Review of Accelerator Alignment

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SUMMARY

The history of twentieth century science and technology is intimately tied to the development of particle accelerators and the discoveries made using them. Today the breadth of science concerned by, and studied using particle accelerators is truly staggering. It ranges from attempts to understand the origin of our universe and what constitutes matter and radiation; to questions concerning the processes that sustain life; to a better understanding of archaeology and palaeontology.

Virtually all accelerators, regardless of their scientific application require precise alignment to operate correctly. The field of accelerator alignment overlaps the fields of metrology and traditional surveying and geodesy. Standard measurement precision is millimetric to sub-millimetric over distances ranging between several hundred metres up to nearly 30 km. New and planned machines go beyond even this and require micro-metre alignment precision on the same scales. The use of specialised techniques and instruments are needed to guarantee that these requirements can be met. This paper will provide a very general overview and characteristic examples of different techniques, instrumentation, and results related to the field of accelerator alignment. Interested readers are referred to a comprehensive collection of articles concerning particle accelerator and experiment alignment available on the International Workshop on Accelerator Alignment (IWAA) website (http://www-conf.slac.stanford.edu/iwaa/default.htm).

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1. INTRODUCTION

A particle accelerator is a device that uses electric fields to accelerate ions or charged subatomic particles such as electrons and protons to high speeds while maintaining them in well-defined trajectories. Beams of high-energy particles are useful for both fundamental and applied research in the sciences. Fundamental particle physics seeks to understand the elementary constituents of matter and radiation and the interactions between them. Elementary particle physicists use machines that accelerate beams of electrons, positrons, protons, and anti-protons, interacting with each other or with the simplest nuclei (e.g. hydrogen) at the highest possible energies, generally hundreds of GeV[1] or more. Nuclear physicists and cosmologists use beams of atomic nuclei[2] of atoms such as iron or gold, to investigate the structure, interactions, and properties of the nuclei and of condensed matter at extremely high temperatures and densities similar to those imagined to have occurred in the first moments of the Big Bang. Interactions or collisions can be provoked between the particle beam and a fixed target or between two particle beams circulating in opposite directions within the accelerator. Examples of these types of accelerators are CERN, DESY (up until 2007), SLAC (up until 2008), KEK and FERMI lab.

Another branch of particle accelerator science works with what is referred to as synchrotron radiation. Synchrotron radiation light sources can be compared to *super microscopes*.[3] High energy electrons passing through bending electromagnets (dipoles), or through periodic magnetic structures composed of many magnets with a special repeating row of N and S poles that force the electrons into a sinusoidal or helical path[4]; emit extremely bright and coherent beams of high energy photons in the ultraviolet and X-ray regions of the electromagnetic spectrum. Application fields for light generated by synchrotron radiation light sources include chemistry, earth science, condensed matter physics, biology, and life sciences and technology. Examples of these types of accelerators are the ESRF, APS, SPRING-8, DIAMOND, the Canadian and Australian Light Sources (CLS and ALS), to name only a few. At the time of

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[1] The electron volt (eV; 1 GeV is 10^9 eV) is a unit of energy used in physics. By definition, it is equal to the amount of kinetic energy gained by a single unbound electron when it accelerates through an electric potential difference of one volt. By mass-energy equivalence, the electron volt is also a unit of mass. It is common in particle physics, where mass and energy are often interchanged, to use eV/c^2 , where c (a constant) is the speed of light in a vacuum (from $E = mc^2$).

[2] Nuclei are atoms stripped of their electrons leaving only protons and neutrons.

[3] With our eyes we can observe the macroscopic world. However, to *see* atoms, which have dimensions of the order of a tenth of a nanometre (i.e. 10^{-9} m), we need to use a different form of *light*, one that has a much shorter wavelength than visible light. This type of *light* is known as X-rays. Synchrotron light sources produce very intense and *bright* X-rays. X-rays have many well-known applications in medicine, but they can also be used to reveal important information about the organisation of the atoms that make up a material.

[4] These devices are called wigglers or undulators.

writing there are close to 70 synchrotron radiation light sources in the world being used by an ever growing number of scientists.

Virtually all accelerators, regardless of their scientific application require precise alignment to function correctly. The field of accelerator alignment overlaps the fields of metrology and traditional surveying and geodesy. Standard measurement precision is millimetric to sub-millimetric over distances ranging between several hundred metres up to nearly 30 km. New and planned machines go beyond even this, requiring micro-metre alignment precision on the same scales. The use of specialised techniques and instruments are needed to guarantee that these requirements can be met. This paper will provide a general overview of different techniques, instrumentation, and results of survey and alignment related to the field of accelerator alignment. [1]

2. ACCELERATOR ALIGNMENT[5]

Accelerator alignment can divided into two broad application fields. The first is the alignment of the different elements that comprise accelerator itself. These include magnetic elements such as dipoles, quadrupoles and sextupoles. The second application field is the alignment of the different experiments used by scientists to study what is actually of interest to them. Additionally, there are typically two phases to the alignment of an element, fiducilization and in-situ alignment.

