisited and their relationship to a lattice coordinate system shown. The chapter continues with a broad overview about the activities involved in the step by step sequence from the initial discussions on alignment strategy to final smoothing. Emphasis is given to the relative alignment of components and the corresponding instrumentation and method. The R&D for the alignment of future accelerators is also introduced. This chapter also aims at considering the benefits of integrating geodetic metrology in the design of new particle physics facilities as early as possible.

II.11.1 Introduction to accelerator alignment

According to the Oxford dictionary, alignment is: "an arrangement in which two or more things are positioned in a straight line". In the context of particle accelerators, the "things" are machine components such as beam instrumentation and vacuum devices, magnets, RF components, etc. In an accelerator, the components must be positioned as close as possible to their theoretical position in order to define a smooth machine, and to fit, in given alignment specifications, to the lattice.

The geodetic metrology, also known as large-scale metrology, guarantees the quality of geometric knowledge of accelerator components at every stage of the project, from prototyping to installation and commissioning [1]. The alignment maintenance over the machine's lifetime is essential to ensure that the beam continues to circulate despite ground movements, stresses applied by various forces and movements due to thermal gradients.

Geodetic metrology is based on a combination of several fields of expertise, the main ones being geodesy, topography with techniques adapted to high-precision and industrial environments, optics, and mechatronics. The latter two provide custom-developed geometric measurement and control technologies.

In the following sections, based mainly on CERN's experience, the principles and tools of geodetic metrology are discussed, the various stages of particle accelerator alignment are enumerated, and a few areas of R&D are addressed.

This chapter should be cited as: Survey and alignment of accelerators, J.-C. Gayde, DOI: 10.23730/CYRSP-2024-003.1601, in: Proceedings of the Joint Universities Accelerator School (JUAS): Courses and exercises, E. Métral (ed.), CERN Yellow Reports: School Proceedings, CERN-2024-003, DOI: 10.23730/CYRSP-2024-003, p. 1601.

II.11.2 Introduction to geodesy

II.11.2.1 Definition of geodesy

Geodesy is the science of accurately measuring and understanding three fundamental properties of the Earth: its geometrical shape, orientation in space, and gravity field [2,3]. The changes of these properties with time are also studied.

Knowing the shape of the Earth and defining parameters to express coordinates is a prerequisite for all survey work. It is necessary not only for the alignment of the accelerator components but also to define the absolute and relative position of all surface areas and underground areas (i.e. sites, buildings, tunnels, accelerators, experiments).

Survey techniques applied to alignment and positioning of accelerators and experiments require a solid geodetic infrastructure covering the entire accelerator complex. Depending on the size of the complex, the requirements are different, but the geodetic infrastructure must include the following elements:

- One or more coordinate reference systems (CRSs) composed of a datum and a coordinate system [4] along with the respective coordinate reference frames (CRFs) i.e. their realizations by means of reference frames consisting of physical points and associated values of the coordinates;
- Technical documentation of all components of the geodetic infrastructure, including guidelines for their use (e.g., for performing measurements, transformations, stabilization of point markers, etc.) and materials for training and education of personnel;
- Internal or external control baselines and calibration sites for geodetic instruments.

II.11.2.2 Coordinate reference systems and frames (CRSs and CRFs)

At a global, national, regional, or local scale, CRSs and their associated frames are established to ensure consistency of the coordinates for an entire area or object. It is common that several CRS coexist in accelerator facilities. They are established to suit specific needs and to be convenient for the users (see Fig. II.11.1). For instance, a global geodetic CRS can be used to link the facility with external infrastructures, and a local cartesian coordinates reference system can be dedicated to the alignment of the particle accelerator or the physics experiments. Specific CRSs can also be defined to compute relative positions between particular points housed on a single component.

When working with multiple coordinate reference systems in the same area, it is essential to determine coordinate transformation models. If a sufficient number of point coordinates are known in two different CRSs, it is possible to compute a set of transformation parameters. Helmert transformation parameters (composed of three translations, three rotations, and potentially a scale factor) are commonly used. The uncertainties of the transformation parameters must be considered when applying transformations between CRSs to estimate the accuracy of the transformed coordinates.

To realize the CRSs, and create the associated frames, the first step is to build a network of physical points anchored on the ground or on the floor, such as concrete pillars and drift nests. Then, various techniques can be used to assign coordinates to the points.

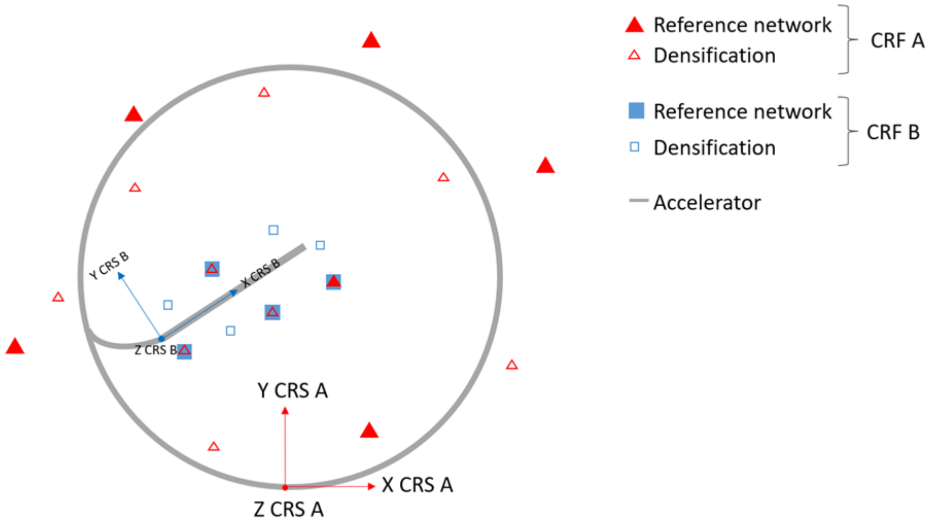


Fig. II.11.1: Schematic representation of two CRSs and their associated CRFs in a particle accelerator facility. In this example, CRS A could be a general CRS and CRS B a local CRS for the linear accelerator, with its X axis aligned to the beamline.

II.11.2.3 Geoid and deflection of vertical

The geoid is a selected equipotential surface of the Earth's gravity field and serves as the reference surface for height determination. It can be considered as an idealised continuation of the mean surface of the oceans beneath the continents.

As a first order approximation, the geoid can be modelled as a sphere with a radius of $R = 6371\,\text{km}$. Up to a certain extent, an approximate value of the impact on height determination s of the Earth's sphericity (see Fig. II.11.2) can be easily computed at a distance d using Eq. II.11.1

$$s = \frac{d^2}{2R} \quad . \tag{II.11.1}$$

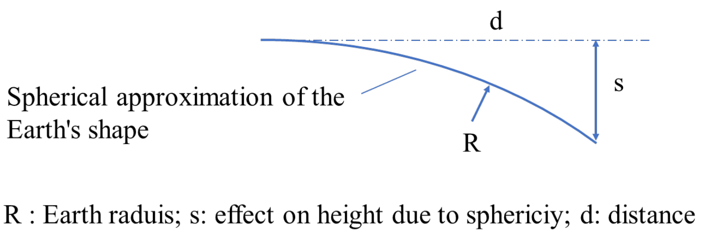


Fig. II.11.2: Illustration of the impact of Earth's sphericity on height.

The effect of the sphericity is $s = 7.8\,\mu\text{m}$ at $d = 10\,\text{m}$, $s = 780\,\mu\text{m}$ at $d = 100\,\text{m}$ and $s = 7.8\,\text{cm}$ at $d = 1000\,\text{m}$. It means, for example, that to compensate for the Earth's sphericity and to maintain the beamline of a $1000\,\text{m}$ long linear accelerator in a Euclidean plane, the difference in altitude between the start and the end of the accelerator will be, to a first approximation, $7.8\,\text{cm}$.

However, modelling the Earth as a sphere can be insufficient to reach the accuracy required by the alignment of the components of a machine. The geoid is irregular due to the gravity field variations caused by local mass anomalies (mountains, valleys or rock of various densities). Hence, the Earth must be modelled as an ellipsoid and, additionally, geoid variations must be known.

Across the Earth' surface, the difference between the geoid and a global normal reference ellipsoid ranges roughly between $\pm 100\,\mathrm{m}$ (see Fig. II.11.3).

The primary task of a geoid model is to allow direct access to altitude from GNSS (Global Navigation Satellite Systems including GPS, Glonass, Galileo, Beidou, etc.) observations, computing the difference between the ellipsoidal height h_e and the geoid height N. Equation II.11.2 gives the relationship between altitude, ellipsoidal height and geoid height

$$H^0 = h_e - N \quad . \tag{II.11.2}$$

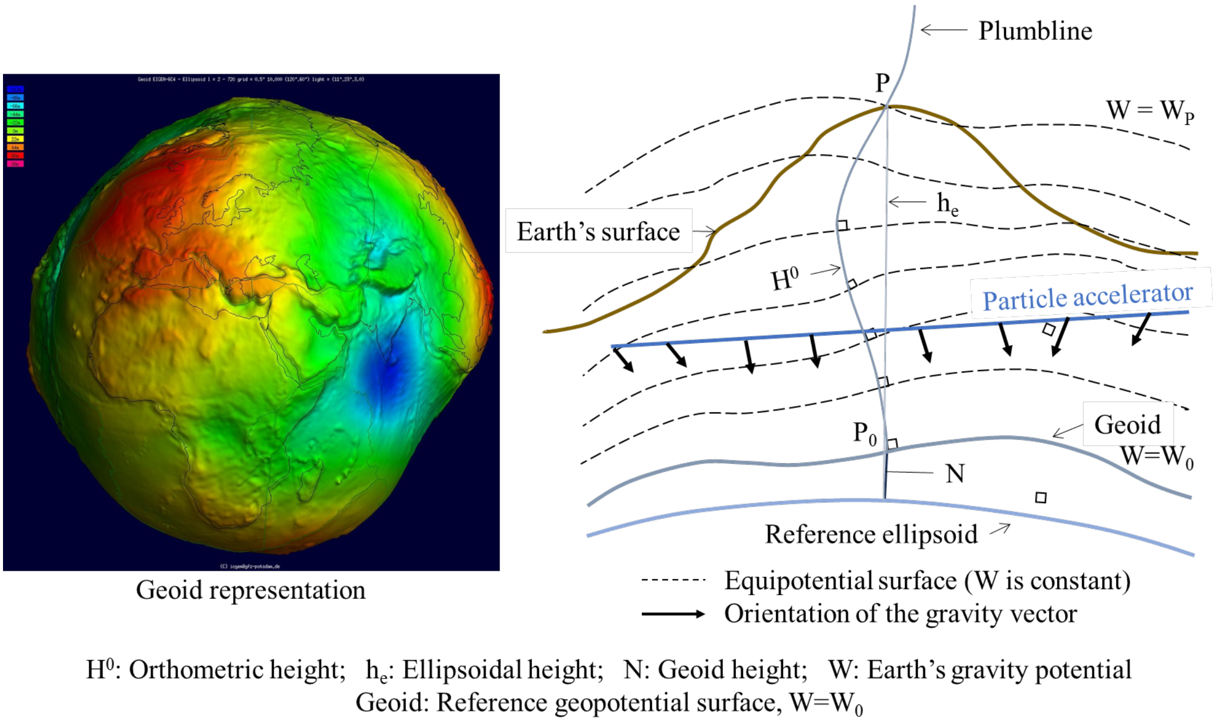


Fig. II.11.3: (Left) geoid representation with radial exaggeration factor of 10000 [5]. (Right) illustration of equipotential surfaces trajectory (inspired by Ref. [6]).

The geoid also models the deflection of the vertical (DoV) (the angle between the normal to the ellipsoid and the plumbline (or the gravity vector)). The DoV (ε) is split into North-South (ξ) and East-West (η) components. Knowing the DoV is crucial for accelerator alignment, as most observations are made using gravity-related measuring instruments. In extreme cases, the plumb line is expected to deviate from the ellipsoid's normal by an angle as large as $109''$ (i.e. local distortions can reach $0.5\,\mathrm{m}$ per km, to be added to the sphericity effect) [7].

