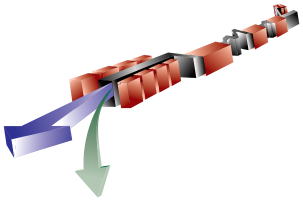
12 Alignment



TECHNICAL SYNOPSIS

This section describes the procedures and methods used to position the LCLS components with their required accuracy. Most of the alignment requirements are well within the range of proven traditional alignment techniques. Alignment of the undulator section is the most demanding. State-of-the-art equipment and procedures will be needed to meet the positioning requirements.

The alignment coordinate system will be the existing Cartesian right-handed system, which was implemented for the SLC project and was also used for the PEPII project. The alignment network will consist of four parts: a small surface network to better integrate the remote hall into the global coordinate system, and three tunnel networks for linac, undulator and transport lines / experimental areas alignment. The network geometry is driven by the tunnel and machine layout and should permit observation of each target point from at least three stations. The design philosophy is based on a 3-D monument design providing the best possible positional accuracy. For the undulator hall network, a triplet of monuments is placed in the tunnel cross-section at each quadrupole location. The other networks are constructed similarly but with fewer monuments.

The alignment instrumentation will be a laser tracker / digital level used in combination. In conjunction with least-squares solutions, the laser tracker will provide excellent 3-D positional accuracy. In addition, the digital level will improve the rotational stability of the narrow linear network. To meet the global straightness and local relative alignment needed for beam-based alignment to converge quickly, the optical measurements will be supported by stretched-wire based straightness measurements and by hydrostatic level system measurements. The position tolerances of injector, linac, transport line, and experimental areas are achievable with standard alignment procedures.

12.1 Procedural Overview

The alignment of the undulator system will be carried out in four distinct steps:

During installation, conventional alignment methods will be used to position the undulator segments, quadrupoles, correctors, BPMs and other components to about 150 µm. Position adjustments will be applied mechanically, i.e., the remote movers will not be used for this task.

To refine the installation alignment and after system changes, the effective centerline of undulator segments, and quadrupoles will be aligned to 50 µm, of BPM modules to 100 µm, with respect to a global straight line. This global straight line may deviate significantly from the nominal axis (which is an extension of the axis of the linac) in position and orientation. A stretched wire system with sensors capable of absolute measurements will be used in the horizontal plane to achieve a 50-µm tolerance. The same tolerance will be achieved in the vertical dimension with the use of an absolute measuring Hydrostatic Level System. Position adjustments will be done remotely for the undulator segments and the permanent magnet quadrupoles, and locally for the BPM modules.

The relative position difference between quadrupoles and adjacent undulator segments will be mapped and recorded. A measurement tolerance of significantly better than 50 µm is expected.

After the conventional alignment and thereafter at periodic intervals of a few weeks, as needed, the Beam-Based-Alignment procedure as described in **Chapter 8**, **Section 8.12** will be applied. The Beam-Based-Alignment procedure moves the quadrupoles to correct the electron beam trajectory and moves the undulator segments to maintain relative alignment to the quadrupoles. This procedure will create a straight beam trajectory (2 µm rms deviation from a straight line both horizontally and vertically over a distance of 10 m). Once this is achieved, the BPM readings will be recorded as the reference zero positions. The BPM modules are expected to move transversely, mostly due to ground motion, by a few micrometers in between two applications of the Beam-Based-Alignment procedure. A high resolution monitoring system will record any BPM motion; this data can then be used to correct BPM readings. Successive alignment procedures are expected to be much quicker than the initial procedure. Feedback systems will be employed to keep the trajectory straight to the BPM modules by using the movable quadrupoles as correctors.

If it turns out that initially the x-ray beam, as produced by the undulator, points too far away from the desired target points in the experimental halls, iterations of the above step sequence can be used to re-point the undulator.

12.2 LCLS Surveying Reference Frame

Horizontal position differences between the projection of points on the geoid[1], or a best fitting local ellipsoid, and those on a local tangential plane are not significant for a project of the size of the LCLS. Hence, it is not necessary to project original observations like angles and distances into the local planar system to arrive at planar rectangular coordinates [1].

However, in the vertical plane, the curvature of the earth needs to be considered (see **Figure 12.1**). Because leveling is done with respect to gravity, the reference surface is the geoid. Due to the relatively small area of the LCLS project, one can substitute the nonparametric geoid with a locally best-fitting sphere. **Table 12.1** shows the projection differences between a tangential plane and a sphere as a function of the distance from the coordinate system's origin. Notice that for distances as short as 20 m the deviation between plane and sphere is already 0.03 mm.

