7. SLS Alignment Proposal

This chapter will describe procedures and methods which, carried out in a professional manor, will yield the aligned position of all SLS components within their position tolerances. Major geodetic principles governing the survey and alignment measurement space are briefly revisited and their relationship to a lattice coordinate system shown. The chapter then continues with a discussion of the activities involved in the step by step sequence from initial lay-out to final alignment.[i]

7.1 SLS Surveying Reference Frame

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

However, in the vertical plane, the curvature of the earth needs to be considered (see Fig. f71_a). Since leveling is done with respect to gravity, the reference surface is the geoid. Table t71_a shows the projection errors 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.

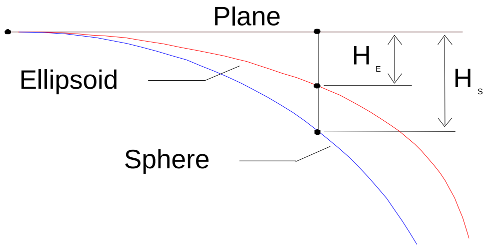


Fig. f71_a Effect of earth curvature

Distance r [m]	Sphere H_S [m]	Ellipsoid H_E [m]
20	0.00003	0.00003
50	0.00020	0.00016
100	0.00078	0.00016
1000	0.07846	0.06357

Table t71_a Curvature Correction

7.1.1 Network Design Philosophy

The global alignment tolerance and advances in surveying make it possible to consider foregoing the traditional design of a two tiered network hierarchy. Omitting a primary network not only removes many constraints for component placement since much fewer lines of sight need to be maintained, but also presents a significant reduction in alignment costs.

Omitting the global structural support of a "surface network" however increases the requirements for the tunnel network. It would be difficult to meet these requirements by traditional forced centered[iii] "2+1-D" triangulation and trilateration techniques.[iv] However, a 3-D "free stationing"[v] approach does not require forced centered instrument set-ups, thus eliminating the need for the set-up hardware and their systematic error contribution. Removable heavy duty metal tripods, translation stages, CERN sockets and optical plummets are not needed (see Fig. f711_a and f711_b). The network design still must consider other systematic error effects, especially lateral refraction.[vi] Another important consideration is the target reference system. The design of such becomes much easier with free stationing since we are dealing only with targets and not with instruments as well. Accordingly, it is proposed to

Fig .f711_a Forced Centered Set-up at SLAC

Fig. f711_b DESY HERA set-up

use a design which is now widely used in high precision metrology. This approach is centered around a 1.5"[vii] 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 into the sphere theodolite targets (see Fig. f711_c), photogrammetric reflective targets as well as glass and air corner cubes (see Fig. f711_d).

Receptacles for the spheres, which are usually referred to as “nests” or “cups”, have been designed to accommodate different functions. CEBAF has a very suitable design for nests to be grouted into the floor, and designs are available at SLAC for cups tack-welded onto magnets, for mounting cups on wall brackets and for a “centered” removable mounting into tooling ball bushings (see Fig. f711_e).

Fig. f711_c Sphere mounted theodolite target

Fig. f711_d Sphere mounted glass and air reflector

7.1.2 Network Lay-Out

The SLS global network consists of three part parts: the injector network, the synchrotron network and the beam line network.

7.1.2.1 Injector Network The injector network is a concatenation of four quadrilaterals, where the quadrilaterals are "rubber-banded" (stretched) to assimilate the geometry of the injector vault. The integration with the synchrotron network is accomplished through temporary windows at both ends of the vault, roughly in the axis of the injector.

Fig. f711_e Sphere receptacles: floor, component, and wall bracket fixed mount versions, removable centered version

7.1.2.2 Synchrotron Network The synchrotron network's overall geometry is dictated by the machine lay-out 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 long term global orientation; they are the equivalent to traditional traverse points or monuments. The following sketch (Fig. f7122_a) shows a typical section of the lay-out. A pair of monuments is always placed in the tunnel cross section containing a dipole magnet with one monument close to the dipole and

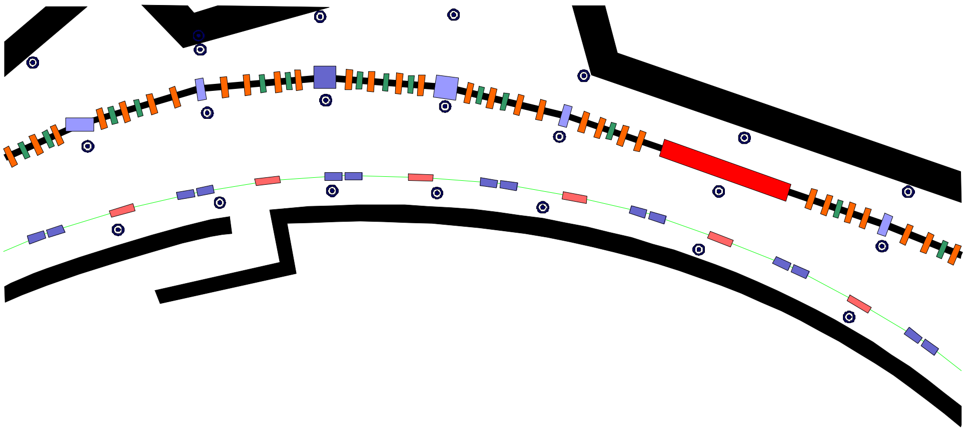


Fig. f122_a Section of synchrotron

the second close to the interior wall.

7.1.2.3 Beam Line Network The beam line network serves as a reference for the installation of photon chambers and experiments. The initial integration into the synchrotron network can be accomplished by measurements using lines of sight through the then open shielding wall sections around the beam lines. Re-surveys will require opening some of these windows.