Astro-geodetic observations (see Fig. II.11.4) using a zenith-camera allow direct access to the

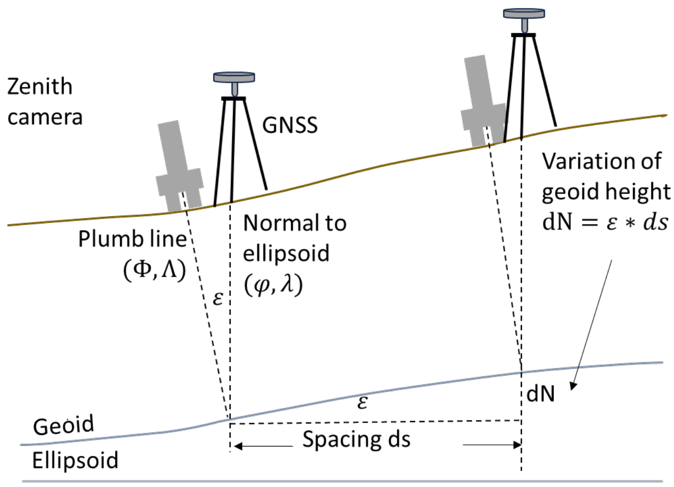


Fig. II.11.4: Basic principle of determination of vertical deflections $\varepsilon(\xi, \eta)$ measurements by combining zenith camera and GNSS [9].

deflection of the vertical, using the difference between the astronomical coordinates (Φ, Λ), determined using a zenith camera, and the geodetic coordinates (φ, λ), determined using GNSS observations.

These two techniques only give local information. Long trends are computed using gravity observations, digital terrain models and satellite or combined global geopotential models. These observations can only be done at the surface of the Earth, with an open sky view. If the particle accelerator is installed in an underground tunnel, values must be transferred at the level of the tunnel [8].

II.11.3 The stages of an accelerator alignment process

II.11.3.1 Introduction to the different steps of an accelerator alignment

The geodetic metrology of a particle accelerator follows different stages along the lifetime of the project [10]. The alignment of accelerators can typically be described schematically by a sequence of tasks which follow a relatively well-known chronological order, as illustrated in Fig. II.11.5. These take place both outside and inside the area where the machine is installed. In the case of an accelerator such as the LHC at CERN, "outside" refers to surface areas and "inside" to the underground areas of tunnels and caverns.

One of the key aspects to be considered is geodesy, particularly for large-scale projects. Following these studies, a geodetic network will be installed and determined to ensure the geometric coherence of the entire project. This will then be transferred to the accelerator area, where an internal geodetic network will be determined.

Each accelerator component is then equipped with external references. These are measured to be representative of the component's geometry in a process known as fiducialisation, which generally takes place in the laboratory or workshop.

At the same time, the beam optics is determined by the physics teams and the theoretical trajectory is calculated. This will provide the theoretical positions at which the components will have to be located.

In the accelerator area, the components are aligned to their so-called absolute position using the

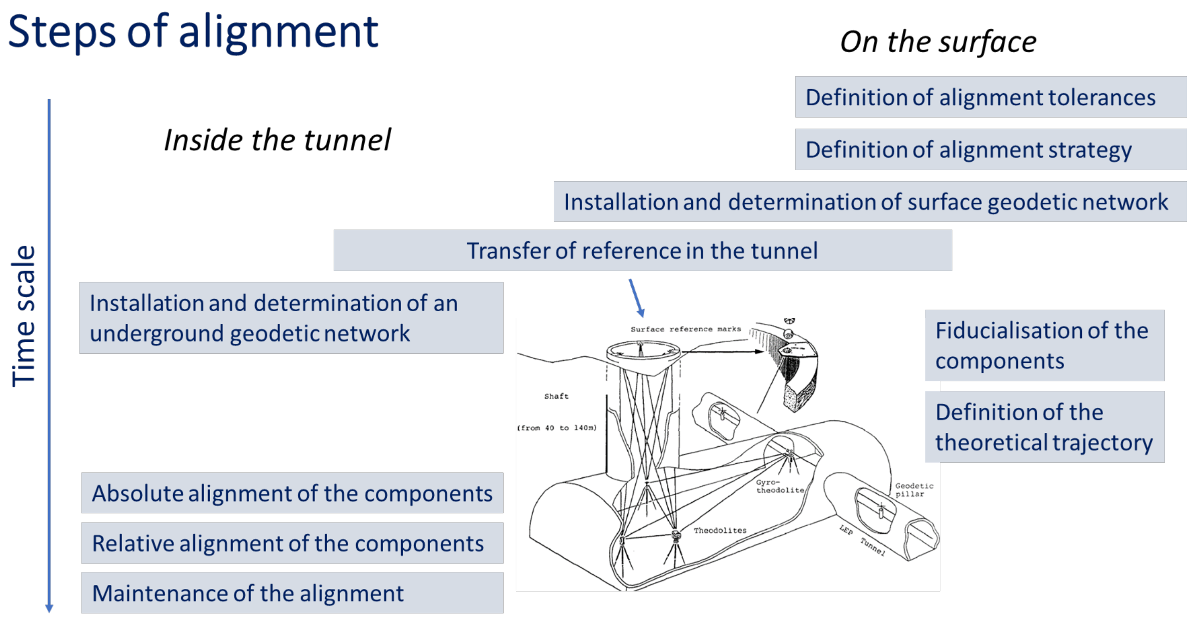


Fig. II.11.5: Alignment steps for a particle accelerator project.

internal geodetic network, and then adjusted in relative position to obtain a smooth machine. Once the accelerator is in operation, its alignment will be regularly maintained.

II.11.3.2 Definition of the alignment requirements

Figure II.11.6 lists the error budget for the LHC dipole magnets at CERN, and shows that alignment and positioning requirements are derived from a global error budget containing contributions from several disciplines, such as geodesic metrology, mechanics, cryogenics and vacuum.

These alignment requirements, which can vary significantly from one project to another, are of two types. The absolute positioning requirement that indicates how much the actual shape of the machine may differ from the theoretical shape is illustrated in Fig. II.11.7 (left). For the LHC at CERN, this difference is around $3\,\mathrm{mm}$ per $3\,\mathrm{km}$. The relative alignment requirement that specifies the maximum deviation of a component from its neighbors, as shown in Fig. II.11.7 (right), are generally significantly smaller than the absolute positioning requirements. It is commonly expressed as an uncertainty at $1\,\sigma$ level within a sliding window of a given length. For the LHC, this uncertainty is $0.2\,\mathrm{mm}$ at the level of the component reference marks in a $150\,\mathrm{m}$ sliding window. For the CLIC project, one of the challenges is to maintain an alignment at the level of the axis with an uncertainty of $14\,\mathrm{\mu m}$ for beam position monitors (BPMs) and accelerating structures (ASs), and $17\,\mathrm{\mu m}$ for MQB quadrupoles, within a $200\,\mathrm{m}$ sliding window [11].

II.11.3.3 Alignment strategy definition

The definition of an alignment strategy at an early stage is an important step of the geodetic metrology for particle accelerators. As illustrated in Fig. II.11.8, this choice is guided by factors that will be refined along the preparation phase in order to find the best compromise between cost and performance: the

Alignment errors table for the Dipoles *All r.m.s. values, in mm.*		(i) Mean (mm) In the plane of the fiducials	(ii) Ends (mm)	%	(iii) Correctors (mm)
Cold mass construction	Mean magnetic axis/ideal geom. axis	0.1 (1)			
	Auxiliary fiducials / ideal geom. axis	0.2 (1) (2)	0.2	6.2%	
	Magn. axis / Spool pieces fiducials				0.1
	Magn. axis of spool pieces / ideal geom. axis of the dipole				0.2
	Cold bores / ideal geom. axis of the dipole	0.33 (2)	0.1	1.6%	
Beam screen	Beam screen / cold bore axis	0.3 (2)	0.3		
Cold mass in the cryostat	Thermal effects on the cold posts	0.1 (1) (2)	0.2	6.2%	0.2
	Ovalisation and straightness of the cryostat	0.2 (1) (2)	0.4	24.9%	0.4
	Mesures of the fiducials / ideal mean axis	0.1 (1) (2)	0.2	6.2%	0.2
	Adjustment of the central post	0.2 (1) (2)	0.2	6.2%	0.2
positioning in the tunnel	Radial pos. of the fiducials / theoretical orbit	0.28 (1) (2)	0.56	48.7%	0.56

(i) (1)	Mean magnetic axis / theoretical orbit	0.48 mm r.m.s.
(i) (2)	Mechanical aperture limitation in the dipole	0.65 mm r.m.s.
(ii)	Mechanical aperture limitation at the ends without beam screen	0.80 mm r.m.s.
(ii)	Mechanical aperture limitation at the ends with beam screen	0.86 mm r.m.s.
(iii)	Magnetic axis of the correctors / theor. orbit	0.80 mm r.m.s.

Fig. II.11.6: Alignment error budget for LHC dipole magnets.

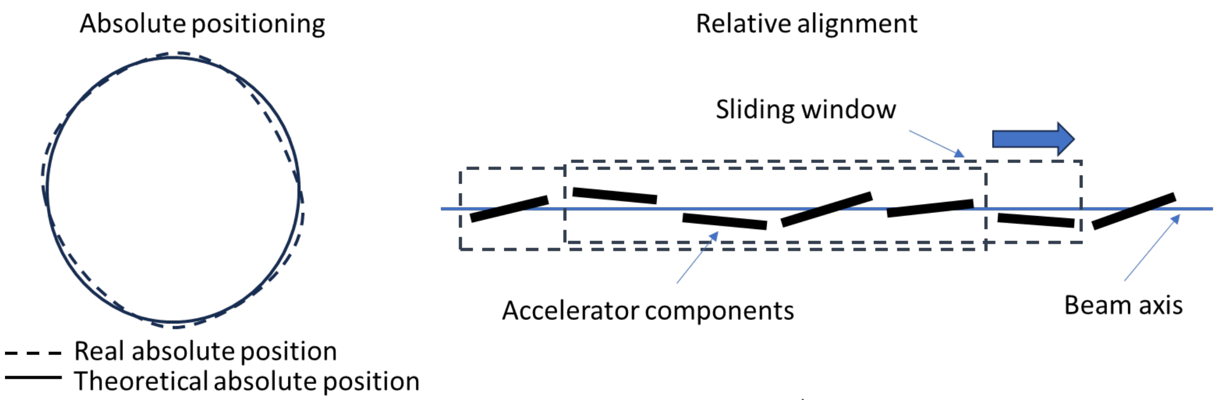


Fig. II.11.7: Sketch illustrating the difference between the real and theoretical position of an accelerator after alignment (left), and the relative alignment of accelerator components in a sliding window representing the relative alignment requirements (right).

general characteristics of the accelerator project; the general environmental constraints in the machine and experimental areas such as location, access, space available, harshness of the environment, thermal stability, stability of the tunnel floor and ground; the design of the components and the supporting structures to be aligned; the beam requirements comprising the specifications for alignment accuracy; the alignment methods and instrumentation that are available or have to be developed; the project constraints (schedule, cost, resources, operation and maintenance time). The strategy can influence the design, the integration model (related for example to needs of free lines of sight, equipment installation, cabling), the budget (resources, instrumentation purchase, R&D) and the planning.

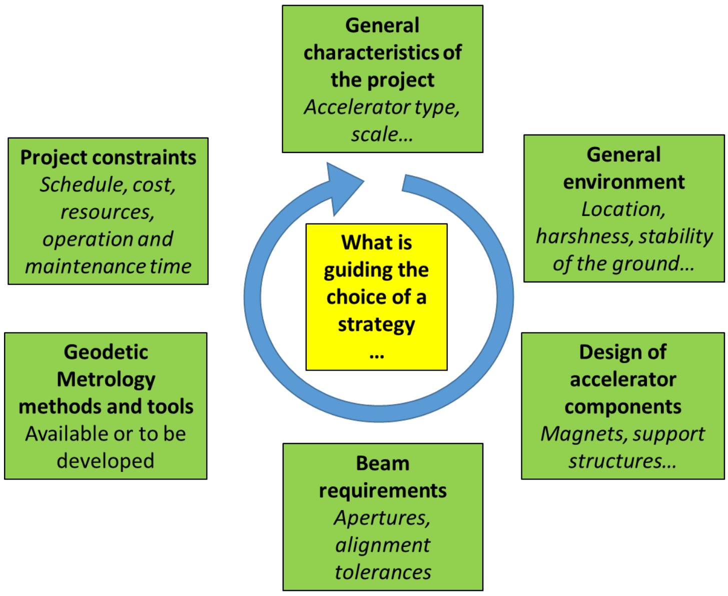


Fig. II.11.8: Schematic view of the alignment strategy definition process.

II.11.3.4 Installation and determination of the surface geodetic network

Before the civil engineering team starts digging, a network of surface geodetic control points is established in order to allow the various trades to work within a coherent framework throughout the lifespan of the accelerator. This network consists of marked reference points such as concrete pillars known as monuments, levelling markers, and GNSS antennas forming the permanent station network.

II.11.3.4.1 Definition of the Geodetic Reference System and its initial determination

The definition of the geodetic reference system in which the coordinates of the network points will be given depends on several factors. The size of the project, ranging from a few tens of meters to nearly $30\,\mathrm{km}$ for the FCC project (a new circular machine $80\,\mathrm{km}$ to $100\,\mathrm{km}$ long), requires different choices to be made regarding the modelling of the Earth's geoid or the long-term stability of the work area. This guides, for example, the type of reference framework to be defined (static and/or dynamic).