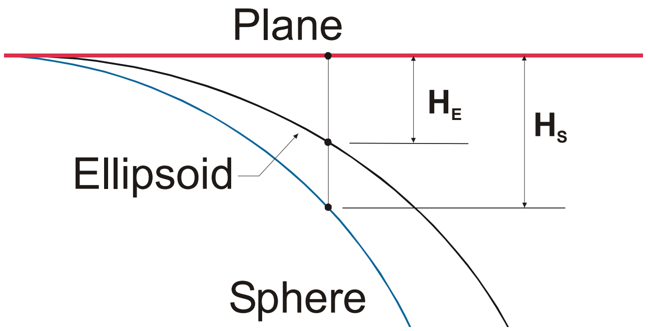


Figure 12.1 Effect of earth curvature.

Table 12.1 Curvature correction

Distance r [m]	Sphere H_S [mm]
20	0.03
50	0.20
100	0.78
1000	78.46

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[1] The geoid is the reference surface described by gravity; it is the equipotential surface at mean sea level that is everywhere normal to the gravity vector. Although it is a more regular figure than the earth's surface, it is still irregular due to local mass anomalies that cause departures of up to 150 m from the reference ellipsoid. As a result, the geoid is nonsymmetric and its mathematical description nonparametric, rendering it unsuitable as a reference surface for calculations. It is, however, the surface on which most survey measurements are made as the majority of survey instruments are set up with respect to gravity.

12.2.1 Network Design Philosophy

The global alignment tolerance, the relatively weak links between machine sections, and advances in surveying make it possible for most of the machine to forego the traditional design of a two-tiered network hierarchy (surface and tunnel networks) covering the whole machine. Instead, each machine section can be considered independent, only connected by tunnel networks. Omitting a primary network not only removes many constraints for component placement, because fewer lines-of-sight need to be maintained, but also presents a significant reduction in alignment costs. The only exception here is a small surface network which is required to connect the remote experiment area into the coordinate system of the undulator.

Traditionally, forced-centered[2] "2+1-D" triangulation and trilateration techniques[3] were used to measure tunnel networks. However, a 3-D "free stationing"[4] approach does not require forced-centered instrument setups, thus eliminating the need for setup hardware and its systematic error contributions. Removable heavy-duty metal tripods, translation stages, CERN sockets, and optical plummets are not needed (see **Figure 12.2**). The network design still must consider other systematic error effects, especially lateral refraction[5]. Another important consideration is the target reference system. Its design becomes much easier with free stationing because we are dealing only with targets and not with instruments as well. Accordingly, it is proposed to use a 3-D design, which is now widely used in high precision metrology. This approach is centered around a 1.5 inch sphere. Different targets can be incorporated into the sphere in such a way that the position of the target is invariant to any rotation of the sphere. At SLAC, designs have been developed to incorporate theodolite targets (see **Figure 12.3**), photogrammetric reflective targets, as well as glass and air corner cubes (see **Figure 12.4**) into the sphere. Receptacles for the spheres,

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[2] Forced-centering refers to a specific instrument mount. This type of mounting system, whether vendor specific or independent, allows the exchange of instruments on a station without losing the measurement point, i.e. all instruments are by mechanical "force" set up in exactly the same position. However, experience has shown that even the best of these forced-centering systems has centering error of about 50-100 μm. Unfortunately, the forced-centering system contributed error is not random. Because a whole set of measurements is usually completed from a slightly offset position, this error behaves mostly systematically. No efficient method is known to determine the offset vector. These errors, vertical refraction and lateral refraction, are the biggest contributors to the systematic error budget in surveying engineering.

[3] 2+1-D refers to the fact that because of mechanical problems in the forced-centering hardware, three-dimensional networks were usually split into separate horizontal (2-D) and vertical (1-D) networks. Both networks were established, measured, and analyzed separately.

[4] Rather than set up the instrument over a known point, the instrument's position is flexible and chosen only following considerations of geometry, line of sight, and convenience. To determine the instrument position, at least three points, whose coordinates are already known or are part of a network solution, need to be included in the measurements.

[5] Lateral refraction is caused by horizontal stationary temperature gradients. In a tunnel environment, the tunnel wall is often warmer than the air. This creates vertical stable temperature layers with gradients of only a few hundredths of a degree Celsius per meter. If one runs a traverse close to a tunnel wall on one side only, the systematic accumulation of the effect can be significant; e.g., during the construction of the channel tunnel, a control measurement using gyro-theodolites revealed that after about 4 km the tunnel had already veered about 0.5 m off the design trajectory.

which are usually referred to as “nests” or “cups,” have been designed to accommodate different functions. Designs are available at SLAC for cups grouted into the floor, tack-welded onto magnets, mounted on wall brackets, and for a “centered” removable mounting placed into tooling ball bushings (see **Figure 12.5**). This reference system performed very well in the alignment of PEP-II components.