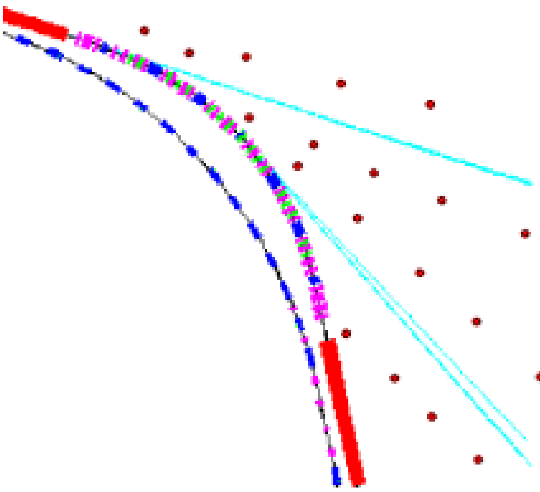


Fig. f7123_a Beam line network incl. synchrotron, injector network

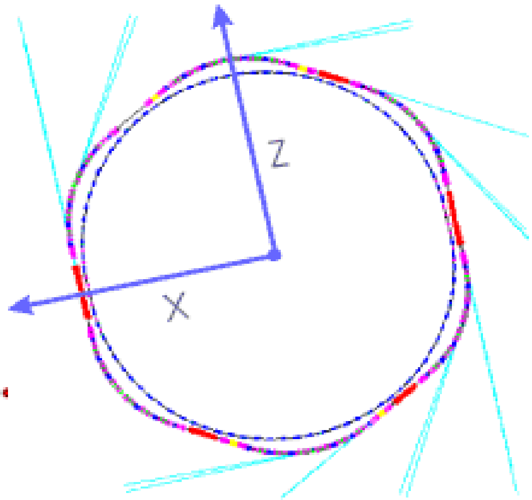


Fig. f713_a Survey coordinate system definition

Along a beam line, floor-marks, five on each sides, spaced equally, make up the principle structure of the network. Narrowly spaced beam lines will be treated as one single beam line with the typical 10 reference points. Where the separation between beam lines becomes wider, tie points will be added. A total of about 170 points will make up the network. Fig. f7123_a shows a section of the resulting lay-out.

7.1.3 Alignment Coordinate System

The alignment coordinate system will be a Cartesian right-handed system. The origin is placed at the center of the ring to reduce the size of the necessary curvature corrections (see above). There will be no monument at the center, it is purely a virtual point. The Y-axis assumes the direction of the gravity vector at the center but with opposite sign, the other axes orientations are defined in symmetry to the machine. The Z-axis is parallel to the long straight sections, and the X-axis is perpendicular to both the Y and Z axes. The signs are defined by the right-handed rule (see Fig. f713_a above).

7.1.4 Network Survey

The most efficient instrumentation for the network observations would be a laser tracker (Fig. f714_a) /total station combination. However, a laser tracker, costing as much as three total stations, but for static measurements not three times more efficient, is difficult to justify. Fortunately, Leica recently released a new total station optimized for industrial metrology, the TDA5000 (Fig. f714_b). It has integrated motorized horizontal and vertical drives, is equipped with automatic target centering, is superior in angular accuracy to a laser tracker, and is sufficiently accurate in distance resolution. Furthermore, Leica has already announced the TDA6000, which is a TDA5000 with significantly improved distance

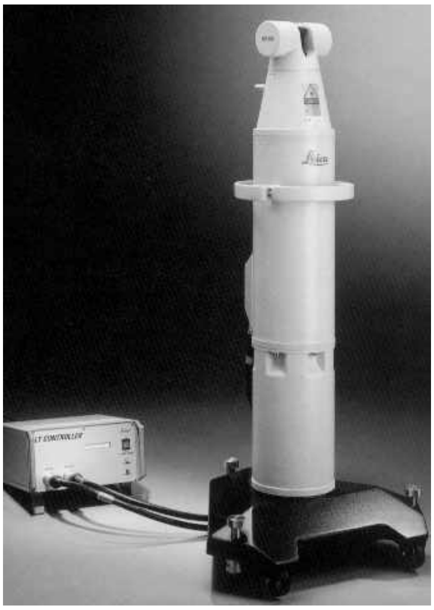


Fig. f714_a Leica Tracker Smart310

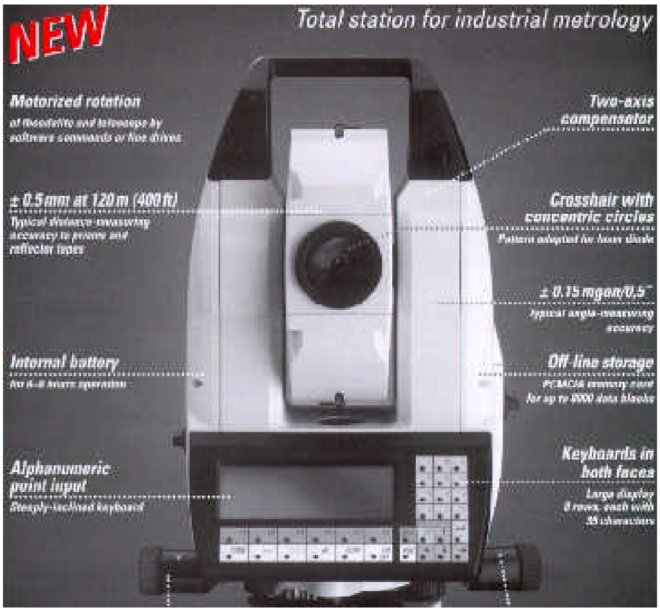


Fig. f714_b Total Station TDM500

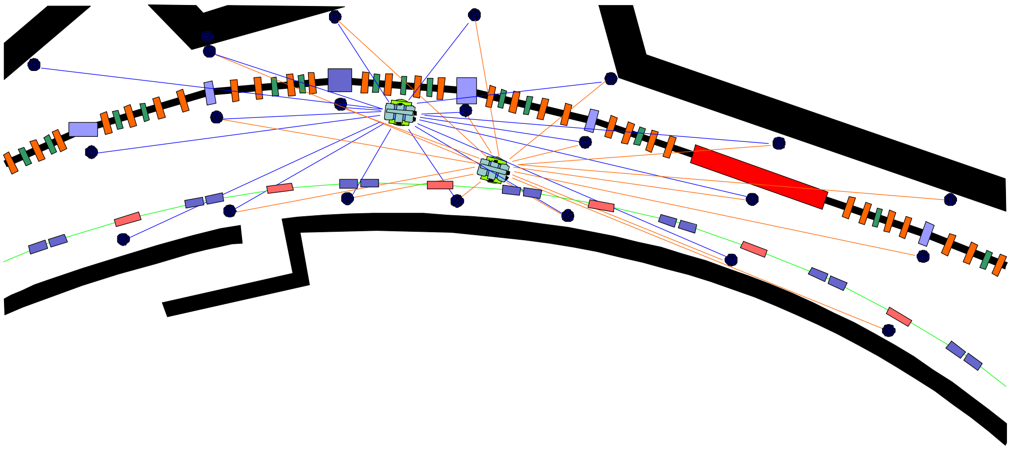


Fig. f714_c TC2002/TDM5000 observation plan schematic measurement resolution. While the TDA5000 is a borderline alternative, the TDA6000 will obliterate the need for laser trackers for static measurements.