2.1 Particle Accelerators

To understand why alignment is of such importance in particle accelerators it is useful to have an elementary understanding of how one works. Typically charged particles are accelerated from a low energy rest position to a generally relativistic (i.e. near the speed of light) high energy. This is accomplished using either one, or a combination of linear and circular accelerators.

Linear acceleration is achieved by applying alternating high-energy fields to an array of plates. As the particles approach a plate they are accelerated towards it by an opposite polarity charge applied to the plate. As they pass through a hole in the plate, the polarity is switched so that the plate repels and accelerates them towards the next plate in the array. In some accelerators, the Stanford Linear Accelerator Complex (SLAC) being a notable example, this linear acceleration continues over several kilometres and particles reach very high energy. There are advantages and disadvantages to this process. The main disadvantage is that to achieve sufficiently high energy, the linear accelerator becomes very long. For very long structures, the complexity of the required infrastructure increases the construction and maintenance costs with respect to circular accelerators. One important advantage is that energy losses due to synchrotron radiation are minimized. It should be noted that all proposed future high energy machines are linear accelerators.

[5] For simplicity, accelerator alignment is taken to refer to both the alignment of the accelerator machine itself and to all fields related to accelerators and their experiments more generally. Context should help to differentiate which case is being used.

In the circular accelerator, particles are accelerated in a circular trajectory until they reach a nominal energy. Particles are steered using electromagnets. The advantage of circular accelerators over linear accelerators is that the constant cycling of the particles around the ring permits continuous acceleration. Circular accelerators are typically smaller than linear accelerators of comparable power; this is to say a linear accelerator would have to be extremely long to have the equivalent power of a circular accelerator. However, as a particle travelling in a circle is always accelerating towards its centre, it continuously radiates (or looses energy) towards the tangent of the circle. This loss of energy, referred to as synchrotron radiation, can be a drawback to using circular acceleration. Indeed, one of the reasons the CERN LEP (now LHC) accelerator is so large (27 km in circumference) is to attenuate this energy loss. Synchrotron radiation light sources, on the other hand, are built specifically to produce and take advantage of synchrotron radiation light.

Nearly all modern large scale machines are circular accelerators. The analogy of classical optics is used to describe how to make charged particle beams (e.g. electrons and protons) follow a circular trajectory. Dipole magnets (a magnetic structure with one N and S pole) bend the particle beam. However, bending the particle beam has a *defocusing* effect upon it. This can be countered with a convergent magnet *lens*. Quadrupole magnets (magnetic structures with two sets of N and S poles) are magnetic lenses that focus the particle beam. Nevertheless, the quadrupole magnets used to focus the beam have the unfortunate property that their focusing strength is dependent on the energy of the particle being focused. High energy particles have longer focal lengths than lower energy particles. Since all realistic beams have some energy spread, continuous focusing results in the size of the beam *blowing up* with distance. Sextupole magnets (magnetic structures with three sets of N and S poles) correct this so-called chromaticity error. The arrangement of dipoles, quadrupoles and sextupoles in the accelerator is referred to as its lattice.

The challenge in accelerator alignment is to ensure that the accelerated particles traverse along the axes, or centres of these electromagnets. In other words, all of the electromagnetic axes in an accelerator must line up to within a certain tolerance. Misalignments of the electromagnetic axes introduce transverse errors in positioning which are seen as imperfections of the magnetic guiding field. These imperfections induce local perturbations of the particle motion. Depending on the magnitude, location and distribution of these alignment errors, the resultant particle orbit may undergo deviations and oscillations of varying amplitude. In the worst case, it is impossible to keep the particles in the accelerator.

2.2 Fiducilization

Fiducilization is the process of relating a typically hidden or inaccessible sensitive part of an object with respect to some visible and accessible reference mark that can be used to position it in situ. One example of fiducilization is the establishment of the geometric relationship between the (invisible) electromagnetic axis of a quadrupole and its reference marks (e.g. survey monuments) positioned on its exterior. Once the relationship between the magnetic axis of the quadrupole and its reference marks has been established through the fiducilization process, the reference marks can be used to align the magnets and their magnetic axes in their theoretical positions and along their theoretical axes in the accelerator. Here, we shall concentrate on two characteristic examples. The first concerns the fiducilization procedures used for the quadrupole magnets used in the French national synchrotron radiation facility SOLEIL. [2] The second concerns the fiducilization of the CERN Large Hadron Collider (LHC) super conducting cryogenic dipole magnets. [3]

Quadrupole fiducilization at SOLEIL was representative of the process and results gained in the last series of European synchrotron radiation light sources that were built, or are presently under construction[6]. As with any solid body, a quadrupole has 6 degrees of freedom: the three translations (x, y, z) along, and the three rotations, roll, pitch and yaw (a, b, c) about it's X, Y and Z axes. Assuming that the quadrupole axis is aligned along the Y axis; due to the dynamics of the particle beam, the x and z directions are most sensitive to alignment errors. These are the directions orthogonal to the travel of the accelerated particle beam.