12.2.2 Network Layout

The alignment network consists of four parts: injector, linac, undulator, and transport line/experimental area.

12.2.2.1 Injector Network

The injector network will support the survey and alignment of the injector components. Standard networking design and measurement techniques can be used since the injector components have fairly loose positioning tolerance requirements. A horizontal sight pipe through the shielding wall will allow a connection of the reference systems in the injector and linac tunnels.

12.2.2.2 Linac Network

The linac network serves a different purpose than the other networks. Because the linac already exists, the linac network does not need to support construction survey and alignment, but rather will only provide local tie-points during the linac straightening (smoothing) procedure (see chapter 12.5.2).

12.2.2.3 Undulator Hall Network

The Undulator Hall network’s overall geometry is dictated by the tunnel geometry, machine layout, and the fact that the free-stationing method requires a greater number of reference points. The geometry should also permit observing each target point from at least three different stations. The reference points can be of two different hierarchical classes. The second order points, or tie points, mainly serve to connect the orientation of free-stationed instruments, while the first order points additionally provide the geometric reference during machine installation; they are the equivalent of traditional traverse points or monuments.

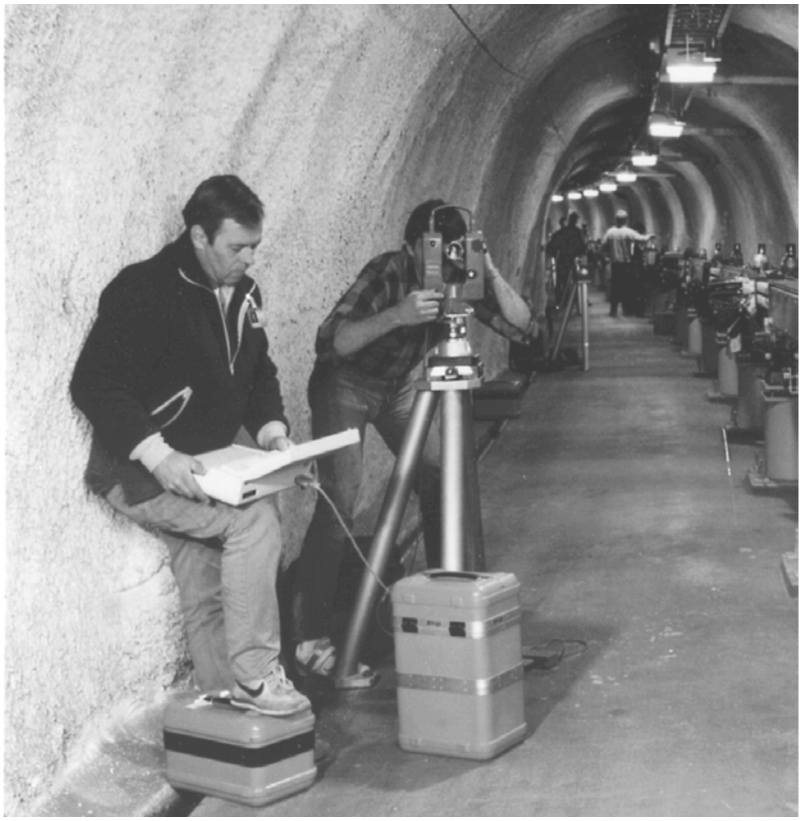

Figure 12.2 Forced-centered setup in SLC tunnel

Figure 12.3 Sphere mounted theodolite targets

Figure 12.4 Sphere mounted glass and air reflectors

Figure 12.5 Sphere receptacles: floor, component, and wall barcket fixed-mount version, removable centered version.

Figure 12.6 shows a typical section of the layout. A triplet of monuments is placed in the tunnel cross section containing a quadrupole magnet. One monument will be placed on the floor close to the quadrupole magnet, the second one mounted to the aisle wall at instrument height, while the third monument is mounted to the back wall.