Inter-compatibility with national legal reference systems, especially for projects such as those at CERN that cross a border, is also an important factor to be considered to simplify surface topography and civil engineering work, as well as the referencing of existing GIS data.

The initial determination of the coordinates for each point in the geodetic reference system is obtained by combining several types of observations, including spatial geodesy measurements (GNSS), gravimetry, direct levelling, trigonometry (angle and distance observations), and astronomical measurements (vertical deviations, astronomical orientation and positioning).

II.11.3.4.2 Surface geodetic network coordinates monitoring and upgrade during operation

During the operational phase, network remeasurement campaigns can assess the stability of each site, and even define a displacement model (vectors and displacement velocities). The observed displacements can be caused by geological movements of varying magnitudes, ranging from a single city block to an entire region. In this regard, the InSAR technology will soon allow better refinement of the analysis. This technology, based on the interferometric analysis of satellite radar images, enables geological movements to be mapped on a local scale (typically a few hectares) with precision at the mm level. It can greatly facilitate the qualification of potential host sites.

Regarding the stability of GNSS antennas, the analysis of the time series of position in the early years of operation assesses the stability of each site.

Based on the results obtained, a new version of the reference system can be calculated. In that case, transferring the new coordinates to underground machine requires a vertical descend campaign.

II.11.3.4.3 Maintenance of the geodetic network infrastructures

The geodetic network must be maintained throughout the lifespan of the accelerator. Concerning the permanent stations (GNSS network), maintenance mainly consists of hardware renewal. For example, it is necessary to replace coaxial antenna cables before UV and weather conditions degrade the quality of transmission of the signal.

The marked points must be protected against damage caused by exposure to outdoor conditions mainly corrosion. Applying an exterior paint preserves the integrity of the concrete. As for sealed markers, usually made of brass, they are protected from oxidation by a cover, the presence of which must be checked regularly.

II.11.3.5 Definition of the theoretical trajectory

The accelerator elements are aligned to the beam trajectory according to the positions defined by the models of beam optics produced by the physics teams.

At CERN, these models are established using MAD-X (Methodical Accelerator Design, version X) software, which provides the beam trajectory in a local system, the location of the accelerator elements along it, and their orientation. The software also delivers the theoretical absolute geometrical position of the accelerator components in the CERN Coordinate System (CCS) once it has been fed with the point of origin and the initial direction in this system. To be more precise, the theoretical location of each component is expressed by the CCS coordinates of the so-called beam reference points named E and S. These non-materialised points, E and S, on which the survey teams base their alignment, respectively correspond to the positions of the entry and exit on the mechanical or magnetic axis of each component, at its upstream and downstream ends.

II.11.3.6 Fiducialisation of the components

Most of the axes of the accelerator components, such as the magnetic axis, are not physically constructed. Nevertheless, they must be aligned along six degrees of freedom.

Since the active reference surfaces of the components (septum blades, magnet laminations, etc.) are no longer accessible after the component's installation, it is necessary to determine a new set of visible fixed reference points on the outer surface of the component. During a dedicated transfer measurement, these reference points, known as fiducials, are determined with respect to the functional reference surfaces or the magnetic axis of the components. This geometric measurement, known as fiducialisation, is usually carried out in a workshop. Fiducialisation is required for all equipment whose precise alignment parameters must be determined, and is often combined with dimensional manufacturing controls.

To this aim, a local reference system for each component, called the RST system, is defined as follows (see Fig. II.11.9): the origin is the beamline point E of the element; the beamline lies in the median plane of the element; the S-axis passes through the beamline points E and S of the element and is positive in the E to S direction; the R-axis is perpendicular to the S-axis, lies in the median plane of the element, and is positive to the right when looking from E to S along the beamline; the T-axis is perpendicular to the median plane of the element and forms a right-handed system with the R-axis and S-axis.

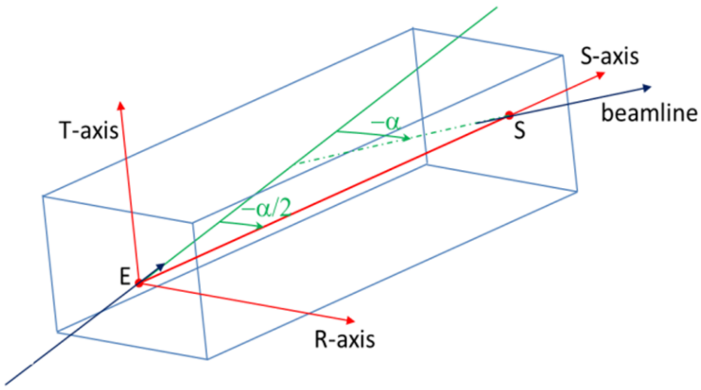


Fig. II.11.9: Illustration of the RST local coordinate system of a dipole magnet.

The axes of a component can be materialised using various techniques such as mechanical moles, rotating wires or stretched wires. Fiducialisation consists of the combined determination of these axes and of the component's fiducial marks, in the same coordinate system, based on measurements carried out using instruments such as mechanical gauges, three-dimensional coordinate measuring machines or laser trackers [12].

Once the fiducial positions are known in this RST-system with respect to the active part of the equipment, the latter will be adjusted to its theoretical position along the trajectory as defined by the beam optics calculations. For larger components (typically horizontal deflection magnets in the arcs of a circular collider), the impact of thermal expansion of the materials must be taken into account and compensated for. For this reason, fiducialisation measurements must be carried out in a controlled environment.

II.11.3.7 Transfer of reference from the surface to the inside of the accelerator area

The geodetic reference system defined on the surface must be extended to the accelerator areas. In case of underground installations, this transfer to the tunnel is performed through access shafts. This step, illustrated in Fig. II.11.10, is referred to as vertical drop. The depth of the shafts directly affects the uncertainty of the points determined underground. Several methods exist to perform this geometric transfer, but the combination of several techniques provides the necessary redundancy for an independent control.

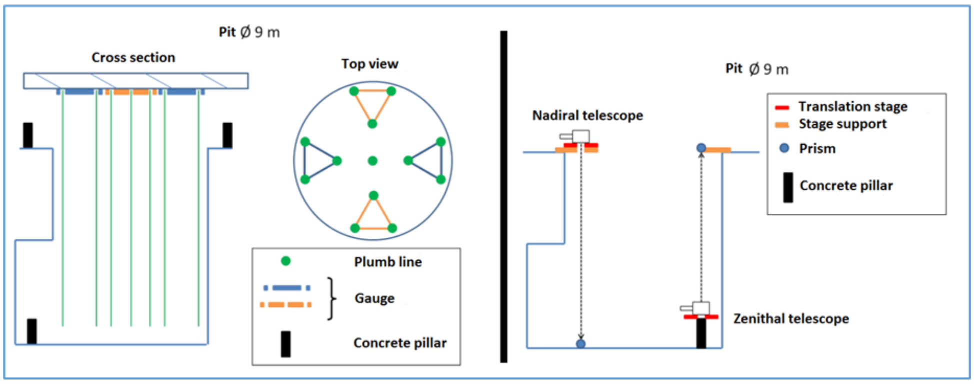


Fig. II.11.10: Illustration of the vertical drop for the transfer of the geodetic network from the surface to the tunnel.

II.11.3.7.1 Transfer of planimetry

The simplest and fastest method to transfer planimetry is the nadir-zenith telescope. Measurements can be taken either from the surface (nadir telescope) or from the tunnel (zenith telescope), although it is often easier to measure the targets from the bottom of the shaft. The target is typically a LED centred in a holder, usually a spherical target. The telescope is mounted on a translation base plate, allowing the adjustment of its position along the vertical passing through the target. The positions of the targets and stations are determined by conventional surveying methods.

As an optical method, this technique is impacted by the variations of the refractive index along the line of sight. Visibility must be as good as possible. The accuracy decreases as distance increases. Nadir-zenith telescopes have a relative precision of approximately $1 : 200000$, i.e. $0.5\,\mathrm{mm}$ / $100\,\mathrm{m}$ (excluding variations in the refractive index along the line of sight). Repeating independent determinations within the same shaft allows validation of the results.

The mechanical method, known as "plumb lines", is not affected by the refractive index but is impacted by the air circulation within the shaft. The setup consists of a set of weighted wires, suspended in the access shaft. The stability of each wire is ensured by an oil bath in which the weight is immersed. The weights are equipped with fins to increase friction with the liquid. The wires are observed and intersected on the surface and in the tunnel from several stations by optical measurements. The accuracy of the position determination mainly depends on the quality of the spatial intersections. It is to be noted that the rotation of the Earth around its axis also affects the orientation of the wires in the East-West direction (due to centrifugal force). This must be compensated for.

A third method, also mechanical, is less common since it is more challenging to implement. It consists of measuring the point of impact of a steel ball released from its suspension created by an electromagnet at the top of the shaft. The position of the impact point needs to be corrected for the rotation of the Earth. The accuracy can be significantly degraded in case of air currents during the fall. Series of measurements allow the repeatability of the system to be estimated.

II.11.3.7.2 Influence of vertical deflection

The methods described above are all affected by vertical deflection. Indeed, the installation of the nadir-zenith telescope is done according to the local vertical, as well as the suspension of a pendulum, or the falling of an object in the Earth's gravitational field. Corrections must be applied accordingly. Knowledge of the geodetic orientation (i.e. the direction of geographic North) is necessary to calculate corrections in both North-South and East-West directions. It is important to note that the vertical deflection must be known at the altitude of the instrument, i.e. at the bottom or top of the shaft (depending on the configuration). While the geoid models easily determine the vertical deflection on the Earth's surface with an accuracy of about $0.2\,\mathrm{mgon}$ (i.e. about $0.3\,\mathrm{mm}$ at a depth of $100\,\mathrm{m}$), the estimation of the vertical deflection at the bottom of the shaft of an underground accelerator is derived from the surface deflection values, corrected by a model of rock density. Thus, the respective accuracies of the geoid and the mass density model have a direct influence on the accuracy of the vertical drop.

II.11.3.7.3 Transfer of altitude

The transfer of altitude from the surface to the tunnels requires the measurement of spatial distances and vertical angles. This is quite a simple step performed from the bottom of the shaft using a tacheometer with an inclined eyepiece or a laser tracker if the depth is within its measurement range. Targets are installed at the top of the shaft, typically the same points used during the planimetric alignment measurements. Collecting the horizontal angles also allows for planimetric determination of the points. This is another cross-check of the results obtained using the methods described above, although the associated accuracy is lower due to the lines of sight being close to vertical.

II.11.3.7.4 Calculations and results validation

All measurements collected from the described techniques, with an appropriate level of redundancy to allow their control, are calculated using least-squares adjustment. The analysis of the results and the comparison of the transferred geometry from one shaft to the next allows for uncertainty evaluation. Previously collected data shows that an uncertainty of $0.2\,\mathrm{mm}$ at $100\,\mathrm{m}$ in altitude and $0.5\,\mathrm{mm}$ at $100\,\mathrm{m}$ in planimetry can be achieved.

II.11.3.8 Installation and determination of a geodetic network inside the accelerator area

The underground geodetic networks consist of a dense set of monuments, preferably installed in the floor or on the walls. They are generally made up of a combination of reference points that are known either in altitude (1D) or in space (3D). Unfortunately, the long and narrow configuration of a tunnel network is quite unfavourable from a geometric point of view. Furthermore, for optical observations, the proximity of walls can also expose lines of sight to a risk of refraction in addition to that due to the vertical temperature gradient.

The 1D deep levelling references are distributed throughout the tunnels. They consist of rods made of a material with a low or well-known thermal expansion coefficient, that are sealed onto stable rocks, with a mechanical interface at their end located just below the floor level and totally independent from it (see Fig. II.11.11).

The 3D geodetic network consists of supports, tripods and reference points installed below the surface of the ground and additional nests fixed to the vault in which spherical targets, generally 1.5 ” in diameter, can be installed during measurement (see Fig. II.11.11 and Fig. II.11.12).