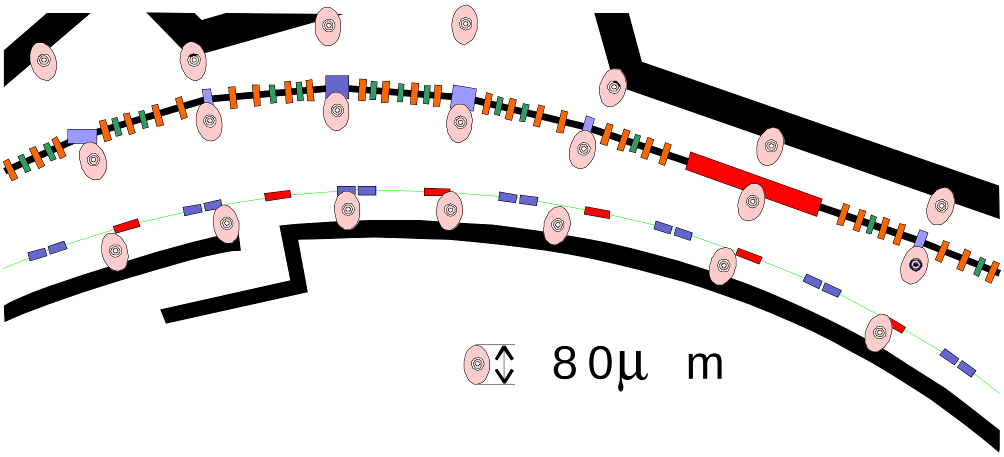


Fig. f714_d Error ellipses for section of tunnel net

The total station will be placed close to the intersection of the diagonals of each reference point quadrilateral (see Fig. f714_c). From there, four points in a forward direction and four points in backward direction will be measured. The measurement procedure will include three sets of direction measurements to the same eight points in both front and reverse positions plus one set of distances in both positions. If more observations are necessary to strengthen the determination, one could first offset the tracker/total station laterally by about 0.5 m and then repeat the same measurement procedure with an offset in the other lateral direction. The procedure in the other network parts follows an equivalent strategy. To strengthen the elevation determination, all reference points should be observed with a standard high precision double-run level procedure. A Zeiss DiNi11 digital level in combination with 2 m invar rods is recommended.. Fig.f714_d previews the anticipated position uncertainties for a small section. A detailed analysis of the network geometry, the observation plan and the required observation accuracies are being carried out.

7.1.4 Data Analysis and Data-Flow

To reduce the data from the measurements as described above, special software is required. This type of analysis software is based on the photogrammetric bundle approach. Since 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 set-up centered on a point to which sufficient measurements have been taken. This analysis approach does not work well with free-stationing, and doesn't work at all with present generation laser trackers, since they cannot be oriented directly to gravity.

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

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

7.2 SLS Lay-out Description Reference Frame

7.2.1 Lattice Coordinate System

The SLS lattice is designed in a right handed beam following 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.

7.2.2 Tolerance Lists

The relative positioning tolerances sx, sy, sz of dipoles, quadrupoles and sextupoles are not included here, since the relative positioning of these components is provided by the self-aligning girder mounting system. The only relevant alignment tolerances are the girder to girder specifications (see Fig. f722_a) and the global tolerance of a girder position in respect to the design trajectory over 120m (see Fig. f722_c).

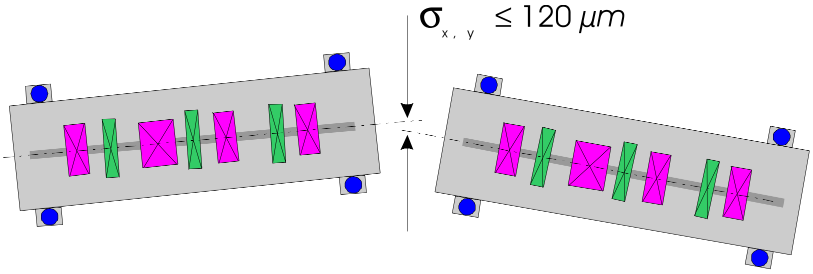


Fig. f722_a Girder to adjacent grider tolerance description

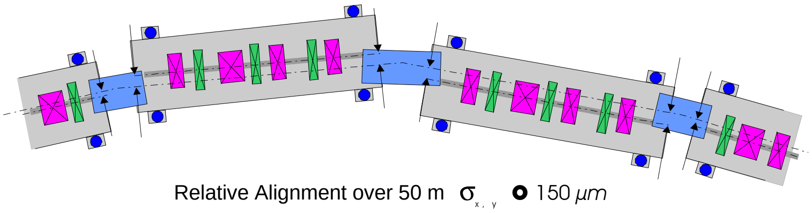


Fig. f722_b Grider to relative design trajectory tolerance description

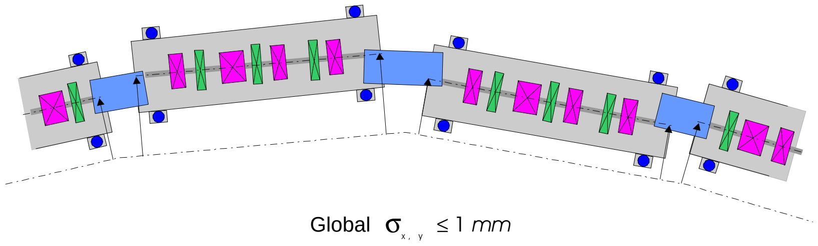


Fig. f722_c Grider to global design trajectory tolerance description

		σx [μm]	σx [μm]	σx [μm]	σr [mr]	σX/Z [mm]	σX/Z [mm]
Storage Ring	Girder relative to design trajectory over 50 m	150	150	150	0.1	n/a	n/a
Storage Ring	Global girder position over whole ring	n/a	n/a	n/a	1	2	1
Storage Ring	Girder to adjacent girder	120	120	120	0.1	2	1
Booster Ring	Magnets relative to design trajectory over 50 m	200	200	200	0.1		
Booster Ring	Global magnet position over whole ring	n/a	n/a	n/a	1	2	1
Booster Ring	Magnet to adjacent magnet	150	150	150	.01		

7.2.3 Relationship between Coordinate Systems

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

7.3 Fiducializing SLS Magnets

An approach has been adopted which eliminates the necessity of fiducializing components in a traditional way and instead relies on accurately machined features.