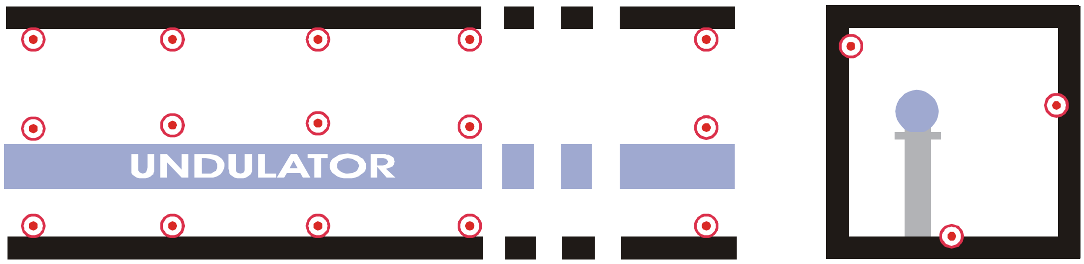

Figure 12.6 Undulator Hall Network layout (plan view & cross section)

12.2.2.4 Transport Line/Experimental Area Networks

The transport line networks (undulator to near experimental area, near experimental area to remote experimental area) will support the survey and alignment of the transport line components. Standard networking design and measurement techniques can be used since the transport line's components have very loose positioning tolerance requirements. The network for the transport lines will be constructed and established similar to the Undulator Hall network. The only differences being that each cross section will have only two monuments, one mounted to the wall on the component side at instrument height and the second one in the floor close to the aisle side wall; the longitudinal spacing will be about three times the spacing in the undulator area.

The directional accuracy of the transport line networks is not sufficient to support the component installation and position requirements in the remote experimental area. A small surface network is necessary to accurately connect this area to the undulator. Present GPS technology easily supports the accuracy requirements. To physically establish the network, about ten concrete monuments equipped with forced-centering adapters need to be constructed. The monument design will be based on the SLC surface monuments. To connect GPS measurements to the undulator axis, the axis needs to be referenced to monuments on the surface. Existing sight shafts in the Beam Switch Yard (BSY) and additional new shafts in the undulator enclosure in the Research Yard will provide the necessary sight connections.

12.2.3 Alignment Coordinate System

The alignment coordinate system will be a Cartesian right-handed system. The origin will be placed at Linac Station 100 (analogous to the SLC coordinate system). There will be no monument at the origin, it is purely a virtual point. The *y*-axis assumes the direction of the gravity vector at the origin but with opposite sign. The *z*-axis is in the direction of the linac, and the *x*-axis is perpendicular to both the *y* and *z*-axes. The signs are defined by the right-handed rule (see **Figure 12.7**).

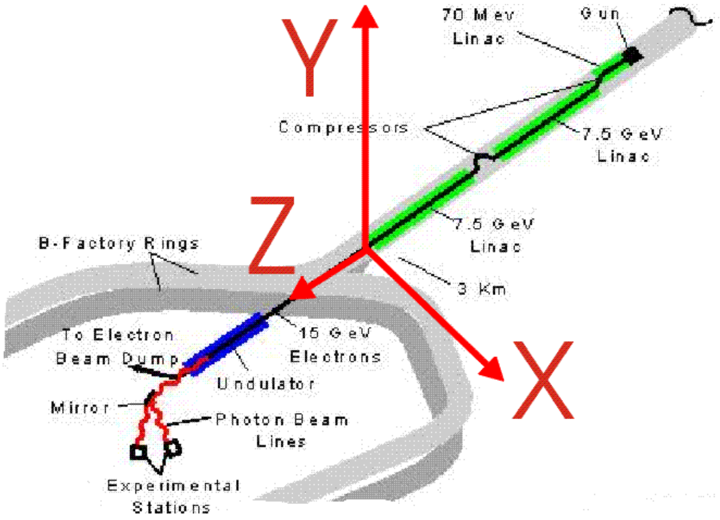

Figure 12.7 Coordinate system definition

12.2.4 Tunnel Network Survey

The most efficient instrumentation for the network observations will be the combination of a laser tracker (see **Figure 12.8**) with a digital level. The alignment group has available state-of-the-art laser trackers (SMX4500, SMX Keystone) , Total Stations optimized for industrial metrology (Leica TDA5000 and TC2002), and digital levels (Leica NA3000, Zeiss DiNi11). Laser trackers will contribute mainly to horizontal positional accuracy and digital levels to vertical positional and rotational accuracy.

Figure 12.8 Target operator carries the SMX laser tracker reflector.

A laser tracker will be placed close to the middle between adjacent reference point cross-sections (see **Figure 12.9**). From there, nine points in the forward direction and nine points in the backward direction will be measured. The measurement procedure will include two sets of distance and direction measurements to the same eighteen points in both front and reverse instrument orientations. All reference points will also be observed with a standard high precision double-run level procedure. A Zeiss DiNi11 digital level in combination with 2 m invar rods is envisioned.