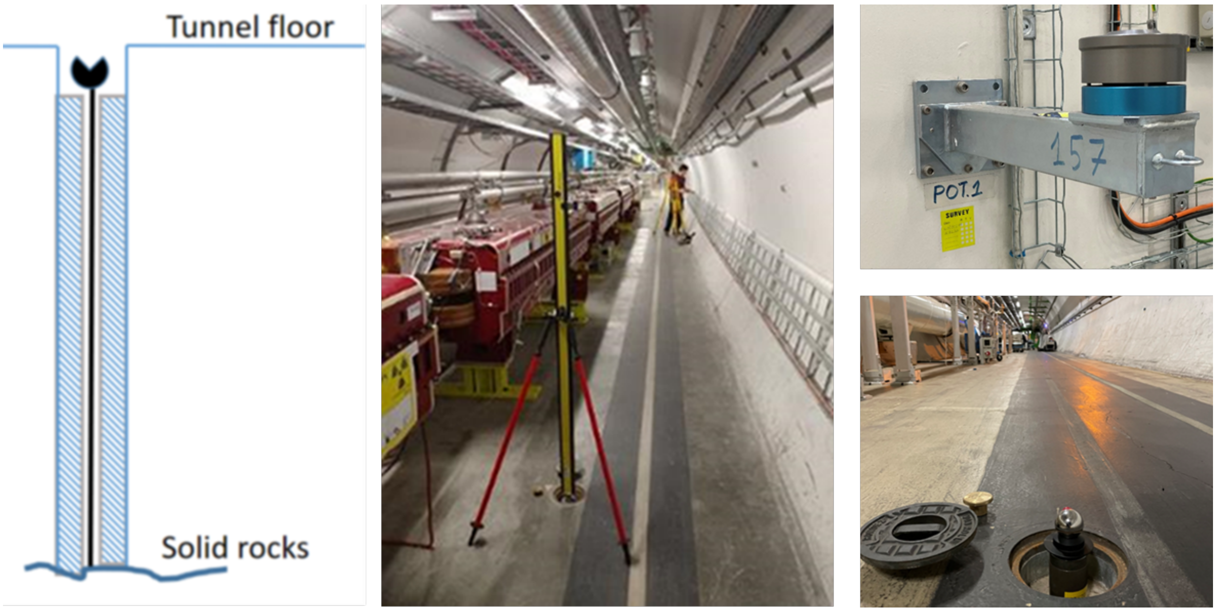


Fig. II.11.11: Geodetic network references in CERN tunnels: the two images on the left show the principle of the 1D deep reference and a levelling work with the levelling rod placed at the top of the deep reference; the two images on the right show examples of 3D references, a plug-in bracket (top right) and a GGPSO reference sealed in the floor equipped with a spherical target (bottom right).

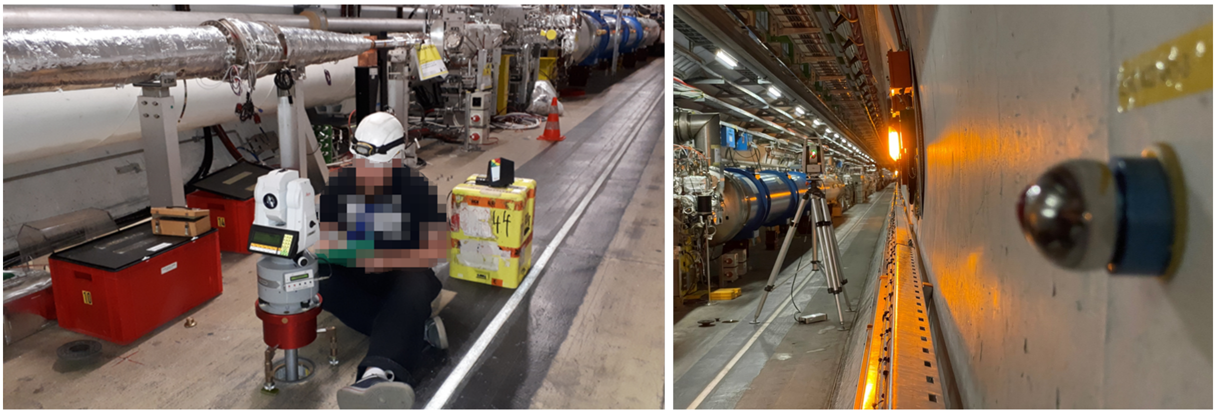


Fig. II.11.12: Measurements of the geodetic network in the LHC at CERN: observations using a gyro-theodolite to accurately determine the direction of North (azimuth) on the left-hand side, observation of a spherical target placed in a reference nest using a laser tracker on the right-hand side.

Several means are proposed to determine these networks. Most of the time the coordinates of their points are the result of least-squares adjustments of multiple measurements such as optical direct levelling observations and polar observations from total stations, laser trackers or gyro-theodolites as shown in Fig. II.11.12. The aim is to reach: an accuracy of the absolute position of 3–4 mm along 3 km;

an accuracy of the relative planimetric position between three consecutive monuments of $0.3\,\mathrm{mm}$ by adding wire offset measurements; and an accuracy in difference of altitude between three consecutive monuments of $0.1\,\mathrm{mm}$.

II.11.3.9 Absolute alignment of the accelerator components

Absolute alignment of equipment, see Fig. II.11.7 (left), consists of adjusting newly installed components or support systems to their theoretical absolute position and orientation in the main coordinate system, known at CERN as CCS. The theoretical position and orientation of components are derived from the transformation of the theoretical trajectory given by the beam optics in this system.

3D polar instruments, such as laser trackers or total stations, are usually used to achieve this absolute alignment. The instrument is located using several reference measurements of the geodetic network.

In general, the geodetic network references located inside the accelerator area, and consequently the absolute coordinates of the aligned components, are known in the main geodetic system to an accuracy of the order of a few mm due to the multiple transfers of geometry from the surface.

Once all the equipment has been installed and aligned to the initial theoretical position, the next step, known as smoothing, can start.

II.11.3.10 Relative alignment of the accelerator components

Although the accelerator components have been aligned to their so-called absolute position, deviations exceeding the alignment requirements between consecutive components may still remain. The aim of the smoothing activity is to prioritize the trajectory aspect by minimizing the relative offsets between adjacent components.

Over a given window length, the curve - usually a polynomial of a suitable degree - that best fits all the components, is defined. The position of components whose vertical and radial (in the horizontal plane) deviations from the smooth curve are greater than the relative alignment requirements is then adjusted. The window, known as a sliding window, is then moved along the beamline, in principle by the length of a component as illustrated in Fig. II.11.7 (right), and the same work is carried out.

This process is iterative. After the displacement of the components, a new position measurement is performed on the area concerned, and a new calculation is made. If unacceptable offsets are detected, new adjustments are carried out.

For example, in the case of the LHC at CERN, the relative alignment requirement is $\pm 0.2\,\mathrm{mm}$ at $1\,\sigma$ level within a sliding window of $150\,\mathrm{m}$ along the beam. To define the smooth curves and the adjustments to be applied, a CERN in-house surveying data processing software, Rabot, is used. It also allows the sliding windows to be defined in terms of distance or in terms of number of significant components. An illustration of a vertical smoothing process step in the LHC at CERN is shown in Fig. II.11.13.

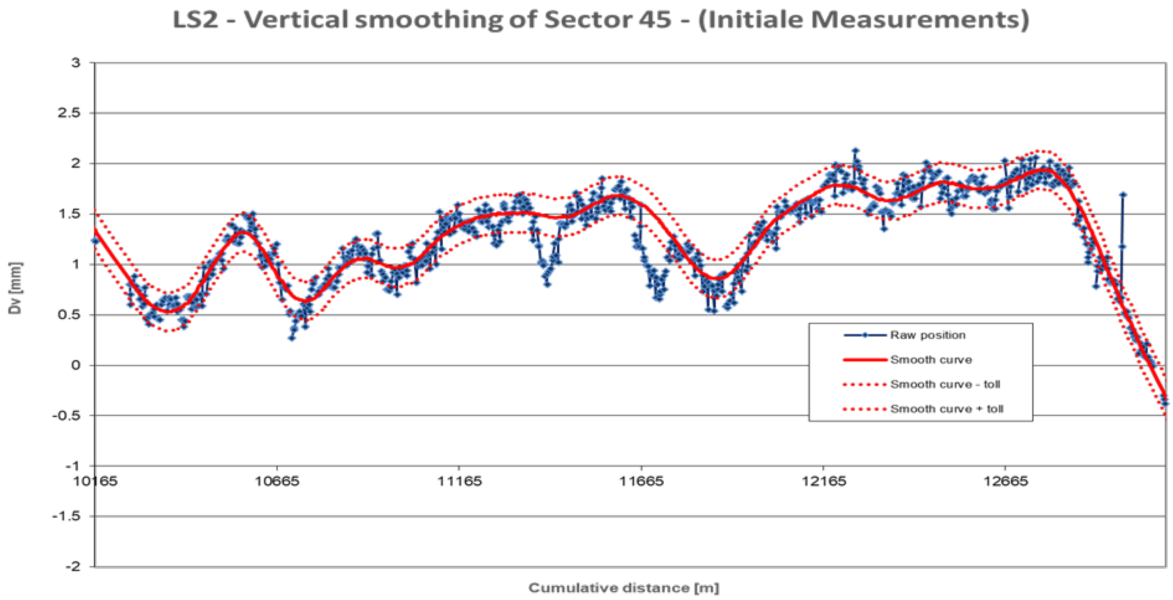


Fig. II.11.13: Graph of the vertical smoothing of sector 4-5 in the LHC at CERN. The blue dots give the initial vertical position of the accelerator components measured before their adjustment. The red solid line represents the best-fit curve and the red dashed lines the relative alignment requirements.

II.11.3.11 Maintenance of the alignment

The Earth's crust is in non-uniform perpetual motion. For example, the stability and behaviour of tunnels are not homogeneous. At CERN, some areas are known to be highly unstable, such as the middle of sector 7-8 at the LHC, where an annual vertical displacement of $1.5\,\mathrm{mm}$ has been detected due to a geological fault. In addition, mechanical constraints, forces due to vacuum, and temperature gradients can generate misalignments.

The frequency of the accelerator alignment maintenance work depends on several factors, such as: the mechanical stresses applied to components; the alignment accuracy specifications; the beam aperture requirements; and the ground motions.

At CERN, the maintenance of the alignment of the components in the accelerator complex and transfer lines is performed during the technical stops, the year end technical stops and the long shutdowns. In addition, sensitive areas are regularly monitored to collect data and analyse movements over a long period.

II.11.3.12 Particular case of the machine detector interface areas

The machine detector interface (MDI) areas are located at the junction of an accelerator and a physics experiment. It is here that the link and consistency between the alignment geometries in the machine and experiment zones are established. In colliders, this is also where the relative alignment and orientation of the accelerator elements placed on either side of the experimental zone is achieved, with no direct visibility possible. Note that the position of the interaction point (IP) of the beams depends on the alignment of the accelerator in these MDI zones.

In the case of the MDI areas of the LHC at CERN, permanent monitoring systems make it possible to continuously measure the alignment of triplets of quadrupoles located on either side of the experimental zones with an accuracy of the order of a tenth of a mm. To ensure that the IP is located at the centre of the experiment, the consistency of alignment between the experiment and the accelerator must also be guaranteed. To do this, the same monitoring systems provide the position of several reference points in the vicinity of the experimental cavern. These will be used to ensure the link between the geometry of the machine and that of the tridimensional geodetic network used to align the detectors and their infrastructure. The LHC experiments are made up of hundreds of detectors and sub-detectors that can reach dimensions of several tens of metres and weigh several hundred tonnes. They are often considered as fixed points of passage for the machine. As a result, smoothing work sometimes requires going a long way back into the machine to obtain relative alignment of the accelerator components within requirements. It is in the MDI zones that the geodetic reference points that are common to the machines and experiments, and considered to be fixed, are located and monitored.

II.11.4 Instrumentation toolkit

Geodetic metrology is largely based on dimensional measurements made either using standard geodetic and surveying techniques or using less conventional technologies developed specially to meet unusual alignment accuracy requirements.

II.11.4.1 Standard instrumentation and techniques

A number of geodetic measurements are carried out using standard, high-precision, commercially-available instruments, together with advanced calibration and methodologies to exploit their performance to the limit.

II.11.4.1.1 Optical level

Levelling is the measurement of the height difference between two points. The most typical instrument used is the optical level. An optical level consists of a high-quality telescope with a crosshair for pointing at a target. In combination with a spirit level, a horizontal plane can be established as the reference for the measurement. In most state of the art levels, the high precision spirit level has been replaced by a compensator, based on a suspended optical element, that ensures the line of sight is horizontal. In this case, only an approximate setting of the level is necessary to get within the working range of the compensator using a simple circular spirit level. Additional stadia marks on the crosshair can be used for an approximate distance measurement. High precision levels can have an additional plane-parallel plate, adjustable with a micrometer, to increase the measurement precision by one order of magnitude.

In most cases, a levelling staff is used and placed vertical as the target. Levelling staffs exist in different models that can have a centimetre graduation or a barcode for automatic measurements. The standard length of the staff is $2\,\mathrm{m}$ or $3\,\mathrm{m}$. Invar staffs are used for precision measurements. The procedure in field starts with the installation of the instrument on a tripod and the setting of its circular spirit level at the centre to be within the working range of the compensator. The operator measures the first point, backsight, on the levelling staff placed vertical by an assistant and registers the value. The assistant then places the levelling staff on the next point to be measured and the foresight reading is registered. The difference in the readings corresponds to the height difference between the points (see Fig. II.11.14).