7.3.1 Traditional Fiducialization

The correct fiducialization of magnets is as important as their correct alignment since an error in either task will effect 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 reference to a magnet's reference features. Detailed descriptions can be found in the literature.[viii]

7.3.2 Forced-centered girder mounting system

The girder mounting and alignment approach proposed for the SLS takes advantage of progress made in the ability to machine large components very accurately without incurring a significant cost penalty. This technology makes it viable to design a self-aligning mounting system where components have a mechanical reference feature machined or stamped into their shape which fits without play onto a straightness ruler incorporated into the girder design. This approach obliterates the need to fiducialize individual components in the traditional sense; the reference feature takes the place of reference fiducials. A first conceptual design is shown in Fig. F732_a. As can be seen, the vertical alignment of components is given by two guide rails on each side of the girder in combination with respective support points or structures on the components' part. The center rail defines the horizontal alignment, again in conjunction with a respectively designed and dimensioned reference surface on the bottom of the magnets or on support structures of other components. The design details need to guarantee that the self-aligning mount is kinematic. The dimensioning of the reference surfaces is done such that a 2 mm shim in the horizontal and vertical plane is provided in case individual components need to be adjusted.

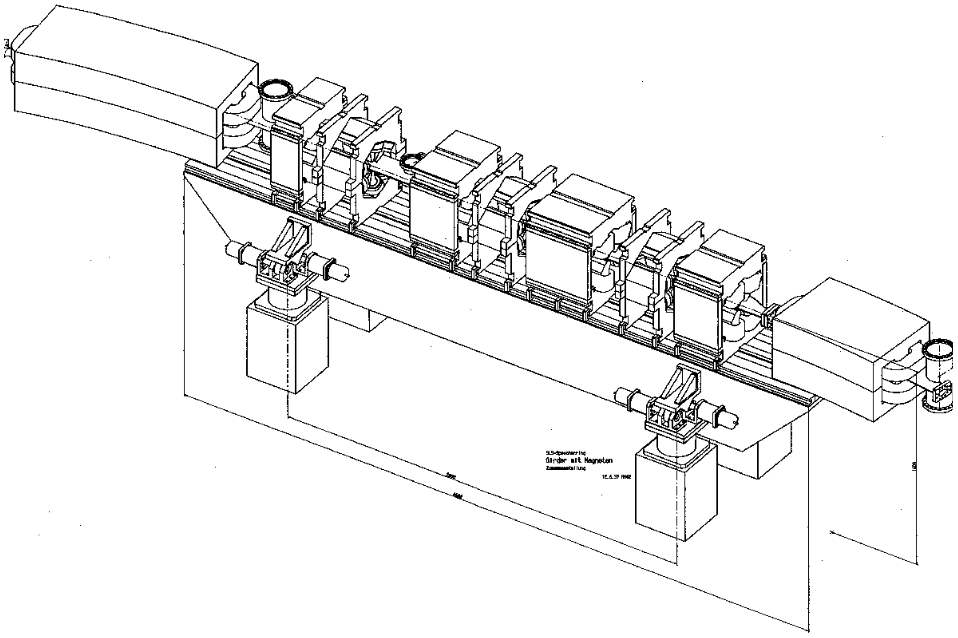


Fig. f732_a Girder with self-aligning mounting system

7.3.3 Fiducialization of BPMs

Knowledge about the relative position of sextupoles and BPMs is one of the key factors in the correction scheme for the synchrotron's closed orbit. Again the BPM alignment is going to be provided by the girder alignment rails. In addition, the beam-based-alignment scheme envisioned will allow the determination of any BPM offsets.

7.3.4 Girder Reference Marks

A girder's vertical and horizontal alignment rails define the girder coordinate system. The origin is given by a precision hole in the horizontal rail at its downstream end. Fixturing will be used to signal the coordinate system. Conceptually, the fixture will be in the form of an arm resting on both vertical rails, restrained in the perpendicular direction by the horizontal rail and in Z by a dowel pin inserted into the rail. To control yaw, the feature which references to the horizontal alignment rail needs to be about as long as the distance with which the fixture extends from the horizontal rail.

7.4 SLS Absolute Positioning

Common to all parts of the machine, free-stationed TDA5000/6000s, oriented to at least four neighboring points, are used for the absolute positioning measurements. The tracking capabilities of these instruments will significantly facilitate the control of any alignment operation (moving components into position).

7.4.1 Synchrotron Absolute Positioning

Each girder, carrying quadrupoles, a sextupole, corrector magnets, and instrumentation will be supported by a motorized adjustment system elevated to beam height by four pedestals sitting on concrete piers. The dipole magnets will be supported at each end by their two adjacent girders.

7.4.1.1 Internal Alignment of SLS Synchrotron Girders As described above, the internal girder alignment is provided by a self-aligning mounting scheme. No individual components will be equipped with fiducial marks or fixtures. Consequently, no optical alignment operation is required.

7.4.1.2 Synchrotron Anchor Hole Layout Survey. During the anchor layout survey, the anchor hole positions for the girder support pedestals are marked on the piers. It is recommended to fabricate a standard template including all anchor holes on a pier thus reducing the number of individual lay-out pointings significantly. A total station from one free-stationed position can locate and position the template with only two pointings. Before the holes are marked, the location of the template should be checked from a second station. In the sequences of work, the last station can then serve for the n+1 girder as its first station. Specialized software is required to improve the efficiency and reliability of this task..

7.4.1.3 Pre-alignment of Girder Supports and Magnet Movers The SLS girders will be supported by motorized adjustment systems elevated to design height by short pedestals sitting on top of concrete piers (see Fig. F7413_a). The motorized adjustment systems are based on the SLAC cam shaft design. Two individually controlled cam shaft pairs and two single cam shafts mounted on four pedestals provide five degrees of freedom per girder. The cam shaft design doesn’t compromise the rigidity of the supports and, consequently, doesn’t show a resonance in an undesirable frequency range. This mover system comes in two vertical slices. The bottom piece consists of a mounting plate, which holds the shafts and stepping motors. The top part is integrated into the girder by mounting the kinematic cams to the girder. The girder is held onto the shafts by gravity.