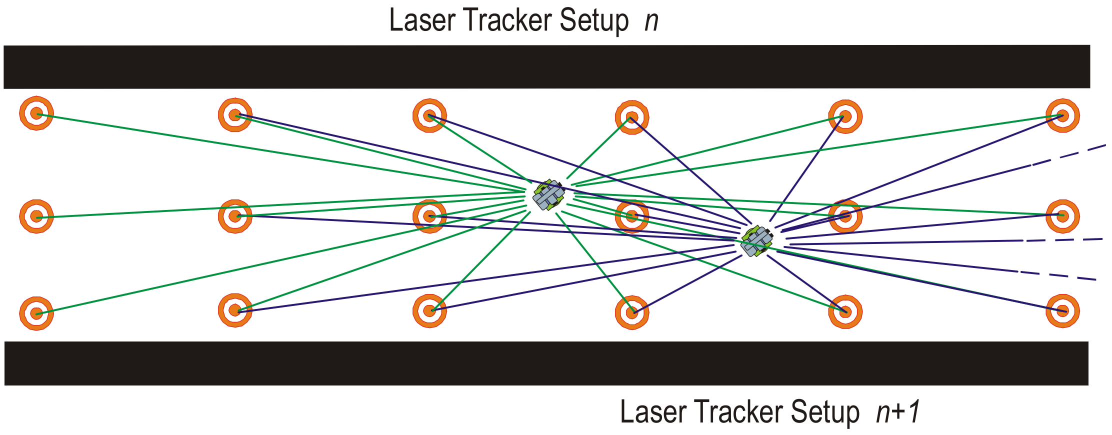

Figure 12.9 Observation plan

12.2.5 Surface Network

Standard GPS technology will provide the required accuracy. The equipment is available at SLAC (Leica 530 receivers). To connect GPS measurements to the undulator axis, the axis needs to be referenced to monuments on the surface. Monuments above and below the shafts will be referenced by optical plummet (Leica NL) measurements. The monuments below the shafts will be integrated into the regular tunnel network. The BSY shaft points will be linked to the undulator hall network by a temporary network. The monuments above the shafts will be connected to adjacent network monuments by GPS or optical triangulation measurements.

12.2.6 Data Analysis and Data-Flow

To reduce the data from the measurements as described above, specialized software has been developed. This type of analysis software is based on the photogrammetric bundle approach. Because a photogrammetric sensor is arbitrarily oriented in space, not only its translational parameters but also its rotational orientation parameters must be treated as unknowns and become part of the solution. With traditional trilateration/triangulation-based analysis software, however, pitch and roll are supposed to be oriented to gravity, and yaw is expressed as a function of translations. Additionally, the traditional software assumes that the instrument is centered on a point to which sufficient measurements have been taken. This analysis approach does not work well with free-stationing, and does not work at all with present generation laser trackers, since they cannot be oriented accurately enough to gravity. The code needs to be expanded to also accept GPS baselines, azimuth measurements and observations derived from the Hydrostatic Level System (HLS) and stretched wire systems.

To reduce errors stemming from transcription of data, the data-flow will be automated. The suggested instruments support direct connection to field computers. The fully automated data-flow will extend from field computers through data analysis to data storage.

Measurements with any type of instrument will be guided by software based on rigid procedures running on field data logging computers. The data-logging software will also pre-analyze the measurements, in an attempt to determine and flag possible outliers before the measurement setup is broken down. This method combined with an automated data-flow will greatly reduce errors and improve measurement consistency and reliability.

12.3 Layout Description Reference Frame

12.3.1 Lattice Coordinate System

The LCLS lattice is designed in a right-handed beam-following (s-axis) coordinate system, where the positive y-axis is perpendicular to the design plane, the z-axis is pointing in the beam direction and perpendicular to the y-axis, and the x-axis is perpendicular to both the y and z-axes.

12.3.2 Tolerance Lists

The alignment system is designed based on the tolerances listed in **Table 12.2**.

Table 12.2 LCLS positioning tolerances

	σ_x [μm]	σ_y [μm]	σ_r [mr]	σ_x/z [μm/m]	σ_y/z [μm/m]
Relative alignment between undulator sections	100	50	1	n/a	n/a
Global straightness of undulator	n/a	n/a	1	300/120	50/120
Quadrupole ab initio	50	50	n/a	n/a	n/a
Linac straightness	n/a	n/a	n/a	150/15	150/15
Injector components	150	150	1	n/a	n/a
Experimental area components	1000	1000	n/a	n/a	n/a

n/a = not applicable

12.3.3 Relationship Between Coordinate Systems

The relationship between the surveying and lattice coordinate systems is given by the building design and machine layout parameters. The result is a transformation matrix (rotations and translations).