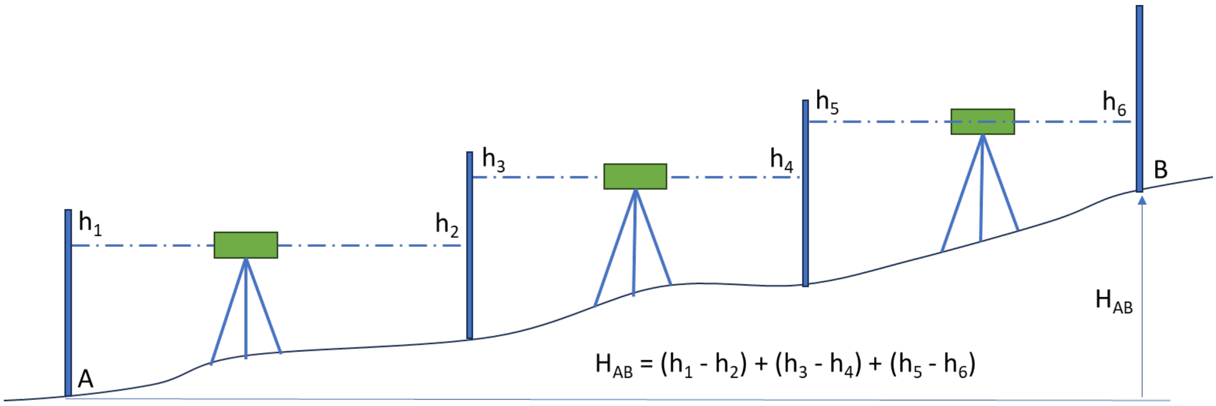


Fig. II.11.14: Optical leveling: principle of measurement of the height difference $\mathrm{H_{AB}}$ going from A to B.

To control the measurement, and to increase the accuracy, a procedure called double levelling has been established as standard, where two backsight and two foresight readings are taken. The typical accuracy for a $1\,\mathrm{km}$ double levelling can be estimated to be at the level of $0.3\,\mathrm{mm/km}$ when a precision instrument and invar staffs are used. To obtain precise results, a regular control and adjustment of the instrumentation is necessary and equal distances for the backsight and foresight are recommended.

II.11.4.1.2 Total station

A total station is a surveying instrument used for the measurement of polar coordinates based on the measurement of the vertical angle, the horizontal angles and the slope distance between the instrument rotation centre and a specific point. It's the logical successor of the theodolite that could measure angles exclusively. Nowadays, electronic and motorized total stations have been established as standard and are widely used. The instrument is remotely controlled by the operator, but it can also be used in manual sighting using the telescope with a crosshair to point on the observed target. Typically, the measurements are done on discrete points, usually signalised by a retroreflector, which demands a direct line of sight between the total station on the point for a successful measurement. The data acquisition uses internal memory and programs or an external computer that can be used in parallel for the data analysis.

Even if total stations are most commonly used for land surveying and construction sites, these instruments have been used intensively for the alignment of accelerators and experiments as the LHC at CERN. An actual model can for example measure up to $3500\,\mathrm{m}$ with an angular accuracy of $0.15\,\mathrm{mgon}$ and $0.6\,\mathrm{mm}\ \pm1\,\mathrm{ppm}$. The accuracy of the distance measurement can be increased by an additional calibration, typically up to $100\,\mathrm{m}$, to be better adapted for the accelerator alignment.

The angle measurements of a total station are based on highly precise glass circles that are scanned by an opto-electronic system. The distance measurement is based on a modulated infrared signal that is reflected by the corner cube reflector. The precise distances are calculated using multiple frequencies and a phase shift approach. Modern instruments often provide the possibility to measure distances on natural surfaces without a dedicated reflector. In this case, the measurement range is significantly reduced as well as the accuracy of the measurement.

II.11.4.1.3 Laser tracker

The laser tracker is another polar measurement system that is considered as a standard metrology tool for the measurement of medium to large parts in industry and accelerator alignment. A laser tracker has an incredible flexibility with an instrument weight of only 8 to 15 kg plus accessories. In comparison to previous systems, the measurement accuracy could be improved while the measurement time could be significantly reduced. Spherical Mounted Retroreflectors (SMRs) of different sizes are used as measurement target and the measurement range can reach more than 100 m. The 3D measurement accuracy is typically better than 100 µm over 10 m and better than 200 µm over 30 m.

The laser tracker initial concept is very similar to the total station for the installation and the angular measurement. The distancemeter has been replaced by a high frequency absolute interferometer or an absolute distance meter (ADM) that has an accuracy of a few µm, even over several tens of meters. Certain models reach measurement frequencies up to the kHz level, which is extremely helpful for the measurement of dynamic processes. The telescope of a Total Station has been replaced by electronic components to recognize and track the SMR automatically. The motorized instrument can be entirely remotely controlled via a Wi-Fi connection.

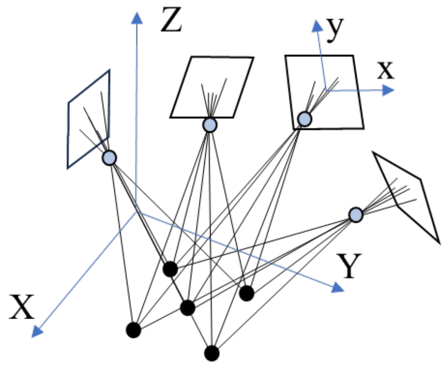
Nowadays, several extensions for the laser tracker systems are proposed by the manufacturer that combines it with dedicated accessories to execute 3D scanning tasks, robot and machine calibrations or probing with a stylus, which increases the application range of the systems. Like this, the system is able to measure not only the XYZ-coordinates of a single point but all six degrees of freedom of an object.

Laser Trackers are used for the fiducialisation of accelerator components and detector parts. At several research institutes these instruments are the first choice for the measurement and alignment of the complete accelerator complex. For large and very large accelerators, such as SPS and LHC at CERN, a measurement solution exclusively based on laser tracker measurements is not recommended as the configuration of tunnels and refraction have a negative influence on the measurement accuracy over long distances. It is unfeasible to satisfy the alignment specifications of these accelerators solely based on laser tracker measurements.

II.11.4.1.4 Photogrammetry

Photogrammetry is a technique that allows the shape and location of an object to be determined from several photographs taken from different viewpoints [13]. The photogrammetry is used as arial photogrammetry for the production of maps and digital terrain models, and is used as close range photogrammetry for architecture and industrial applications (see Fig. II.11.15). The typical purpose of a photogrammetric measurement is the 3D reconstruction of an object by measured points. A photo reduces the 3D space to a 2D space, but multiple 2D photos permit a reconstruction of the 3D space that is covered in the images.

The mathematical model for the 3D reconstruction is based on central projection. The shape and position of an object can be reconstructed by a bundle of rays passing from the measured points in the image plane and the projection centre of the camera. The intersection of rays from different photos for a corresponding point calculates the 3D coordinates by triangulation. The scale of the measured object is introduced by one or more distances known in the object space, for example by calibrated scale bars, that are placed and measured in the object space. In addition to the 3D coordinates of the points, the camera positions and rotations, also called exterior orientations, have to be determined. Another fundamental set of parameters that needs to be calculated is the inner orientation that includes the camera geometry, image coordinate definition and parameters to define the distortion correction. The resolution of all parameters is combined in a single large equation system, which is called bundle adjustment.



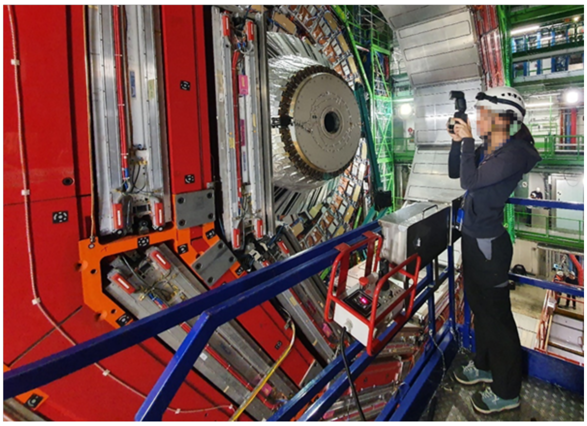


Fig. II.11.15: Close range photogrammetry principle (left). Photogrammetry data acquisition in CMS detector at CERN (right).

When the close range photogrammetry is applied in industrial fields, such as particle accelerators and detectors, high precision targets or signalised points are generally used. At CERN the interfaces are typically 8H7 reference holes or 0.5 inch nests that can be equipped with dedicated targets. The measurement of signalised points permits an increase of accuracy in comparison to the measurements of natural points without any signalisation. Additionally, this facilitates a combination with other measurement systems.

The accuracy that can be reached with systems for industrial photogrammetry depends on the size of the object and the quality of the camera system. Relative precision of $1{:}100000$ and better can be reached. The photogrammetry has several advantages in comparison to other measurement systems. The system can be highly automated using coded targets and image processing algorithms, it's a non-contact technique that can acquire many points in a short time and in addition, the photos can be taken hand-held and a stable support, such as a tripod, is not needed, which increases the flexibility.

II.11.4.1.5 Roll angle measurement

Adjusting the rotation of accelerator components around the beam axis, known as roll angle adjustment, is an integral part of the alignment process. This is because the accelerator components must be installed and tilted in relation to the plane of the machine as defined by physics. For this purpose, most components have an external reference surface, known as the roll surface, defined with respect to the internal reference plane of the equipment. Components without a roll surface are equipped with at least a third fiducial mark, properly arranged to form a plane.

The roll angles are measured using tiltmeters (see Fig. II.11.16) or determined using the fiducials on the components.

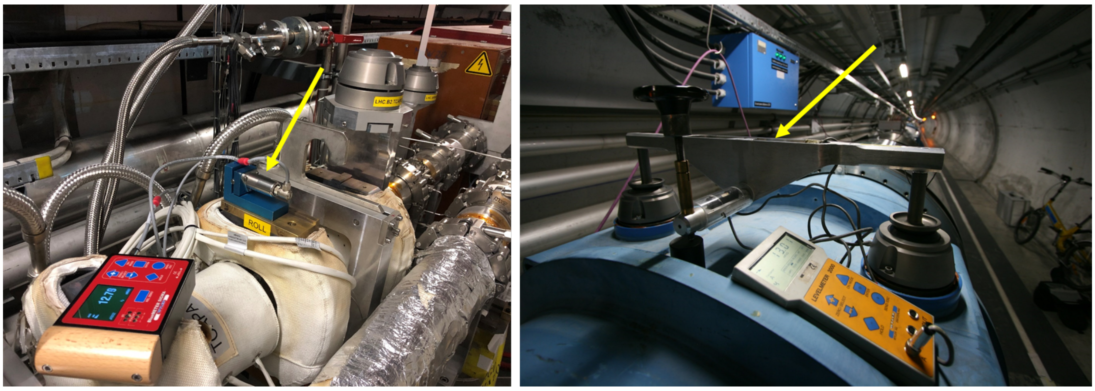


Fig. II.11.16: Measurement of the roll angle in the LHC at CERN using a tiltmeter placed on the tilt reference surface of a collimator on the left-hand side and on fiducials of a cryo-magnet using an adapter on the right-hand side. Arrows show the sensitive part of the tiltmeters.

II.11.4.2 Specific alignment systems

At CERN, the accelerator complex consists of a huge variety of components, from different epochs, of varying sizes and weights, installed in different areas, and with alignment requirements ranging from a few µm to a few mm. Specific methods and tools have been developed to meet these very particular requirements, which are presented in the following sections.

II.11.4.2.1 Offset to a stretched wire

The measurement of offsets to stretched wires is a very specific technique used at CERN and is still one of the most accurate techniques for long, narrow geometrical configurations such as the one found in accelerator tunnels.

The strategy is based on a simple temporarily stretched wire, approximately parallel to the accelerator components. In most cases, this is a simple 0.2 mm diameter fishing wire. To increase the tension and minimise the sag, a wire made from a high-tech fibre called Vectran can also be used. The wire is anchored to the machine elements over a distance of 120 m and stretched under a tension of approximately 15 kg. The wire is then used as temporary reference for straightness (see Fig. II.11.17). The only constraints regarding this wire are that its projection in the horizontal plane must be a straight line and that it must be stable throughout the measurement sequence. The horizontal offset of all the machine's components can then be measured with respect to this straight reference. After measurement and control, the wire is repositioned along the beamline, maintaining a 50 % overlap with the previous measurement location to ensure the necessary level of redundancy.

The offset measurement device is a modified digital calliper (see Fig. II.11.18, left), typically 1 m long, which is inserted and fixed in the magnet fiducial. The sliding part is equipped with an optical telescope enabling the operator to point the wire precisely (see Fig. II.11.18, right). It can rotate around

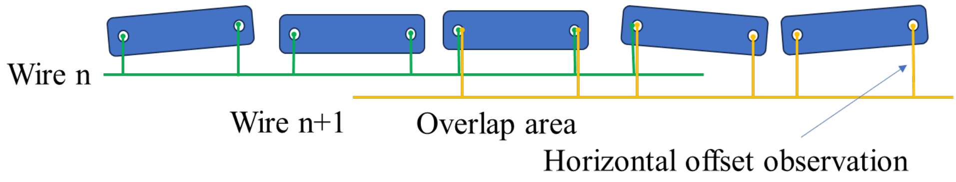


Fig. II.11.17: Principle of offset to a stretched wire measurement, top view.

the fiducial vertical axis and is adjusted in a perpendicular direction to the wire by finding the smallest distance between the wire and the fiducial.