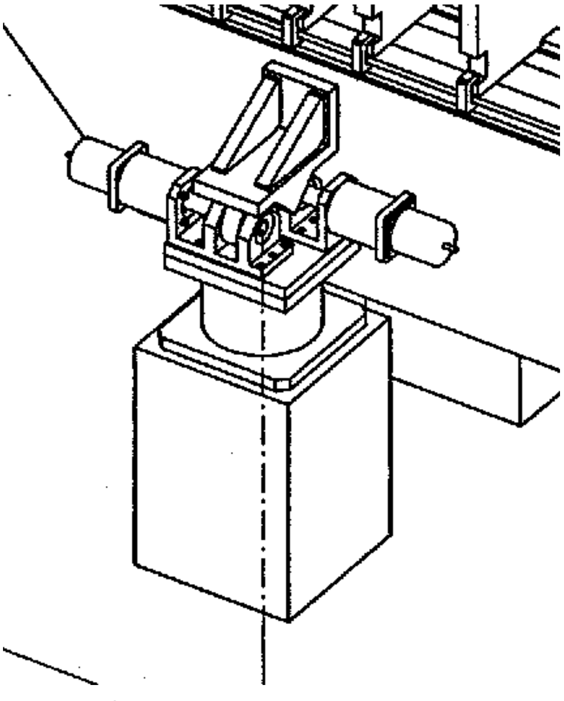


Fig. f7413_a Girder Support Arrangement

To accommodate easy installation, the bottom parts of the movers, set to mid range, have to be aligned relatively to each other. The required tolerance, however, is only about 1 mm in all coordinate axes, since the two axes cams are only paired with a single axis cam. On the other hand, to retain as much magnet mover range as possible, the bottom part of the magnet movers should be within 0.5 mm of their nominal positions.

To facilitate placing a pedestal such that its top is within 0.5 mm of its nominal position, a widely used method can be used where the pedestal is mounted to the pier by four standoff screws, which are grouted/epoxied into the concrete. The vertical/horizontal pre-alignment of the pedestal is accomplished by the following sequence of steps: After the four bolts are epoxied into the concrete, a nut with a washer on top is screwed onto each bolt. These nuts are set to their nominal heights by a simple level operation. Next the pedestal is set on the nuts, and a set of washers and nuts is then screwed on the bolts to fasten it down. However, the top nuts remain only hand tight at this point. Next, the elevation and tilts of the pedestal are set by adjusting the position of the lower nuts, and subsequently checked with a level in respect to local benchmarks. Then a total station with a “free station Bundle” software package is used to determine the horizontal offset and to simultaneously double-check the vertical offset of the pedestal from its nominal position. Finally, the pedestal is moved into horizontal alignment using a clamp-on adjustment fixture (push - push screw arrangement), and the nuts are tightened to the prescribed torque. To vibrationally stiffen the set-up, the vertical space between the floor and the bottom of the pedestal should be filled with non-shrinking grout after the alignment has been confirmed.

7.4.1.4 Fine Alignment of Girders into SLS Coordinate System In this step the girders will be moved to their nominal positions under the control of a total station/level using the magnet movers to apply the adjustment. The girder’s position is signaled by two targets referencing to the self-alignment mounting rails in the x, y-coordinate directions and to dowel pins acting as z reference. A bridge type fixture in combination with an electronic inclinometer set across the two vertical reference rails of a girder will be used to set roll.

7.4.1.5 Alignment of Dipoles Each dipole will be supported by its two adjacent girders. These supports will reference to the self-alignment rails, and such do not require manual alignment.

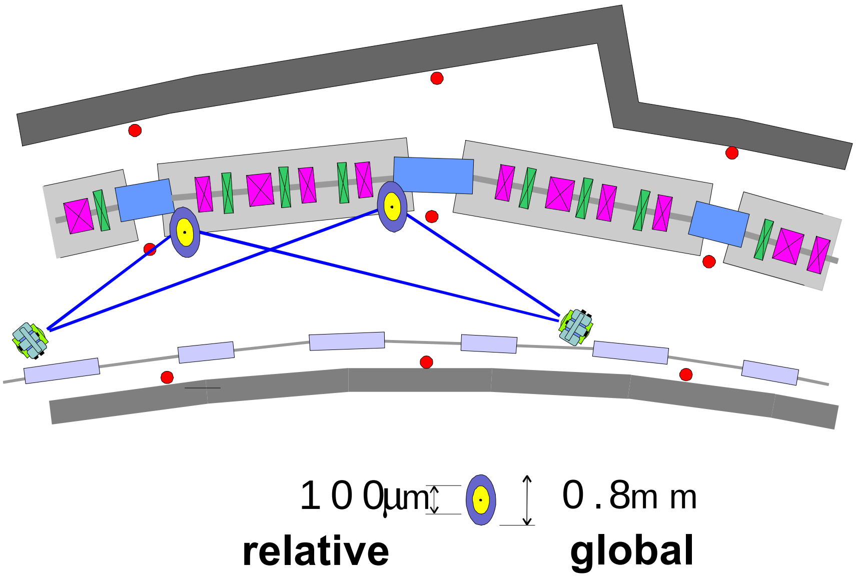


Fig. f415_a Simulated error ellipses of component fiducial point absolute/relative accuracy

7.4.1.6 Quality Control Survey Once the above step is completed in at least one arc, the girder positions will be mapped. If the positional residuals exceed the tolerance, a second iteration can be jump started by using the quality control map to quantify the position corrections, which need to be applied. Should a second iteration be necessitated, a new quality control survey is required after completion of the alignment process. Fig. f7415_a shows the simulated absolute and relative position accuracies which are expected for girder components.

7.4.2 Injector and Booster Absolute Positioning

7.4.2.1 Internal Alignment of Injection Girders This operation here should follow the same principle as described for the synchrotron girders.

7.4.2.2 Injector and Booster Lay-out Survey The injector blue line survey should be done the same way as the synchrotron survey. The booster lay-out points can also be marked in the same fashion if a special fixture is created which represents the virtual magnet fiducials with respect to its ceiling/ wall anchor bolt pattern.