12.4 Fiducializing LCLS Magnets

The correct fiducialization of magnets is as important as their correct alignment since an error in either task will affect the particles' trajectory and cannot be distinguished from each other. Fiducialization can be accomplished either through opto-mechanical and opto-electrical measurements or by using fixtures, which refer to a magnet's reference features. Detailed descriptions can be found in the literature [2].

The most demanding task is the vertical positioning of the undulator to 50 µm over the total length. Since the undulator sections will be aligned relative to their adjacent downstream quadrupoles, both the undulator segments and the quadrupoles need to be fiducialized to better than 25 µm in order to leave a reasonable error budget for the alignment process.

The quadrupoles are permanent magnets of fairly small size. Hence, thermal expansion can be neglected. It is planned to use the same pulsed wire/straightness interferometer technique as was used to fiducialize the VISA undulator magnets [3]. Such a pulsed wire test stand prototype has been developed and setup at SLAC, and it has been demonstrated that the axis of an undulator quadrupole prototype can be repeatably determined to better than 5 µm.

While most of the magnetic measurements of the undulator segments will be carried out elsewhere, it is deemed necessary to check these measurements at SLAC to verify the magnet's homogeneity after transportation across the country (see also **Section 8.3.3**). The fiducialization measurements will become an integral part of the magnetic measurements. This can be accomplished by integrating a Coordinate Measurements Machine (CMM) into the test stand setup.

Components for the injector, linac, and dump line will be fiducialized using standard techniques.

12.5 Absolute Positioning of Components

Common to all parts of the machine, free-stationed laser trackers, oriented to at least four neighboring points, are used for the absolute positioning measurements. The tracking capabilities of these instruments will significantly aid in facilitating the control of any alignment operation (moving components into position).

12.5.1 Undulator Absolute Positioning

The absolute positioning is carried out in several steps. At first, the anchor hole positions for the component supports are marked on the floor. Next, after the supports and the magnet movers are installed, they will be aligned to within 0.5 mm of their nominal positions in order to retain as much mover range as possible. At this stage, the components can be installed. Since the components mechanically register to the support/magnet mover geometry, the installation will already place them to within 0.5 mm. Finally, the position of the components will be surveyed and adjusted using a laser tracker in reference to adjacent network points. Absolute position accuracy relative to the network points of about 150 µm can be achieved.

12.5.2 Injector, Transport Line and Experimental Area Absolute Positioning

The absolute positioning of these components will follow the same procedure as described above. No relative alignment step is required to achieve these position tolerances.

12.5.3 Quality Control

Once the above steps are completed, the components will be mapped as a quality control measure. If any positional residuals exceed the tolerance, a second iteration can be "jump started" by using the quality control map to quantify the position corrections, which then need to be applied. A quality control survey will always follow the completion of the alignment process.

12.6 Relative Alignment

12.6.1 Relative Undulator Alignment

12.6.1.1 Introduction

The undulator sections will be aligned relative to their downstream quadrupole. The quadrupole position is a result of an initial optical/mechanical alignment process, which subsequently is refined by a beam-based alignment procedure[6]. For the beam-based alignment algorithm to converge efficiently, a 50 µm *ab initio* placement is desired. Taking fiducialization error contributions into account, these quadrupoles need to be aligned to 30 µm over a string of three quadrupoles. BPMs, taking fiducialization and acquisition errors into account, need to be aligned to 80 µm relative to adjacent quadrupoles.

12.6.1.2 Relative Quadrupole Positioning

In principle, the absolute alignment process is repeated with the important difference, however, that measurements to a quadrupole are taken with respect to its neighbors and not to network points. Consequently, systematic errors stemming from the network are not propagated into the relative quadrupole positioning. This step will yield a position tolerance of about 80 µm.

To achieve the required accuracy, each quadrupole will be referenced by means of a laser tracker and Pellisier level [4] to a hydrostatic level system (HLS) and a stretched wire system (SWS), both equipped with sensors, which can be calibrated for absolute measurements. The absolute measurement requirement precludes the use of commonly used relatively inexpensive capacitive and inductive sensors, which will later be installed for monitoring purposes. Instead, a single specially developed sensor[7] each for both the SWS and HLS will be used on all

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[6] The electron trajectory within the undulator needs to be straight to a high degree of accuracy so that the undulator radiation overlaps the electron beam sufficiently within each gain length of the undulator. This level of trajectory straightness, ~2 μm rms over 10 m, cannot reliably be achieved with optical alignment methods. Therefore, a beam-based alignment technique has been developed that determines quadrupole position corrections from BPM readings as a function of large, deliberate variations in the electron energy. Remotely controlled movers are used to apply the corrections. For an in-depth discussion see **Section 8.1.1**.