For reference, the SOLEIL quadrupoles, typical of synchrotron radiation quadrupole magnets, are less than 0.5 m long with a total volume less than 1 m^3. Fiducilization starts by installing the quadrupole on a perfectly horizontal $a = b = 0$ support. The quadrupole axis is determined (materialised) using a rotating coil. This coil system produces a *minimum* when it is coincident with the quadrupole axis and (simultaneously) the electron beam axis. Real quadrupoles have imperfections. Each magnet has a small offset of its nominal axis with respect to the *theoretical* or *master* quadrupole axes materialized by the spatially static rotating coil. These small *magnetic* offsets are compensated by physically adjusting the quadrupole and its magnetic axis. This is accomplished by inserting shims between the quadrupole and its support girder. The thicknesses of the shims are a function of the magnetic offsets determined by the rotating coil.

At the same time as the quadrupole magnetic axis is measured, the positions of the survey reference marks machined into the quadrupole are determined with respect to the rotating coil system. These reference marks also have small mechanical imperfections with respect to their *theoretical* positions. These measurements, made with a dedicated instrument referred to as a *magnetic comparator*; provide a data base of mechanical offsets between the survey reference marks and the quadrupole electromagnet axes. The fiducilization of the SOLEIL quadrupole magnets was achieved with an uncertainty at 1σ in the x and z directions most sensitive to alignment errors of $\sigma_x = 15$ μm and $\sigma_z = 11$ μm.

At CERN, the cryogenic dipole magnets used to steer particles along a circular trajectory are composed of a cold mass inserted into a vacuum vessel. When the magnet is operating the cold mass is maintained at 1.9 degrees Kelvin (i.e. -271.1 ºC). The cryogenic dipole magnet is a 15 m long, 1 m diameter, slightly arced cylinder. Its geometry is defined by the geometry of the two particle beam channels referred to as cold bore tubes (CBTs) running through its centre.

[6] This series of acclerators includes the Swiss Light Source, SLS; the UK light source, DIAMOND; and the Spanish light source, ALBA.

These magnets are considerably larger than those used by SOLEIL. Fiducilization was performed in a dedicated building located above ground before the magnets were transported to their nominal positions underground in the LHC tunnel. The fiducilization technique relied upon a network of survey points installed around the cryogenic dipole magnet. These survey network points were located over an area approximately 22 m long by 7 m wide and in planes at different heights. Some points were installed on the floor while others were on top of tripods above the magnet. Due to the sheer number of dipoles that were fiducilized (1232), the fiducilization procedure had to be as straightforward as possible.

A mechanical *mole* was moved through the CBTs to determine their geometry. The mole was equipped with a reflector whose position was measured by a laser tracker. In order to get the maximum precision, both CBTs were measured from both sides of the magnet. This approach resulted in four different sets of measurements, each obtained from a different laser tracker station. The survey network points described above were measured at the same time as the CBTs for each of the four laser tracker stations. These points were then used to link the four laser tracker stations together through a least squares bundle adjustment.

At CERN, because of the complexity of the cryogenic dipole magnets and a variety of other reasons, an acceptance tolerance scheme was devised. [4] It was estimated that the:

- Linkage of the laser tracker positions characterised by the bundle adjustment was 0.08 mm at 1σ;
- The uncertainty in the measurement error of a point by the laser tracker given by the manufacturer as 5 ppm at 1σ;
- Centring error of the *mole* inside the CBT determined to be 0.07 mm at 1σ.

The maximum allowable measurement error was derived by combining quadratically these component errors. This gave an error tolerance of 0.47 mm at the 3σ (i.e. 99.7 % confidence interval). If the deviations between measurements made at the two laser tracker positions at opposite sides of the CBT exceeded this value they were re-measured. Thus, the fiducilization of the CERN cryogenic dipole magnets is known to better than 160 µm at 1σ.