7.4.2.3 Prealignment of Girder/Component Supports and Adjustment Systems This operation for the injector girders again should follow the same principle as described for the synchrotron girders. The booster single component support prealignment also follows very much the same routine. The mechanical adjustment system is not used to move the support, instead the support is tapped into place. The required motion is allowed by oversized mounting holes. When the support system is in position, the mounting screws *are tightened to specification by the alignment team.*

7.4.2.4 Alignment of Girders/ Components into SLS Coordinate System This operation should follow the same principle as described for the synchrotron girders. If the installation schedule allows, both synchrotron and booster alignment operations can be carried out simultaneously.

7.4.2.5 Quality Control Survey This operation again should follow the same principle as described for the synchrotron. If the installation schedule allows, both synchrotron and booster quality control surveys can be carried out simultaneously.

7.5 Smoothing for the SLS

7.5.1 Synchrotron

The absolute positioning for the SLS is quite different from that of large size accelerators. The relative alignment of components on girders is guaranteed to a high degree of accuracy by mechanical means. Therefore, a smoothing operation will focus on the relative alignment of the girders only. Before the dipoles are installed, the horizontal and vertical offsets between two adjacent girders can be directly measured using a special fixture. The fixture will extend the alignment rails of one girder to overlap the adjacent girder thus creating a virtual intersection. Dial gauges can then be used to measure the offsets.

7.5.2 Booster

According to the present thinking, the booster's mechanical lay-out will be quite different. Since the individual components are spread out, a girder system would not be economical. Therefore, the components will be mounted on individual support systems attached to brackets on the interior wall of the synchrotron tunnel. While even under these circumstances a traditional smoothing operation is not a must, it should be kept an option depending on the analysis of absolute positioning data.

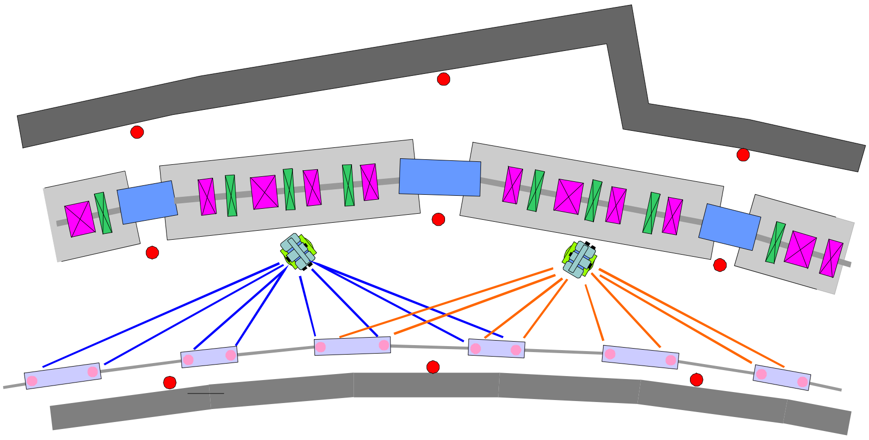


Fig. f752_a Observation plan for smoothing of booster

7.6 Position Monitoring System

The synchrotron and the photon beam lines will be monitored by real time dynamic survey systems in both the horizontal and vertical plane. Monitoring systems can be built as absolute systems, where a component is monitored with respect to an independent reference, or as relative systems, where one component is monitored with respect to another component.

To monitor vertical motion, gravity provides a unique reference. The most commonly known implementation of such systems is the hydrostatic water level. There is a wide variety of designs, with the only real difference being the water level pick-up system. The capacitive pick-up system of the ESRF HLS has proven to be very stable and is simple to build.

The situation is different in the horizontal plane, since there is no natural reference.

7.6.1 Proposed Method

In the vertical dimension a hydrostatic leveling system cloned after ESRF's HLS will accurately monitor relative and global vertical position changes. Three sensors per girder are required, a fourth will provide some redundancy. It is planned to mount the sensors on the side of the girder next support brackets holding the mover cams. To eliminate temperature effects on the hydrostatic leveling results, any vertical deviations from a plane of the water runs must

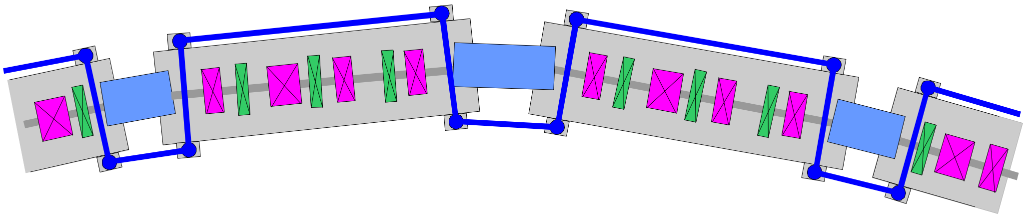


Fig. f771_a Proposed HLS water run routing be avoided. This condition is guaranteed using the “half-filled” pipe approach. However, this approqch requires a significantly larger pipe diameter and consequently, makes the routing of the pipe around the ring much more difficult. Temperature effects can also be mitigated by circulating the water before a measurement is taken. A proposed water run routing is shown (see Fig. f771_a). The hydrostatic leveling system could easily be extended to include the beam lines. Assuming three sensors per beam line, this would add another 33 sensors.

Since there is no natural absolute reference in the horizontal plane, some kind of artificial local reference needs to be created. A single straight wire doesn’t deal very well with a circular machine; however, one can shorten the sagittas by using many short wires instead. To overlap these wires with a long lever-arm will not be necessary, because the purpose of the system is only to detect position changes of a girder in respect to its neighbors. Therefore, a propagation of the motion of individual girders to compute a global deformation picture will not be attempted. A first lay-out suggests one wire per girder strechted from the upstream end of the first girder to downstream end of the third girder spanning the second to-be-monitored girder (see Fig. f761_b). In the vertical plane, the wires will be positioned below the mounting surface of the girder. Three sensors per girder will provide redundant information.