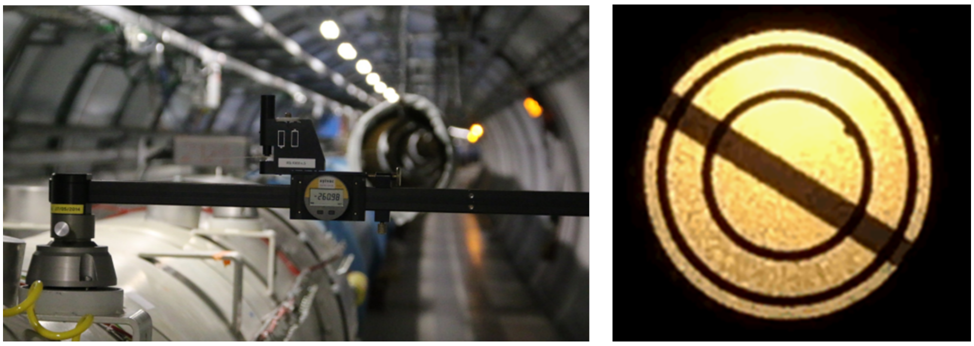


Fig. II.11.18: An offset measurement device installed on an LHC magnet fiducial at CERN on the left-hand side. The right-hand side shows the image of the wire centred in the circular reticle of the offset measurement device, as it is seen by the operator through the telescope.

With a minimum of 50% overlap between the measurement positions, the calculated accuracy of the horizontal offsets is around $40\,\mu\mathrm{m}$ when systematic effects are excluded. Using a line stretched over $120\,\mathrm{m}$, the wire offset method is about twice as good as conventional angular measurements, which have an accuracy of $1.5\,''$. This technique is used to complement classical angular and Laser Tracker measurements and clearly improves the overall geometry.

II.11.4.2.2 The hydrostatic levelling system

The hydrostatic levelling system (HLS) is used to determine the difference in height between points by taking an equipotential surface formed by a water surface as a reference. The system works on the principle of communicating vessels (see Fig. II.11.19).

A HLS consists of a sensor assembled on top of a vessel that can be connected to a water and air network. The HLS vessels must be interconnected to allow free circulation of the water and air. It is essential to ensure constant pressure at the water's surface.

There are several operating principles for measuring distance to water. Capacitive, optical, interferometric and ultrasonic technologies are the most commonly used for alignment. Capacitive technology is currently used in the HLS sensors installed in the LHC at CERN (see Fig. II.11.20).

The HLS sensor is fitted with a single electrode. The measured capacitance is translated, using Eq. II.11.3, into the distance between the electrode and the water.

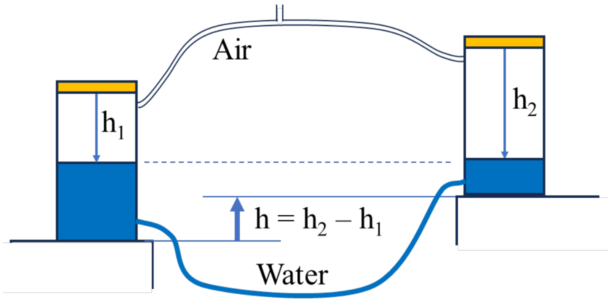


Fig. II.11.19: Hydrostatic Levelling System principle.

Fig. II.11.20: HLS sensor (Left). HLS network on top of the yellow pillars in the LHC at CERN (Right).

$$C = \varepsilon_R.\varepsilon_0.\frac{S}{d} \quad , \tag{II.11.3}$$

where C is the electrical capacitance, ε_R and ε_0 are the relative permitivity of air and the permitivity of vacuum respectively, S the surface of the electrode and d represents the distance.

The typical characteristics of an HLS system, whose principle of distance measurement to the reference water surface is based on capacitive technology, can be summarised as follows:

– Measurement range: $5\,\mathrm{mm}$;
– Resolution: $0.1\,\mu\mathrm{m}$;
– Precision (relative motion): $1\,\mu\mathrm{m}$ at $1\,\sigma$ level;
– Accuracy (position of water surface in the local HLS sensor coordinate system): $5\,\mu\mathrm{m}$ at $1\,\sigma$ level.

II.11.4.2.3 The wire positioning system

The wire positioning system (WPS) measures radial and vertical offsets with respect to a stretched wire used as a reference for straightness. The stretched wire can be modelled by a straight line in the horizontal plane and by a catenary in the vertical plane (see Fig. II.11.21) which can be approximated by a second-order polynomial with the vertical sag (see Eq. II.11.4) as a parameter

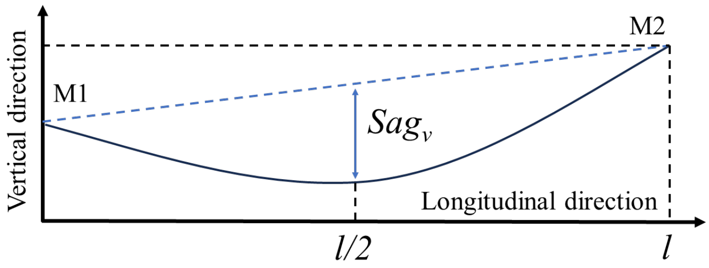


Fig. II.11.21: Illustration of the stretched wire vertical sag Sag_v in the middle.

$$Sag_v = \frac{g * q * l^2}{8 * T} \quad , \tag{II.11.4}$$

where g is the acceleration due to gravitaty, q is the linear mass of the wire, l is the length of the wire, and T is the tension applied to the wire.

The WPS sensor can be based on different technologies. Capacitive and optical technologies are the most widely used at CERN. The capacitive WPS performs the measurement with respect to a conductive wire. Each WPS sensor is equipped with a kinematic base to be mounted on a 3-ball interface (see Fig. II.11.22) creating an isostatic centring system. The local coordinate system of the WPS sensor can be defined using this 3-ball interface.

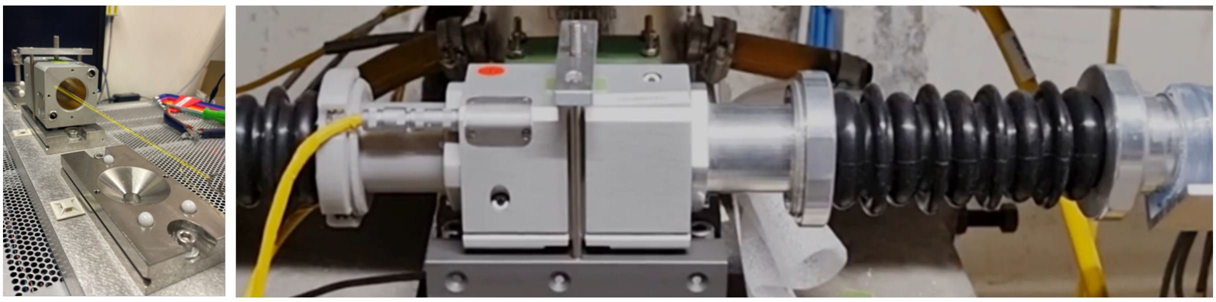


Fig. II.11.22: (Left) WPS sensor on a test bench at CERN (background) and example of 3-ball interface (foreground). (Right) WPS with protected wire in a measurement installation.

The position of the wire in this coordinate system is determined using two 5^{th} degree polynomial functions (see Eqs. II.11.5 and II.11.6)

$$X(\text{mm}) = \sum_{i=0}^{5}\sum_{j=0}^{5} a_{ij}.X_{\text{volt}}^{i}.Y_{\text{volt}}^{j} \quad , \tag{II.11.5}$$

$$Y(\text{mm}) = \sum_{i=0}^{5}\sum_{j=0}^{5} b_{ij}.X_{\text{volt}}^{i}.Y_{\text{volt}}^{j} \quad , \tag{II.11.6}$$

where X_{volt} and Y_{volt} represent the raw data of the sensor's measurement in Volt.

The main characteristics of a capacitive WPS can be summarised as follows:

- Measurement range: $10\,\mathrm{mm}$;
- Resolution: $0.1\,\mu\mathrm{m}$;
- Precision (relative motion): $1\,\mu\mathrm{m}$ at $1\,\sigma$ level;
- Accuracy (position of wire in the 3-ball interface coordinate system): $5\,\mu\mathrm{m}$ at $1\,\sigma$ level.

II.11.4.3 The position adjustment of accelerator components

II.11.4.3.1 The component adjustment solutions and systems

An alignment solution is composed of a "measurement system" such as a laser tracker, a level, or positioning sensors used to determine the position of the component, and an "adjustment system" that allows the effective displacement of the component to its nominal position, manually or remotely, within the requested accuracy.

An adjustment system is a key element for precise and stable alignments. The most important criterion is that it should be isostatic, so that it does not create stresses in the supporting and positioning elements. This can be achieved by distributing the six degrees of freedom to the different adjustment possibilities. The basis is the vertical adjustment stage which is usually done by three vertically adjustable jacks or rods. It covers the vertical translation as well as the pitch and roll rotations. On top of the vertical adjustment module, a translation unit is added that enables the last two translations and the yaw rotation to be modified. This is generally performed by using a push-pull adjustment system. It is essential that the elements are secured and rigidly fixed to the support in order to guarantee their stability over time. This is even more important if external forces, such as those due to the vacuum, are acting on the elements.

To be efficient and limit the number of iterations, it is wise to position the adjustment possibilities exactly below the fiducials of the elements. The movement performed is therefore directly correlated with the measured quantities.

II.11.4.3.2 Standard adjustment systems

Among the standard adjustment systems, there are various alternatives, which can be divided into two groups: those based on individual jacks or feet; and those based on mechanical adjustment platforms.

The main criteria here is the dimension and weight of the objects to be supported. The bigger the element, the more it makes sense to use individual jacks or feet. On the other hand, small elements will be supported by a single platform. Over the years, a number of systems have been developed to meet the different needs. Options include combined vertical and horizontal movement jacks, which are either fully mechanical or combined with an auxiliary and temporary hydraulic actuator, or vertical movement jacks topped by a translation plate. Among the adjustment systems, mechanical platforms offer the greatest number of variants by far.

II.11.4.3.3 The universal alignment platform

This standardized system, called the universal adjustment platform (UAP) (see Fig. II.11.23), proposes a modular approach to design six degrees of freedom (DOF) adjustment platforms, with ±10 mm range, to position components. By using uniform kinematics, standardized components (adjustment jigs and joints) and design guidelines, the integration of different UAPs turns out to be an easy task. Moreover, with such an approach, the design process is much faster, so the overall cost can be optimized.

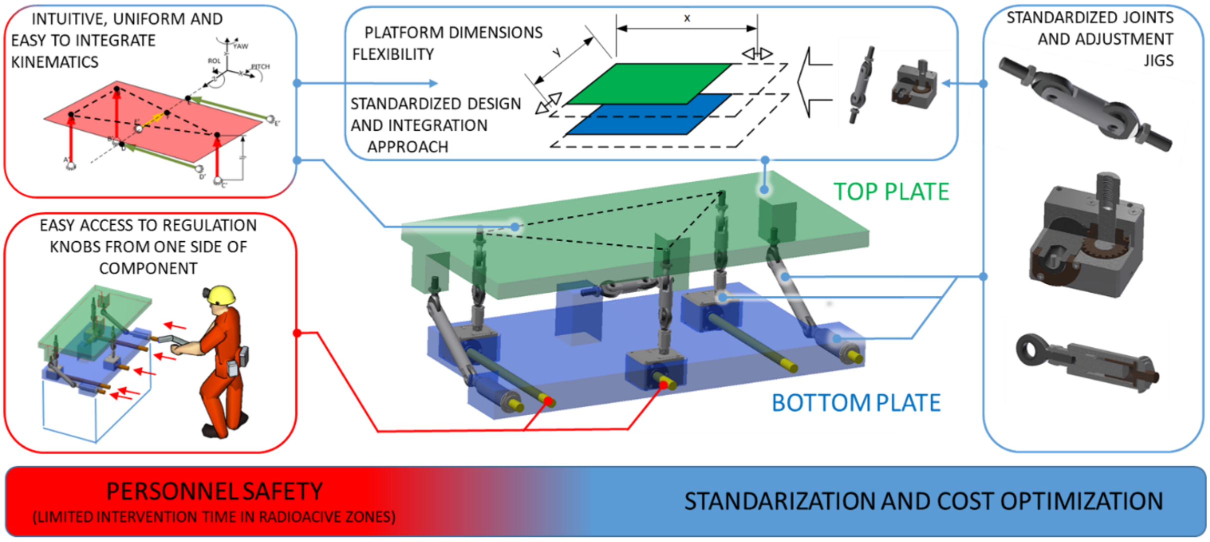


Fig. II.11.23: The universal adjustment platform (UAP) concept.