2.3 Accelerator Alignment

Once the accelerator magnets have been fiducilized they must be installed in their theoretical positions in the tunnel[7]. Typically this is accomplished in several steps. First a survey network of pillars and/or a combination of wall, floor and/or ceiling reference marks is installed and measured in the tunnel. This network of reference marks is commonly referred to as the geodetic network. The geodetic network coordinates are used to install and pre-align the accelerator elements.

The complexity of the determination of the coordinates of the geodetic network is variable. For a large accelerator such as CERN or SLAC this operation can be quite daunting. The LHC

[7] It is common to call the enclosure in which the accelerator is installed a *tunnel* although it may not resemble a tunnel in the pure sense of the word.

(formerly LEP) is a circular accelerator 27 km in circumference. Generally, circular accelerators lie in a plane. A plane intersecting a sphere (assuming the earth is spherical) forms a circular equipotential surface (i.e. a surface where water is at rest). In reality the equipotential surface is best approximated by the geoid. In the case of the LHC, the accelerator plane is underground and for technical reasons, it is on an inclined plane with a slope of 1.4%. The absolute alignment tolerance of the accelerator magnets over the 27 km LHC circumference was ±3 mm. [5] Therefore, the absolute alignment of the LHC can be summarized as positioning an element to within ±3 mm in x, y and z with respect to a reference circle that is 27 km in circumference and located on a tilted plane. This must be done while working in a complicated gravity reference frame[8], in an underground tunnel with access to the surface only every 3.5 km through 30 to 150 m deep vertical shafts. [6-8]

For comparison, at the ESRF, where the main accelerator has an 842 m circumference, and the absolute alignment of the accelerator is less challenging than the conditions described above; the standard deviation of the magnets with respect to their nominal theoretical position in the radial direction is 0.6 mm at 1σ. The uncertainty in the alignment of the ESRF machine in the vertical direction with respect to a horizontal reference plane is typically maintained at less than 150 µm at 1σ. These results are comparable to those achieved at SOLEIL. [2]

Often several elements are aligned on one girder support. For example, at the ESRF one girder supports up to four quadrupoles and three sextupoles. These elements are aligned in a laboratory before installation in the tunnel. In the case of the ESRF, the uncertainty in this alignment in the two sensitive directions (i.e. orthogonal to the travel of the particle beam) at 1σ was $\sigma_x = \sigma_z < 30$ µm.

After the magnets comprising the accelerator have been placed in their nominal positions, they must be aligned to their final positions. This final alignment employs what is commonly referred to a *smoothing*. This operation aims to remove local jumps in the alignment between adjacent elements. One attempts to align the magnets in the plane with respect to an *arbitrary* smooth line that best approximates the actual positions of the installed magnets, rather than trying to position each magnet exactly in its nominal theoretical position. The smooth line oscillates about the nominal theoretical circle of the accelerator with maximum deviations

[8] Recall that optical levels and theodolites used for aligning accelerator components work in the gravity frame of reference. The gravity field and the vertical direction varies due to the uneven way in which masses are distributed at the surface of the Earth and below. To correct their instruments' measurements for the effects caused by these gravitational anomalies, surveyors must determine the shape of the geoid. In [6] the deviation of the gravity from the vertical due to the geoidal variations was measured to be:

- The vertical deflections range from 0 to 15 arc seconds at surface level and from 0 to 9 arc seconds at zero level,
- The resulting separation between the local reference ellipsoid and the geoid reaches 200 mm at 10.5 km from the origin,
- The Altimetric corrections along the LEP machine to obtain a true plane in space vary between -40 mm and + 100 mm.

These values have since been refined (see [7] and [8]) within a defined uncertainty envelope. In the case of the ESRF, as with most synchrotron radiation light sources, the smoothing operation is made between adjacent girder supports.

For the LHC at CERN, the goal, which was achieved, was to have a smoothing uncertainty at 1σ of 150 µm over any 150 m long section of magnets over its full 27 km circumference. The way in which this was achieved is discussed in [9]. At the ESRF, the smoothing of the machine is typically maintained at less than 150 µm over its 842 circumference. Other accelerators such as SLAC, KEK and APS, for example, have similar tolerances and alignment results.

2.4 Experiments Alignment

In high energy machines, when the accelerated particles have enough energy they are forced to collide with a target or another group of particles travelling in the opposite direction. The LHC at CERN is designed to collide two counter rotating beams of protons or heavy ions. This collision is referred to as an event. It occurs at the interaction point. Physicists are interested in the events that occur during and after a particle's (i.e. protons at the LHC) collision. For this reason, they place detectors in the regions which will be showered with particles[9] resulting from an event.