[7] Sensors have been developed in the framework of a collaboration with DESY on the development of the "Rapid Tunnel Survey System" for future linear colliders.

measurement points [5, 6, 7]. It is planned to use a single 130 m long wire[8]. First simulations show absolute station standard deviations of less than 150 µm without wires and less than 40 µm with wire measurements. A hydrostatic leveling system based on the half-filled pipe approach will also be integrated into the undulator support system. Experience at CERN has demonstrated that a vertical plane over the length of the undulator can be established to better than 25 µm with the utilization of a hydrostatic level system.

The combination of all these measurements will yield position results better than 50 µm over a string of three quadrupoles horizontally and over the whole length vertically including fiducialization errors.

12.6.1.3 Undulator Alignment

After the quadrupoles are aligned, the undulator segments can now be accurately positioned using the same combination of optical alignment procedures and HLS/SWS measurements as were used before for the quadrupole alignment. The difference in the HLS/SWS readings to an undulator section and to its adjacent quadrupole will be stored and, after the completion of a beam-based alignment iteration, used to restore the undulator-to-quadrupole relative alignment.

12.6.1.4 Quality Control

After all position adjustments are completed, a final mapping of all undulator, quadrupole, and BPM fiducials is carried out.

12.6.2 Linac Smoothing

12.6.2.1 Purpose of Linac Smoothing

To generate an optimal beam for injection into the undulator, the present local straightness of the linac is not sufficient. To achieve the desired beam parameters, the straightness quality needs to be mapped, and where necessary mechanically adjusted. In particular, the straightness of individual linac structures, the straightness alignment of structures on a girder, and the relative alignment of the sections on either side of a quadrupole with respect to each other and with respect to all other components need to be mapped.

12.6.2.2 Linac Straightness Measurement Procedure

Because of the required resolution, reliability and the large amount of work (about 1 km of beam line), the task is best performed with a system which does not require an operator to point and adjust micrometers. It also should allow online data logging. It is therefore proposed to use a laser system developed by Hamar [8]. The instrument generates two laser light planes by bouncing a laser beam off rotating mirrors. The two light planes are truly perpendicular to each other. The flatness or wobble-induced error of each light plane is specified as 5 µrad, which is well below the straightness specification at maximum distance. The light source would be set up at about the

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[8] Stretched wire measurements over an equivalent distance are performed routinely at the CTF, CERN.

middle between two quadrupoles offset horizontally and vertically such that the light planes clear all beam line components. This setup, versus a setup at an endpoint, reduces the length of the line-of-sight to about 5 m, thus greatly lessening the effects of potential refraction and air turbulence on the light beam. After aligning the light planes both horizontally and vertically to two points on the measured object, intermediate offsets between, for example, the accelerator structure and the light planes are measured with a photo-sensitive-detector (PSD) attached to an offset arm. The detector is linked to an interface box by a cable, which can be as long as 15 m. The interface box provides a serial link to a data logger. To measure the offsets, the offset arm is held against the accelerator structure sequentially in both planes. To determine the perpendicular offset, the alignment technician will arc the arm. While the arm is being arced, the light position is continuously read-out and stored. Software will then determine the perpendicular offset by finding the smallest read-out value. Because the PSD measurement range is limited to about 8 mm, the arm will be adjustable in length. To avoid errors due to the adjustability, the adjustment length will be monitored by an electronic dial gauge, which also reports its reading to the data-logging software. The total straightness measurement error budget is expected to be below 75 µm.

The relative alignment of a linac quadrupole in relation to its adjacent accelerator sections will be determined analogously. However, since these quadrupoles are not fiducialized and also do not have any precision reference surfaces, the offset will be measured to their BPMs instead. Each BPM has a cylindrical body, which is inserted between the poles with a very close fit, and protrudes from the poles on either side of the magnet. The BPM is expected to reference the magnet's axis to about 100 µm. The adjustment range of the offset arm will be adequate to allow the same arm to measure both BPMs and accelerator structure offsets.

The readings will be evaluated using "smoothing" software developed for the alignment of the SLC arcs [9]. Position corrections will be applied under the control of a laser tracker. The present support systems are mechanically adequate.