With adjustment knobs located on one side of the platform, the UAP meets ergonomic access requirements for manual operations. It is also fully compatible with the easy integration of motorized and portable adjustment solutions.

II.11.4.3.4 The adjustment based on motorised jacks

In the accelerator area, the heavy components can be supported by three jacks which allow their correct adjustment with respect to the beam trajectories. The configuration of the jacks supporting the components follow typically the layout from Fig. II.11.24. Each of the jacks provides both horizontal and vertical motion capability, allowing an adjustment of the components along the six DOF.

The jacks are operated manually for the first alignment of the magnets and can then be motorized, using motorized adapters, for remote alignment during the accelerator operation (see Fig. II.11.25).

II.11.5 Software and database

To align mechanical structures accurately, i.e components or detectors belonging to the accelerator complex or to the physics experimental areas, the surveyors typically collect hundreds of observations in the field. This number of independent observations is greater than strictly necessary to determine the unknowns, and must provide an adequate level of redundancy to ensure controls and statistical analysis of the results. Different computing steps are then generally required to correct raw data depending on

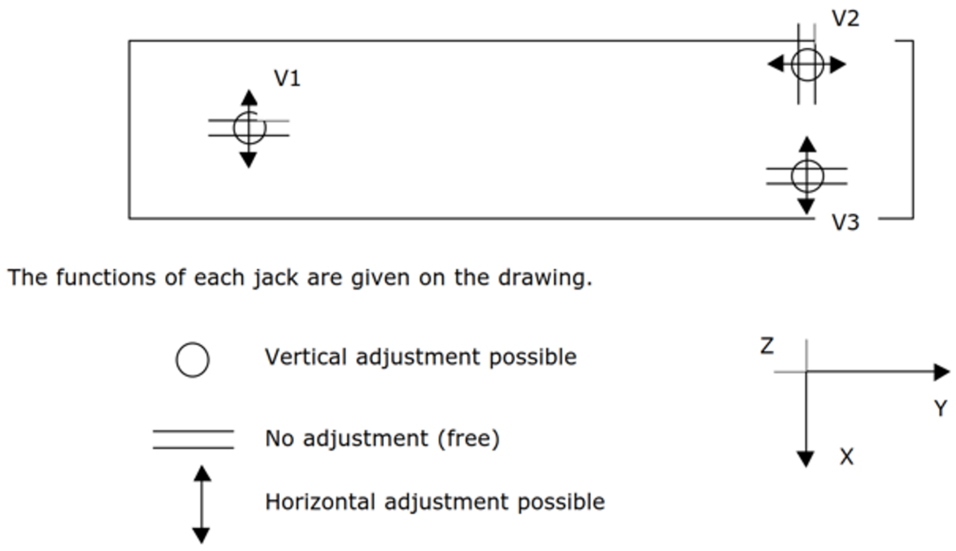


Fig. II.11.24: Configuration of the jacks allowing six DOF component adjustment.

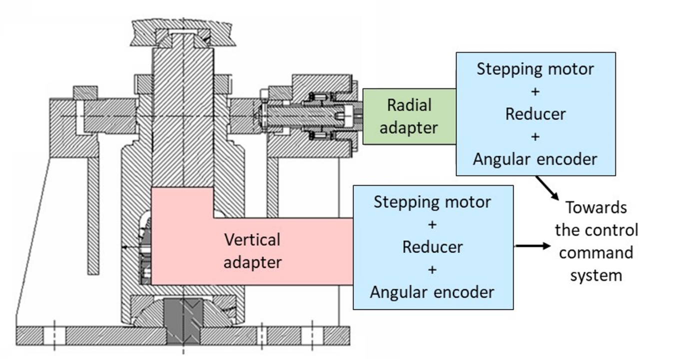


Fig. II.11.25: Motorized jack under LHC triplet magnet and its principle of operation.

devices and measurement conditions, to permanently store the data and to determine the spatial positions of the measured elements. The surveyor's workflow relies on a variety of complementary software tools and interfaces as illustrated in Fig. II.11.26. This software environment must at least cover the data acquisition, their post processing and analysis, and the storage of the relevant information into dedicated databases.

II.11.5.1 Data acquisition software

In surveying, various measurements such as distances, angles, and coordinates are collected using instruments including total stations, precision levels, and GPS receivers. The measured values can either be recorded manually by operators in the field or collected automatically via dedicated software communicating with the instruments. Commercial solutions are available on the market for standard geodesy and metrology tasks, but these applications only partially meet the specific needs for adjusting and maintaining the alignment of components of accelerators and of physics experiments, or for large-scale precise positioning. The software used in the field should not be limited to record raw measurements, but it

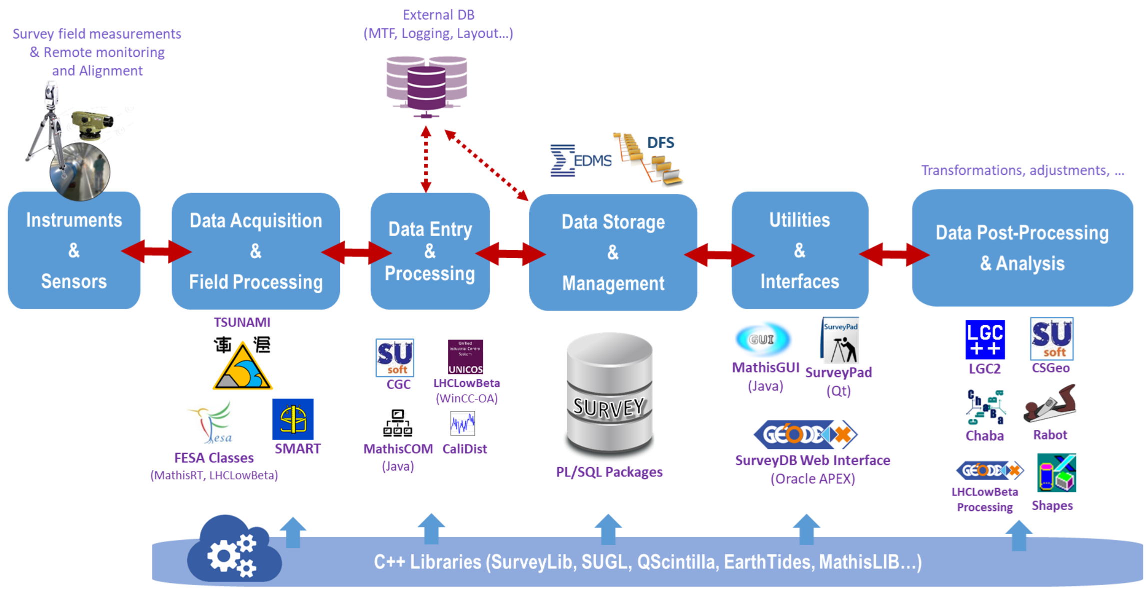


Fig. II.11.26: The geodetic metrology computing.

should also integrate some specific data processing to fit surveyor's workflow. In addition, surveyors also use exotic instrumentations and sensors, for example systems based on stretched wires or deviation to a local vertical, that need to be taken in account.

For example, most of the survey instruments refer to a vertical direction that follows the Earth's sphericity and depends on the local gravity field. Combining measurements from distant stations requires the precise knowledge of corrections to apply. Moreover, the position of each accelerator component is defined within a global Cartesian coordinate system. When mechanically re-aligning such elements in the field, with respect to given nominal positions, the data acquisition software must apply various coordinate transformations and express results along spatial orientations that locally correspond to the particle beam direction. During this operation, the software may also need access to the calibrated position of the reference targets of the component to be aligned, expressed in the component's internal coordinate system and representing the component's main axis, which is not visible in most cases.

Manufacturers generally provide code libraries allowing the control and the communication with their instruments. In-house developments can be done on top of these low-level interfaces to build appropriate survey software.

II.11.5.2 Data processing software

Least-squares adjustment is a mathematical method extensively used in surveying applications to determine the most accurate values for unknown parameters based on a set of observed measurements. These parameters might, for example, represent point coordinates in a given reference system or describe the three-dimensional positions (in terms of translations and rotations) of rigid bodies such as accelerator components or mechanical supporting structures. The parameters might also include sets of unknown data related to instruments and measurement conditions. In all cases, the adjustment principle always relies on a higher number of observations than the minimal number strictly necessary for determining parameters. This redundancy ensures quality and precision of the estimated parameters and offers the possibility to provide useful statistics about results. However, observations are prone to errors due to instrumental limitations, environmental conditions and human factors. Least-squares adjustment helps to account for these errors and provide a more reliable estimation of the true values of the surveyed parameters.

The basic principle behind least-squares adjustment is to find the set of unknown parameters that minimizes the sum of the squares of the residuals. Residuals are the differences between the observed measurements and the values predicted by the mathematical model. By minimizing the sum of squared residuals, the adjustment aims to distribute the errors in the measurements in the best possible way.

The adjustment process involves formulating a system of mathematical equations that relate the observed measurements to the unknown parameters. These equations can be linear or nonlinear, depending on the nature of the surveying problem. The goal is to solve this system of equations to obtain the adjusted values of the unknown parameters. To achieve this, least-squares adjustment uses statistical techniques to estimate the unknown parameters. It assumes that the errors in the measurements follow a Gaussian (normal) distribution, and it aims to find the parameters that maximize the likelihood of the observed measurements given the model.

The adjustment is performed in an iterative way, where an initial set of estimated values is refined through a series of computations. In each iteration, some corrections (or adjustments) are applied to the estimated parameters based on their influence on the residuals. This process continues until a convergence criterion is met, indicating that further iterations would not significantly improve the fit of the observed measurements.

The output of a least-squares adjustment includes the adjusted values of the unknown parameters, along with the estimated errors associated with each parameter. These error estimates provide a measure of the accuracy of the adjusted values. Additionally, statistical tests can be conducted to assess the goodness-of-fit of the adjusted model and detect any potential outliers or blunders in the measurements.

Least-squares adjustment is widely used in various surveying applications, including geodetic network adjustments, deformation monitoring, control surveys, and geodetic positioning. This principle also rules post-processing algorithms that use estimated positions for specific procedures such as the smoothing of the accelerator components. This operation consists of mechanically re-positioning some of the measured components to ensure smooth transitions between elements and to limit corrections of the particle beam orbits. In that case, in-house developed software estimates a smoothed curve representing the trajectory of the beam through the accelerator, and computes “smoothed offsets”, i.e., the radial and vertical differences between measured positions and the estimated smoothed curve. Components with smoothed offsets larger than a fixed value will be physically displaced and realigned by surveying teams in the field. This process can be iterative and lead to several smoothing operations while repeating measurements of the successive element positions.

All these complementary calculation features should ideally be integrated in one single application. However, in practice, surveyors often use separate applications to achieve a variety of specific tasks. Combining them into a functional processing workflow and in a common user interface, adapted for daily survey activities, might require additional in-house development. Homogenization of input and output data formats, or the development of data conversion scripts, is done where possible.

II.11.5.3 Survey database

This ecosystem of processing tools is generally built around a central database, which feeds it with and represents the heart of the survey activities. It contains all the measurements done by surveying teams in the field, as well as detailed information on the survey instruments and equipment. It also keeps track of the various data processing steps, and stores calculated results in the form of point coordinates or estimated radial, vertical , longitudinal and roll deviations with respect to nominal positions given by physicists. This data is the result of successive measurement campaigns during the accelerator's lifetime; therefore, stored estimated positions are only valid within a certain time interval and the database keeps the history of changes. To allow further analysis and post-processing, the database should also store the accuracy estimates of the various calculated parameters.

The database should also contain, or have a direct access to, nominal positions of accelerator components and related particle beam trajectories. Information on voluntary displacements applied to some elements, decided for instance by physicists to optimize beam dynamics, are jointly stored in the database. In other words, it contains all the geometric information needed for processing tools to transform coordinates and position parameters from any local reference system attached to a component and its real measured position, to any other local or geodetic reference system.

II.11.6 Geodetic metrology and associated R&D

The requirements for accurate alignment of components and regular or continuous monitoring of changes in the shape and dimensions of equipment, combined with environmental constraints in accelerators, particularly during the operating phases, are leading to the constant development of new geodetic metrology tools and systems [14–16]. Two examples of R&D projects underway in 2023 are briefly introduced below: the multi-target frequency scanning interfrometry (MTFSI) and the study of the structured laser beam (SLB). The FRAS, an example of a complete control and alignment system developed for the HL-LHC at CERN, is then presented.

II.11.6.1 The multipoint target frequency scanning interferometry

The multi target frequency scanning interferometry (MTFSI) [17], which is in an advanced development phase at CERN in 2023, is a Fourier analysis based frequency scanning interferometry (FSI) technique. It enables the absolute distance of several targets to be measured simultaneously from the same source, with a precision at the micron level.