The physicist's goal is to isolate each event, collect data from it, and check whether the resultant particle processes agree with the theory they are testing. Each event is very complicated and produces many particles. Most of these particles have lifetimes so short that they only travel an extremely short distance before decaying into other particles. Therefore, they leave no detectable tracks. To look for these various particles and decay products, physicists have designed multi-component detectors that test different aspects of an event. Each component of a modern detector is used for measuring particle energies and momenta, and/or distinguishing different particle types. When all of the components work together to detect an event, individual particles can be singled out from the multitude of others for analysis. During a colliding-beam experiment, the particles radiate in all directions, so the detector is spherical or, more commonly, cylindrical. Following each event, computers collect and interpret the vast quantity of data measured by the detectors and present the extrapolated results to the physicist.

These types of experiments have different alignment problems to accelerator machines. This is particularly true of the large physics experiments such as CMS, ATLAS and ALICE located at CERN. Other examples include the BaBar experiment at SLAC, the D0 experiment at FERMI lab and the Belle experiment at KEK. Whereas an accelerator is essentially planar, large scale physics experiments are volumetric objects. For example, the ESRF Storage Ring accelerator has height variations of less than ±0.3 mm over its 842 m circumference. On the other hand, the 12,500-tonne Compact Muon Solenoid [10] (CMS) experiment at CERN is 21 m long, 15 m wide and 15 m high.

[9] The collision produces particles that are different from the colliding protons.
[10] CMS is designed to see a wide range of particles and phenomena produced in high-energy collisions in the LHC. http://cms.web.cern.ch/cms/Detector/WhatCMS/index.html

Large scale physics experiments are compared metaphorically to the Russian nested doll. This design paradigm denotes a relationship between objects within objects. The onion metaphor is similar. If the outer layer is peeled off an onion, a similar onion exists within. Large scale physics experiments are composed of a series of detectors within detectors. Like a cylindrical onion, different layers of detector stop and measure the different particles. This data is used to build up a picture of events that occurred at the heart of the collision between the protons in the LHC.

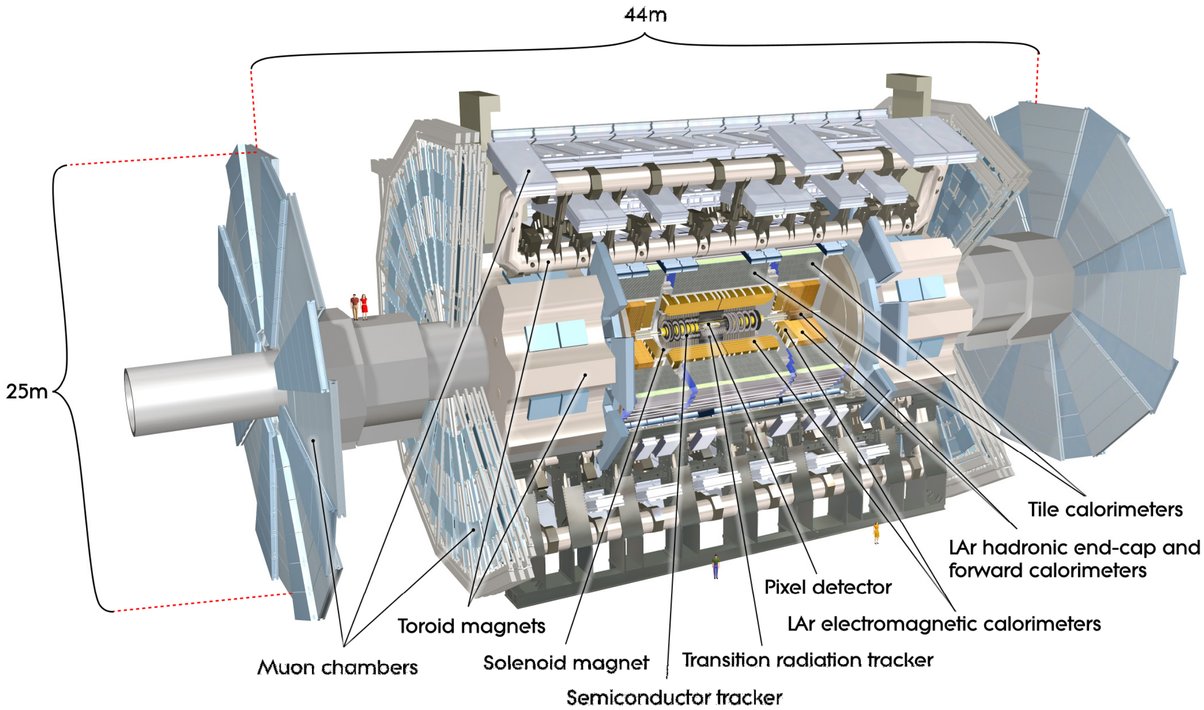

Figure 1 The ATLAS experiment at CERN http://ATLAS.ch (http://cdsweb.cern.ch/record/1095924)

For example, the ATLAS detector consists of a series of ever-larger concentric cylinders around the interaction point where the proton beams from the LHC collide. It can be divided into four major parts: the inner detector, the calorimeters, the muon spectrometer and the magnet systems. Each of these is in turn made of multiple layers. The detectors are complementary: the inner detector tracks particles precisely, the calorimeters measure the energy of easily stopped particles, and the muon system makes additional measurements of highly penetrating muons. The two magnet systems bend charged particles in the inner detector and the muon spectrometer, so that their momenta can be measured.[11] A computer generated image of the ATLAS detector is shown in **Figure 1**.