12.6.3 Relative Alignment of Transport Line and Experimental Area Components

The position tolerances of these components will be achieved during the absolute alignment step. A relative alignment is not required.

12.7 Undulator Monitoring System

In order to keep the undulator optimally tuned, the BPMs must not drift from their position at the time of the last beam-based-alignment by more than a few µm. A high resolution monitoring system will be installed to measure possible BPM position drifts, and subsequently, correct BPM readings. Additionally, the system can be used to independantly verify position changes intentionally induced by the magnet mover system.

Monitoring sensors should always be mounted in the respective principle measurement planes to avoid first order measurement errors. However, because of geometrical and mechanical lay-out limitations, this is here not possible. Placing the sensors away from the principle planes can cause errors due to non-zero roll or pitch, respectively. In order to be able to correct for possible errors, roll and pitch need to be accurately determined. Hence, a minimum of three sensors each for the horizontal and vertical plane monitoring systems are required; for redundancy reasons four sensors of each type per unit would be preferable (see **Figure 12.10**, and **Figure 12.11**). Both systems are controlled by a common PC based data acquisition system which is interfaced to the machine control system.

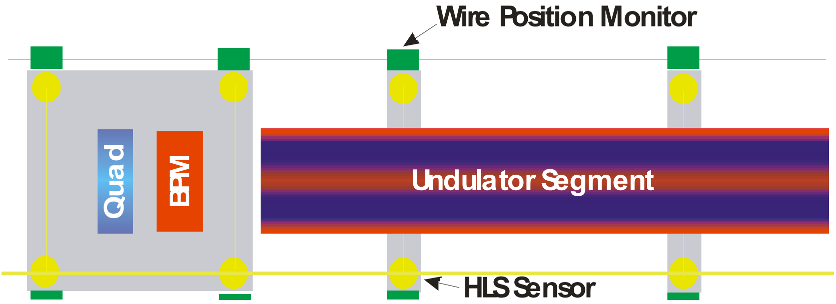

Figure 12.10 Monitoring System Layout, HLS (yellow), Wire System (green)

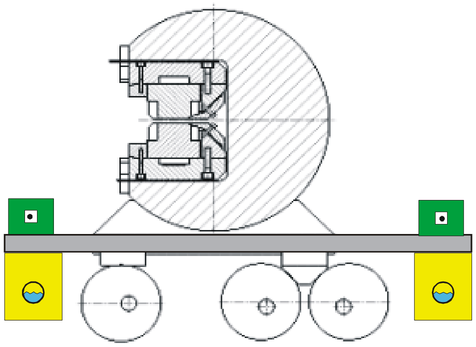

Figure 12.11 Monitoring System Lay-out Cross-section

Because there is no natural absolute reference in the horizontal plane, some kind of artificial local reference needs to be created as is done by stretched wires. Two wires, one on either side of the undulator sections/magnets will provide the straight line reference (see **Figure 12.12**). Inductive sensors will provide wire position information. The system is modeled after the FFTB wire monitoring system. Each Wire Position Monitor (WPM) is similar to a beam position monitor (BPM) in that it contains 4 antennas and that the differential signal strength received from opposite pairs of antennas is the quantity of interest. However, unlike a BPM, which receives its signal from a packet of charged particles, the WPMs receive their signals from a stretched wire, which is excited at the fixed end with a 3 W, 140 MHz signal and which is grounded through a 250 W resistor at the pulley end. The wire is contained inside an 8 mm (inner diameter) brass tube. The tube serves as the outer conductor in a coaxial structure which presents a constant impedance to the 3-Watt signal and which shields the signal from the outside world where it would interfere with FM radio broadcasts. A precision-made aluminum extrusion provides a straight and rigid support for the brass tube. The signals detected by the WPM antenna are mixed with a 50 kHz signal and are digitized with 16 bit ADCs, resulting in a resolution of better than 100 nm over a total range of ± 1.5 mm [10, 11, 12].

Figure 12.12 Wire Position Monitoring System

In the vertical dimension, a hydrostatic leveling system will accurately monitor relative and global vertical position changes. To eliminate temperature effects on the hydrostatic leveling results, the water piping must not deviate from a common horizontal plane. This condition is guaranteed using the "half-filled" pipe approach. Capacitive sensors like the ones developed by the BINP, FNAL, SLAC collaboration for NLC ground motion studies will be used (**Figure 12.13**) [13].

Figure 12.13 "Half-filled" pipe HLS Sensor

12.8 References

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