The MTFSI uses the Michelson interferometer principle layout with sweeping laser source (see Fig. II.11.27). To simplify the optical architecture of an interferometer, the configuration uses optical fibre with semi-transparent ferrule tip as a reference mirror. It reflects $4\,\%$ of incident light, thus forming the reference arm of the interferometer. The remaining $96\,\%$ of light is emitted towards the reflective targets, using additional collimating optics.

The reflecting targets placed within the emitted beam reflect portions of the light back to the fibre and via the circulator to the photodetector, where both the reference beam and the beams reflected from

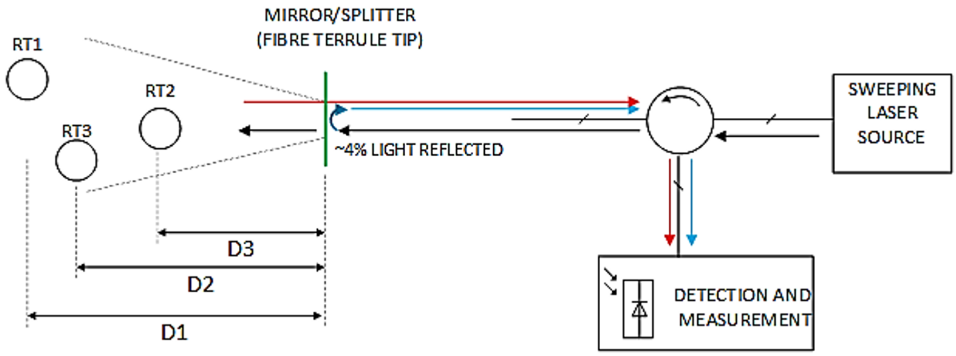


Fig. II.11.27: Principle of the Multiple Target Frequency Scanning Interferometer (MTFSI).

the targets are recombined, creating a signal, composed of a sum of various targets interference beat frequencies. The response I of the photodetector is described by Eq. II.11.7

$$I(t,\tau) = A_1 \cos\left[2\pi\left(\alpha\tau_1 t + f_0\tau_1\right)\right] + A_2 \cos\left[2\pi\left(\alpha\tau_2 t + f_0\tau_2\right)\right] + A_3 \cos\left[2\pi\left(\alpha\tau_3 t + f_0\tau_3\right)\right]\cdots \tag{II.11.7}$$

where A is the magnitude of the signal, τ is the time delay between the signals from the reflecting target and the reference mirror arrival to the photodetector (see Fig. II.11.27), α is a sweep rate of the laser ($\alpha = \frac{d\nu}{dt}$ is the laser frequency change in time), f_0 is the optical frequency of the laser at the time t_0.

If the laser sweep speed α is constant, the signal from Eq. II.11.7 becomes a mix of constant beat frequencies (f_{beat}), retrievable from the sampled photodetector output using a fast Fourier transform (FFT). The measured absolute distance is proportional to f_{beat} (cf. Eq. II.11.8) and can be calculated using Eq. II.11.9:

$$f_{\text{beat}} = \alpha\tau = \alpha\frac{2D}{c} \quad , \tag{II.11.8}$$

$$D_n = c\frac{f_{\text{beat}[n]}}{2\frac{d\nu}{dt}} \quad . \tag{II.11.9}$$

This new FSI technology is used in the development of new alignment sensors, such as the FSI based HLS sensors and inclinometers [18], and for the position monitoring of cold components (cold masses or crab cavities) inside their cryostat.

II.11.6.2 The structured laser beam

The structured laser beam (SLB), part of the pseudo-non-diffractive optical beam family, has a transverse optical intensity profile similar to that of a quasi-Bessel beam. It is characterized by a sharply defined core propagating with a low divergence (down to $10\,\mu\text{rad}$), surrounded by alternating bright and dark concentric circles (see Fig. II.11.28). Furthermore, the SLB has the capability to propagate over very long distances, theoretically to infinity, without changing the generator parameters, and it has been tested up to $900\,\text{m}$. This makes the SLB an interesting candidate for developing a long-range optical reference line for geodetic metrology [19].

The SLB is the result of the superposition of waves coming from a wavefront with a special

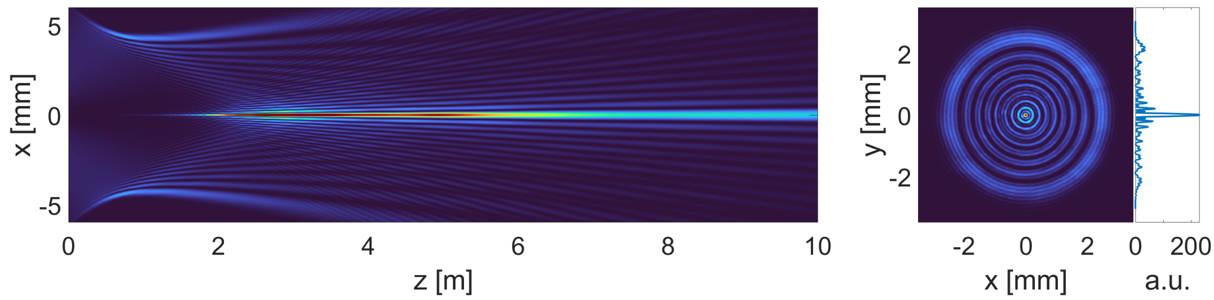


Fig. II.11.28: Structured laser beam (SLB): longitudinal profile from simulation on the left-hand side, example of the transverse intensity distribution and intensity profile of a real SLB on the right-hand side.

shape obtained after the spherical aberration and the defocus aberration produced by the generator. The properties of the SLB are currently being studied. These include the shape of the beam, the intensity distribution, the effect of symmetry breaking on straightness, the propagation in inhomogeneous media and the special polarization [20–22].

A research program aimed at describing this beam and its properties, as well as studying its potential use, was launched as part of a collaboration between CERN and the Institute of Plasma Physics of the Czech Academy of Sciences, which was subsequently extended to the Technical University of Liberec, also located in the Czech Republic. Since 2022, ETH Zurich, Switzerland, has also been involved. In 2023, this program is making promising progress and is continuing. In the future, the SLB could become an alternative to stretched-wire-based alignment systems for particle accelerators.

II.11.6.3 Full Remote Alignment System (FRAS) for HL-LHC at CERN

The High-Luminosity Large Hadron Collider (HL-LHC) is an upgrade of the LHC to achieve instantaneous luminosity a factor five larger than the LHC nominal values. During the Long Shutdown 3, scheduled between 2026 and 2028, nearly $1.2\,\mathrm{km}$ of accelerator components will be replaced by new ones, relying on key innovative technologies [23, 24]. The Full Remote Alignment System (FRAS) [25] is being developed to perform the remote alignment of these new HL-LHC components. FRAS will enhance the accelerator performance, decrease the required orbit corrector strengths, all of this while limiting the radiation doses for personnel intervening during alignment campaigns. Innovative solutions for the remote adjustment and position determination of the components have been qualified, including the internal monitoring of the position of cold masses and crab cavities inside their cryostat [26].

FRAS will perform the continuous position determination and remote adjustment of components located on both sides of the IPs 1 and 5 of the LHC (see Fig. II.11.29) within a range of $\pm 2.5\,\mathrm{mm}$. Once the first beams have circulated, it will be used to correct the initial machine misalignment with respect to the centre of the Inner Tracker of the two detectors. On a more standard operational basis it will be employed to correct for the ground motion without the need of interventions in the tunnel. The alignment goal is to have all components on one side of the IP, from quadrupole Q1 to quadrupole Q5, adjusted beyond $100\,\mu\mathrm{m}$ in the transverse directions. Furthermore, the adjustment between Q5 left and Q5 right of the IP shall be better than $330\,\mu\mathrm{m}$ at $1\,\sigma$ level. This goal entails considerable challenges for

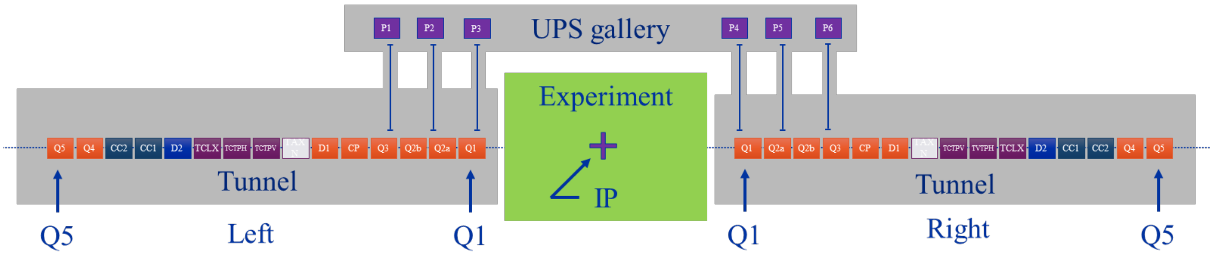


Fig. II.11.29: Schematic layout of HL-LHC components on either side of an experiment.

the alignment teams to design adequate sensors and systems that have to be integrated into the existing tunnel environment and require to withstand up to 2 MGy of total ionising dose.

Over the 210 m on each side of the IP, the position of 17 components will be continuously and remotely determined by a redundant configuration of different types of sensors, using diverse technologies, namely: WPS based on a capacitive technology, HLS based on FSI technology, and two types of inclinometers based on FSI and capacitive technologies. For their remote adjustment, the components will be supported by motorised supports that can either be motorised jacks or a Universal Adjustment Platform (UAP) depending on the size and weight of the component.

The alignment sensors are typically located on the cryostats, i.e. the external envelopes of the components, and their interfaces are determined with respect to the mechanic and magnetic axis. For two types of specific components, the inner triplet quadrupoles (Q1–Q3) and the crab cavities, a new system will be added for a better knowledge of the position of the beam through the thermal cycles of the components. This internal monitoring system continuously measures the position of the cold masses of the quadrupoles and the crab cavities with respect to their cryostat within an accuracy of $\pm 100\,\mu\mathrm{m}$ and within a micrometric resolution. This is achieved by welding specific targets onto the cold masses and by using FSI technology to perform a contact free measurement of the absolute distances between optical heads, located on the cryostats operating at ambient temperature, and the targets that are cooled down to 1.9 K. The targets and feedthroughs have been designed in-house and successfully validated to avoid cryo-condensation [27]. The principle of the cold mass monitoring and the respective distribution of sensors situated on the cryo assembly is shown in Fig. II.11.30.

Conclusion

Geodetic metrology is essential and beneficial in a particle accelerator project, saving time, improving accuracy and increasing efficiency. The topics developed in this chapter provide an overview of the geodetic metrology and of the methods and techniques used in accelerator alignment. They cover the actions required for geometric validation throughout the project, from the initial discussion phase through to prototyping, manufacturing, fiducialisation, installation, alignment and maintenance.

Lines of sight in accelerator and experimental areas, geodetic networks and the corresponding referential frames must be defined as soon as possible, even before the official green light of a project. Then the alignment requirements of all components must be defined to establish a clear strategy of alignment and choose the most appropriate solution and instrumentation, in terms of accuracy, integration

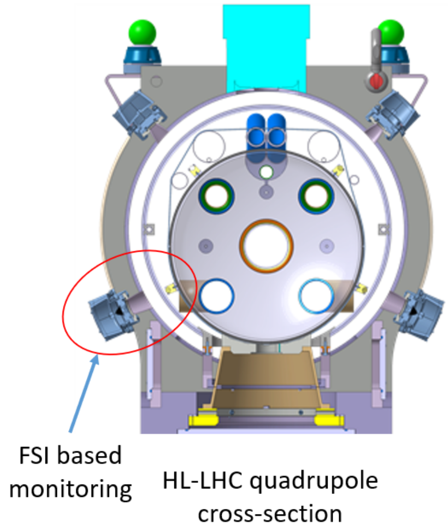


Fig. II.11.30: HL-LHC quadrupole cross-section.

and cost. The fiducialisation process must be adapted to the alignment requirements and the number of components, as well as the alignment methods.

For the next generation of colliders, robust, high-performance alignment methods must be developed that are sustainable and affordable in terms of cost and integration. The automation of standard alignment activities will also become crucial, in order to limit personnel radiation doses and increase the duration of operations.

Acknowledgements

The author wishes to express his sincere gratitude to Charlotte Basilico, Patrick Bestmann, Jean-Frédéric Fuchs, Andreas Herty, Guillaume Kautzmann, Francis Klumb, Hélène Mainaud Durand, Dirk Mergelkuhl, Krystof Polak, Vivien Rude, Mateusz Sosin, Pierre Valentin, Camille Vendeuvre and Benjamin Weyer for their invaluable contribution to this chapter through their writing, proofreading and insightful comments. Without their support, this work would not have seen the light of day.

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