In modern large scale physics experiments such as ATLAS at CERN, the alignment can be divided into two broad categories. The first is concerned with the control and assembly of a multitude of parts manufactured all over the world which comprise the experiment. The

[11] http://en.wikipedia.org/wiki/ATLAS_experiment

second is the continual real time control of its movements while it is taking data. Because the experiment detectors are fabricated in different parts of the world, before delivery, it was essential to control sometimes quite voluminous parts to ensure they will fit together with parts manufactured elsewhere. As with accelerator magnets discussed above, each component of an experiment must be fiducialized. Ultimately, these fiducial marks are used in the assembly of the detector when everything must fit together under very tight tolerances in the experimental enclosure.

The ATLAS detector datum (interaction point, radial orientation of the colliding beams and reference LHC plane) is defined by the final positioning of the so-called low-beta quadrupole magnets. These crucial magnets are used to focus the particle beam at the interaction point. They are located at each end of the cavern at a distance of 60 m from the nominal interaction point. The reference line upon which the ATLAS detector is aligned is defined by the best fit line between survey reference monuments installed on the low-beta quadrupole magnets. The survey reference network in the cavern is linked to the machine geometry via standard survey measurements as well as a permanent hydrostatic levelling system (HLS) and wire positioning system (WPS) monitoring systems.[12] These systems are installed in dedicated survey galleries adjacent to the LHC tunnel and detector. They provide a permanent real time link between the low-beta quadrupole magnets installed on either side of the detector cavern. The final control was carried out on the elements themselves and relative to each other. Depending upon its location, a spatial uncertainty tolerance between 0.5 mm and 1.2 mm at 1σ was required for any fiducial mark with respect to the nominal beam axis. [10] Overall accuracy in the order of 0.2 mm at 1σ was achieved. [11]

Other experiments require precision alignment on much larger scales. Scientists from around the world are searching for non-zero neutrino mass by looking for neutrino oscillations. [13] To this end several long baseline experiments have been conceived. Three examples are: the K2K Long Baseline Neutrino Oscillation Experiment between KEK laboratory in Tsukuba and the Kamioka Neutrino facility in Japan; the MINOS Experiment and NuMI Beamline between Fermi lab in Illinois to Soudan mine in northern Minnesota in the United States; and CNGS between CERN in Geneva and Gran Sasso in Italy. These projects are characterised by an accelerator source which creates and aims a beam of neutrinos at a distant target. Source to

[12] An HLS is a powerful tool that can be used effectively in the precise monitoring of vertical motion in sensitive applications. The ESRF HLS, for example, is based on a water equi-potential surface common to all measuring points. The ESRF instruments are composed of two parts. The captor vessel which holds the liquid and a probe that measures the capacitance, which is proportional to the distance between its electrode and the water surface. Assuming there is no net loss or gain of water to the system, if a vessel and probe move down – because the support upon which they are installed moves down - for example, then the distance between the probe and the water surface decreases. One can measure very precise displacements with sensors installed over quite large distances and areas. The WPS is a similar instruments based on capacitive probes. It measures distances to a reference wire.

[13] The *standard model* of particle physics is a theory of three of the four known fundamental interactions and the elementary particles that take part in these interactions. These particles make up all visible matter in the universe. In the simplest version of the *standard model*, neutrinos had no mass. Experiments designed to detect neutrinos from the sun found only one third of the expected number. The explanation for this is electron neutrinos produced in the sun oscillate as they travel to earth, sometimes appearing as muon or tau neutrinos. Neutrino experiments are designed to provide a more detailed understanding of this phenomenon.

target distances are 730 km for the CNGS project, 735 km for the NuMI MINOS project and 250 km for the K2K project.

There are two main challenges for these projects. The first is to align the different parts of the experiment (i.e. accelerator, near detector and far detector) with respect to one another. The second is to ensure the internal sub millimetric alignment of the component parts of the two ends of the experiment. Tolerances for absolute alignment of the NuMI MINOS and CNGS projects were ±75 m (~21 arc seconds) and ±37.5 m (~10 arc seconds) respectively. However, the pointing error of the NuMI MINOS was ±12 m or 3.4 arc seconds. Achieving this tolerance requires a fairly exact knowledge of the geometry of the beam, expressed in terms of the azimuth and the slope of the vector joining the two sites.