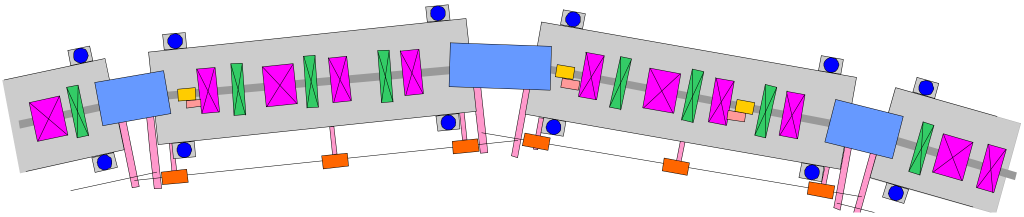


Fig. f761_b Wire layout for girder monitoring system

Also the BPM position should be monitored in the wire reference system. To connect the BPMs directly to the wire, a reference arm, mounted kinematically and without friction, is required. Because of the horizontal and vertical differences in position between BPM and wire, the reference arm would have to be very substantial in size and adding a non-acceptable torque to the chamber. This can be avoided, if the BPMs are monitored relative to adjacent quadrupoles, and not relative to the wire. However, since the quadrupoles are rigidly fastened to the girder, and the girder is monitored relative to the wire, the BPM and vacuum chamber position will also be known in the wire system.

Many different wire systems have been implemented. Besides application specific details, they differ mostly in the wire pick-up method. Inductive pick-ups provide the best cost to resolution ratio and are adequate with the range and resolution requirements. The BPM position sensors will be identical to the wire sensors, with the only difference that the wire is substituted by a short rod. The rod is attached to the BPM and the position sensor is attached to the quadrupole.

To extend the horizontal reference system into the beam line area is more difficult. The most direct approach, setting up a wire parallel to the individual beam line’s part which is inside the shielding wall, connecting this wire to a monitored girder, and extending this wire through the shielding wall into the experimental area is not possible because of radiation protection reasons. Any penetration of the shielding wall requires a maze like arrangement, which makes the lay-out complicated and reduces the data reliability. Although the CERN *Laser Beam Reference with Multiple Position Sensors* scheme[ix] should be directly applicable, its implementation is prohibitively expensive. However, since the components inside and outside of the shielding wall are sitting on the same continuous concrete slab, it should be possible to assume that if motion occurs, both sets of components will move consistently. If this assumption can be confirmed, a physical connection of the horizontal monitoring systems will not be necessary.

7.6.2 Monitoring Systems Specifications

The following schematic (see Fig. f762_a) shows the building blocks of the wire electronics. The analog signals from the wire, BPM position sensors of a sector (4 girders, about 16 WPMs) will be multiplexes into one set of drive electronics. Similarly, the analog signals of the hydrostatic level system will be combined into one set of drive electronics per girder. The sector electronics communicate with the central monitoring system control PC through a CAN bus (see Fig. f762_b).

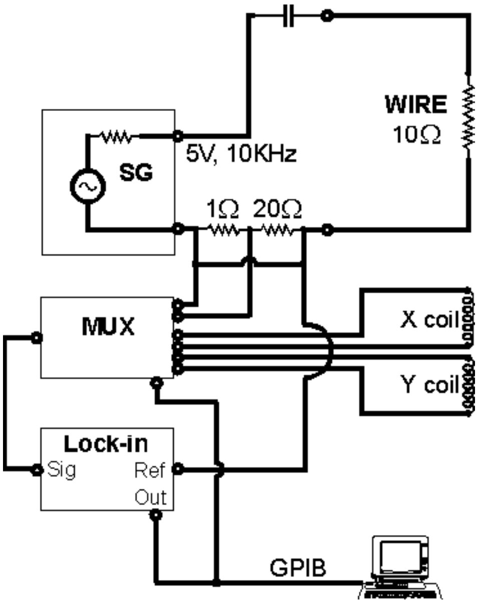


Fig. f762_a Wire Electronics

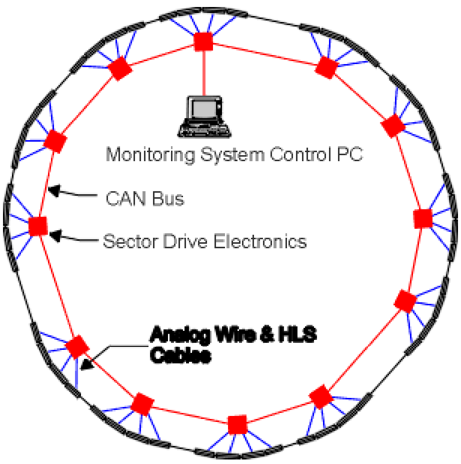


Fig. f762_b Electronics Architecture

Appendices A and B show the specification lists for the wire position monitoring system and the hydrostatic water level system.

7.7 Survey and Alignment Toolbox

The following list represents a first cut of a list of instruments, other hardware, and software essential for the successful alignment of the SLS.

7.7.1 Hardware

Only main instruments are listed, other attachments and accessories are not specified.

7.7.1.1 Angle and Distance Measurements

2 Leica TDA5000
1 Leica TDA6000
3 Leica Aluminum Tripods AT

7.7.1.2 Elevation Measurements

1 Zeiss Ni001
2 Zeiss Digital Level DiNi 11
1 Zeiss Wooden Tripod
2 Leica Aluminum, Tripods AT
2 1m Invar Rods, ½cm graduation
2 0.5m Invar Rods, ½cm graduation
2 2m Invar Rods, ½cm graduation
4 1m Invar Rods, barcode graduation
4 0.5m Invar Rods, barcode graduation
4 2m Invar Rods, barcode graduation

7.7.1.3 Tilt Measurements

2 Whyler Inclinometer
2 Machinist Precision Levels, Set

7.7.1.4 Monumentation, Fixturing, Targeting

500 1.5" sphere receptacles, wall or floor mount
40 Sphere-Mounted-Reflectors (Air Cubes)
40 Sphere-Mounted-Targets
10 Girder Target Fixtures
Various Mounting Hole Templates

7.7.1.5 Miscellaneous Tools

7.7.2 Data Flow, Data Analysis Hardware

7.7.2.1 Data Analysis Computer

PC, 200Mhz Pentium Pro, 128 MB RAM, 2x4 GB Hard disk

7.7.2.2 Field Computer

6 HP320

7.7.3 Data Flow, Data Analysis Software

7.7.3.1 General Office Software

7.7.3.2 Survey and Alignment Software

Bundle based data analysis package
Simulation
Outlier Detection
Database
Industrial Measurement System
Transformation
Ideal Coordinates

7.7.3.3 Field/Data Collection Programs

Horizontal Direction
Vertical Angle

Simultaneous horizontal, vertical and distance
Distance
Level
Set-out

7.7.4 Instrument Calibration

The survey and alignment instrumentation needs to be maintained and the calibration regularly checked to control systematic errors. However, the required instrumentation inventory is too small to make the set-up of a calibration laboratory economical. Fortunately, the Geodetic Institute at the ETH Zürich runs a first class calibration facility and accepts contract work.