With modern GNSS surveying techniques, in principle the error in the absolute positions of the origin and target of the beam line contributes little to the overall error budget. Knowledge of the gravity vector at the origin is far more important because it defines the reference surface (vertical datum or geoid and the deviation of the vertical) upon which the alignment and aiming of the beam line components is based. Recall at CERN, vertical deflections were determined to range between 0 and 15 arc seconds at surface level and between 0 and 9 arc seconds at underground. To this end, extensive work was done at both CERN and Fermi lab to better understand the shape of the geoid. At CERN, the geodetic problem is further complicated by the fact that only one underground point, near the origin, can be directly linked to the surface network through a shaft. As a consequence, the final azimuth of the beam relies upon 2 km of accurate gyro-theodolite measurements in addition to a very good knowledge of the local geoid. The problem in the NuMI MINOS experiment is complicated by the fact that the MINOS neutrino detector is located 710 m below the surface in a cavern in the Soudan mine. This required an extensive inertial survey to connect it the experiment to the surface. [8, 12] All of the cited neutrino experiments are operational (K2K operated successfully between 1999 and 2004) attesting to the quality of the alignment.

2.5 Future Accelerators, Real Time Monitoring and Ground Motion Measurements

At present at least two new high energy physics linear accelerators are on the drawing boards; an international collaboration referred to as the International Linear Collider (ILC) and the CERN Compact Linear Collider (CLIC). As their names imply, both of these projects are linear accelerators. Present overall design lengths are 31 km and 48.2 km for the ILC and CLIC respectively.[14] Alignment requirements for adjacent components are 3 µm. However, the tolerances are scale dependent. The most stringent requirement is only for components within about 160 m of the point of investigation; further downstream the tolerances quickly drop off. [13] Nevertheless, placement errors of several consecutive elements of 3 µm over 160 m will be particularly challenging and certainly require real time monitoring and alignment systems. [14]

[14] For more information on the ILC project refer to http://www.linearcollider.org/cms/
For more information on the CLIC project refer to http://clic-study.web.cern.ch/CLIC-Study/

At this level of uncertainty, the earth is in perpetual motion. For this reason, considerable efforts have been made in the accelerator alignment community to develop instruments capable of measuring real time ground displacements.[15] For example, because of the relative instability of the ground, engineers and physicists in Japan have extensively studied ground motion at a large variety of sites. [15] These studies have been made using both accelerometers as well as high precision HLS.

The positions of the active detector elements within a large scale physics experiment such as ATLAS must be very well known to accurately reconstruct tracks left by long lived charged particles. Short time scales and complex deformations of the 5.6 m long ATLAS Semi-Conductor Tracker (SCT) must be determined to a precision of 12 µm for appropriate corrections to be applied to the particle physics analysis. Even the impressive alignment results achieved in the assembly of the ATLAS detector with *classical* survey techniques are insufficient for these operational alignment requirements. Furthermore, conventional survey techniques cannot be used inside the operational particle tracker of ATLAS, due to its inaccessible, confined spaces and high radiation levels. To overcome these challenges a novel alignment system was developed to remotely measure the tracker shape on a time scale of a few minutes. This alignment system consists of a grid of length measurements between nodes attached to the ATLAS SCT. Combining these measurements allows the node positions to be reconstructed and interpolated to determine the co-ordinates of the active detector elements. The 842 lengths in the geodetic grid will be measured simultaneously, to a precision of < 1 µm using a purpose developed technique referred to as Frequency Scanning Interferometry. [16]

Alignment given by classical surveying techniques provides a base line from which high precision real time monitoring systems take over. This complementarity is employed often in accelerator alignment. A recent study encompassing the ten year period ending in January 2010 found that the standard deviation of vertical ground movements over the 842 m ESRF Storage Ring (SR) machine circumference was 0.93 mm. However, there were also highly systematic peak to peak movements of ±2 mm. At the ESRF, a combination of HLS, levelling and motorised jacks are used to monitor and provide active realignment while the machine is in operation. This allows the machine physicists to both follow and perfection the realignment in real time. A similar active monitoring and alignment scheme using HLS and WPS is employed on the low beta quadrupoles that focus the proton beams to the interaction point in the LHC. [17]

Challenging alignment issues are not limited to future linear colliders and large scale physics experiments. The ESRF is presently in the process of implementing an upgrade program to prepare for future synchrotron radiation science requirements. This upgrade program will provide the ESRF with a unique opportunity to continue and improve upon its world-leading role in the development synchrotron X-ray science. A programme of instrumentation development is underway, encompassing new detectors, focusing optics, sample environments and beamline engineering at the nanometre level. Exploring, manipulating and

[15] A fairly comprehensive summary of tolerance requirements and ground motion measurements can be found at http://www-project.slac.stanford.edu/lc/wkshp/gm2000/proceedings/_the_proceedings.pdf

designing forms of matter at the scale of nanometres (i.e. 10^{-9} metre) is a rapidly expanding area, particularly in electronics, medical diagnosis and treatment, and consumer manufacturing. In addition to being extremely small, nanoscale objects have exceptional properties linked to their high surface area to volume ratio. Imaging nanoscale features in larger objects will provide better insight into the interactions within living cells and the functioning of man-made materials, including catalysts and electronic devices. These future ESRF nanometre beamlines are between 120 and 150 m long.[16] Ensuring nanometres over 150 m is indeed challenging.

Recently in the cadre of studies made for the upgrade program, an HLS monitoring experiment made on the existing ESRF experimental hall slabs showed similar highly systematic movements to those observed on the machine slab. These systematic movements at the edges of the experimental hall floor slabs appear to be related to thermal gradient changes in the slab. Curling is intrinsic to all concrete slabs. However, only recently has the magnitude of this curling become an issue for accelerator alignment.

Depending upon the proximity to the slab edge, temperature changes of ±0.5 ° Celsius were found to induce vertical curling motion between 1 µm and 7 µm over a 12 hour period. Although these movements are extremely small, one must recall that the nanoscale experiments described above are installed on the experimental hall floor slab. In addition to vertical motion, slab angular deviations of up to 2.5 µrad over the same 12 hour time period were also observed. Note that an angular deviation of 2.5 µrad is equivalent to vertical movement of 375 µm at a distance of 150 m. Ground movement studies have always been an important activity at the ESRF. However, recently they have become vital in the definition of the construction parameters of the new experimental hall slab being designed for the ESRF upgrade beamlines. [18]

3. INSTRUMENTATION

To attain the requisite accelerator alignment tolerances, special techniques and high precision instrumentation must be used. For their primary networks most accelerator alignment groups use either laser tracker instruments (e.g. SLAC, APS, ALBA) [19, 20] or high precision robotic total stations (e.g. ESRF, SOLEIL). [2, 21] In addition, certain facilities use wire offset devices in the final smoothing of the machine (e.g. CERN, SOLEIL).[2, 9] For the huge CERN experiments a mixture of classical survey techniques and digital photogrammetry was used. [22, 23] For the alignment of the CNGS and NuMI MINOS neutrino experiments and the determination of the gravity vector a combination of GNSS, inertial/gyro theodolite and astro-geodetic techniques were employed. [7, 8, 12]

Alignment techniques for the proposed future linear colliders rely upon a variety of innovative techniques. One proposition is to install a type of remote controlled train system to provide a monitoring system for the exceptionally long tunnels required for the proposed ILC. [24] For the CLIC, a combination of WPS and HLS are proposed. [14] WPS and HLS systems are based on a high precision capacitive probe system measuring to a reference. In the case of the

[16] http://www.esrf.fr/AboutUs/Upgrade

HLS the reference is a water surface. With the WPS, the reference is a stretched wire. These systems have resolutions in the order of the micro-metre and uncertainties in the order of 5 to 10 μm over extended time periods. [25] Studies to maintain the straightness of the new 3.4 km long European X-Ray Laser Project XFEL have been made using the so-called Poisson-Alignment-System. [26] For the ground motion studies, a combination of high precision levelling, HLS and velocity sensors are used. [15, 18, 27]

Finally, instrument calibration is an integral part of the accelerator alignment activity. SLAC, CERN and the ESRF all have highly developed instrument calibration activities for HLS, WPS as well as laser trackers and robotic total station distances and angles. [28-32]

4. SUMMARY

Virtually all accelerators and related experiments, regardless of their scientific application area, require precise alignment to operate correctly. The field of accelerator alignment overlaps the fields of metrology and traditional surveying and geodesy. Standard measurement precision is millimetric to sub-millimetric over distances ranging between several hundred metres up to nearly 30 km. New and planned machines as well as experiments go beyond even this and require micro-metre alignment precision on the same scales. The use of specialised techniques and instruments are needed to guarantee that these requirements can be met. This paper has provided a brief overview and characteristic examples of different techniques, instrumentation, and results related to the broad and dynamic field of accelerator alignment. For reasons of brevity and space, important techniques and examples have been omitted. Interested persons are encouraged to consult the comprehensive IWAA collection of articles related to accelerator alignment for more detailed information concerning subjects only touched upon here. [1]

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