Appendix A

System Specifications for Hydrostatic Water-level

Resolution	2 µm
Accuracy	10 µm
Range	± 2.5 mm
Sampling Rate	15 min whole ring, less than one minute per sector
Method	Separate Air and Water lines
Pick-up	Capacitive Proximity Gage or Load Cell
Drift	Each sector shall have one sensor with fixed reference surface to monitor electrical drift of sector electronics
Fluid	Purified Water
Water Container	10 cm dia., 5 cm height
Plumbing	Nylon Hose
Fluid Circuitry	Water Container separated by remote valves, girders separated by manual valves
Misc.	Pump to circulate Water, automatic water level control and refill system
Lay-out	Four sensors per girder, closed loop water run around ring, branches with three sensors along each experimental beam lines
Electronic Circuitry	Each sensor of a sector connected to one set of electronics on interior side of inner shielding wall, sectors are linked by CAN based network to central PC based processor, Central PC linked to Main Control computer by networking
Control Program	Controls measurement procedure, incl. Control of valves, recirculating water, level and refill control, read-out of fluid level height. At least two modes: general procedure, runs measurement procedure once every 15 minutes, processes data, updates Main Control Computer; girder adjustment procedure, interrupts general procedure and instead measures sensors only in one sector as feed-back to girder adjustment. Data stored in relational data base, adjusts data for water level variations, temperature fluid expansion, calculates running average for each sensor, provides warning if a reading is outside defined bracket. Software shall have intuitive GUI, printing and data export capabilities.

Appendix B

Specifications for Wire System

Resolution	2 µm
Accuracy	10 µm
Range	±2.5 mm
Sampling Rate	15 min whole ring, less than one minute per sector
Method	Active Wire based
Pick-up	Inductive Sensors
Drift	Each sector shall have one sensor with fixed reference surface to monitor electrical drift of sector electronics
Wire material	BeCu
Wire Signal	5 V, 10 KHz
Wire Tension	20 kg
Noise suppression	Lock-in Amplifier
Misc.	Wire shielded by stainless pipe
Lay-out	Three sensors per girder, + sensor(s) for BPM(s)
Electronic Circuitry	Each sensor of a sector multiplexed to one set of electronics on interior side of inner shielding wall, sectors are linked by CAN based network to central PC based processor, Central PC linked by network to Main Control computer
Control Program	Controls measurement procedure. At least two modes: general procedure, runs measurement procedure once every 15 minutes, processes data, updates Main Control Computer; girder adjustment procedure, interrupts general procedure and instead measures sensors only in one sector as feed-back to girder adjustment. Data stored in relational data base, calculates running average for each sensor, provides warning if a reading is outside defined bracket. Software shall have intuitive GUI, printing and data export capabilities.

Notes and Bibliography

[i] For more information see also: Ruland, R.: Magnet Support and Alignment, in: H. Winick, Editor, Synchrotron Radiation Sources - A Primer, pp. 274 - 304.

[ii] 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 is set-up with respect to gravity.The reference ellipsoid is the regular figure that most closely approximates the shape of the earth, and is therefore widely used in astronomy and geodesy to model the earth. Being a regular mathematical figure, it is the surface on which calculations can be made.

[iii] 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 loosing 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 system have a σ of about 50-100 μm. Unfortunately, the forced centering system contributed error is not random. Since 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. This error, vertical refraction, and lateral refraction are the biggest contributors to the systematic error budget in surveying engineering.

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

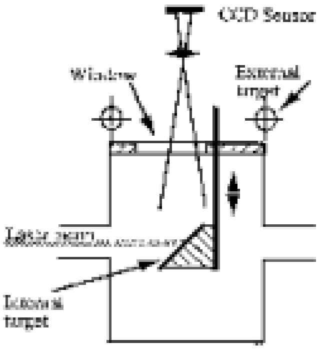
[v] Rather than setting up the instrument over a known point, the instrument's position is flexible and chosen only following considerations of geometry, line of sight and convenience. To determine the instrument position, at least three points, whose coordinates are already known or are part of a network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

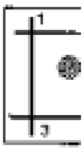
[vi] Lateral refraction is caused by horizontal stationary temperature gradients. In a tunnel environment, the tunnel wall is often warmer than the air. This creates vertical stable temperature layers with gradients of only a few hundredth of a degree Celsius per meter. If one runs a traverse close to 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 they had already veered about 0.5 m off the design trajectory.

[vii] The " character indicates inches; 1 in = 2.54 cm, hence the diameter of the 1.5" sphere is equivalent to 3.81 cm.

[viii] Ruland, R., Setting Reference Targets, in Proceedings of the CERN Accelerator School on "Magnetic Measurements and Alignment", Capri, 1997, in print.

[ix] A laser beam can serve as a reference to multiple position sensors by using beam splitters to split off a part of the beam onto each individual position sensor. If the expected motion is slow and therefore a simultaneous reading of all position sensors is not required, one can use position sensors which are individually inserted into and retracted out of the laser beam. At CERN, a system based on this principle was developed to provide a position reference connecting the final focus regions on either side of a particle detector (see figure below). This arrangement makes parasitic use of the accelerator's vacuum system. For the measurement process, a laser beam is reflected into the beam pipe. This beam produces an image on one of the four measurement screens which is inserted into the pipe. Each screen is at a 45 degree angle and has four reference marks; the image's position is then measured with respect to these reference marks with a CCD camera through a window from outside the vacuum system. It is reported that a positional accuracy of 20 μm was achieved. See also: Peterson, H., Quesnel, J.P.: Improvement of the Alignment Process of Superconducting Magnets and Low-b-Sections, in: Proceedings of the Third International Workshop on Accelerator Alignment, Annecy, 1993, pp. 189-196.


CCD Sensor
Window
External target
Laser beam
Internal target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