7.0 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 alignment to final smoothing. Emphasis is given to the relative alignment of components, in particular to the importance of incorporating methods to remove residual systematic effects.[1]

7.1. SLS Surveying Reference Frame

Horizontal position differences between the projection of points on the geoid 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 1 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 (see table t71_a.

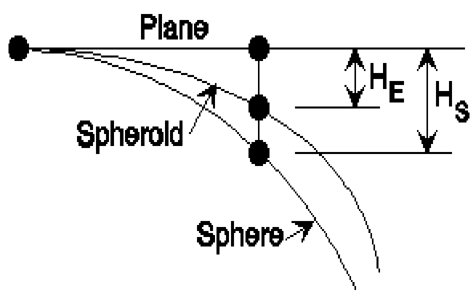

Fig. f71_a Effect of earth curvature

Distance r [m]	Sphere H_S [m]	Ellipsoid H_E [m]
20	0.00003	0.00003
50	0.00020	0.00016
100	0.00078	0.00063
1000	0.07846	0.06257

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 many 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" increases the requirements for the tunnel network. It would be difficult to meet these requirements by traditional forced centered[2] „2+1-D" triangulation and trilateration techniques.[3] However, a 3-D „free stationing"[4] approach does not require forced centered instrument set-ups, eliminating their systematic error contribution. This approach also eliminates the need for the set-up hardware. 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[5]. 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

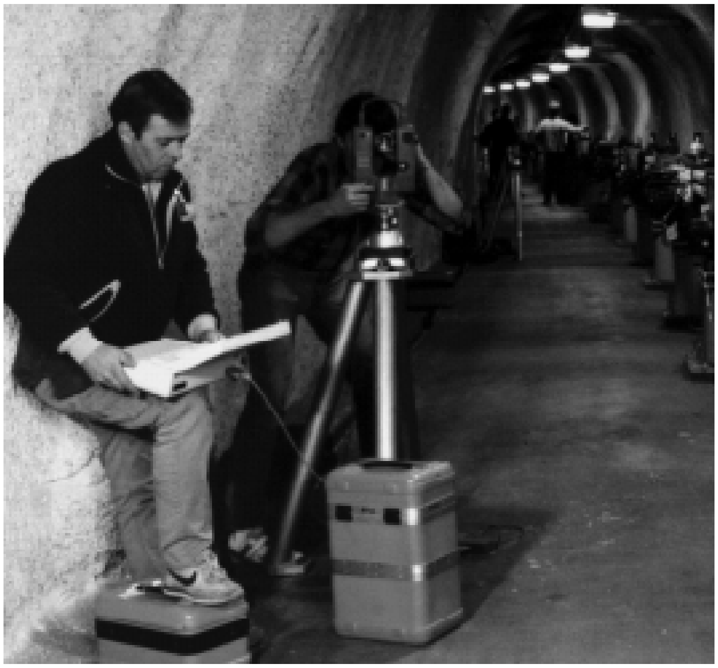

Fig. f711_a   Forced Centered Set-up at SLAC

Fig. f711_b   DESY HERA set-up

is proposed to use a design which is now widely used in high precision metrology. This approach is centered around a 1,5" [6] 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 reflectors

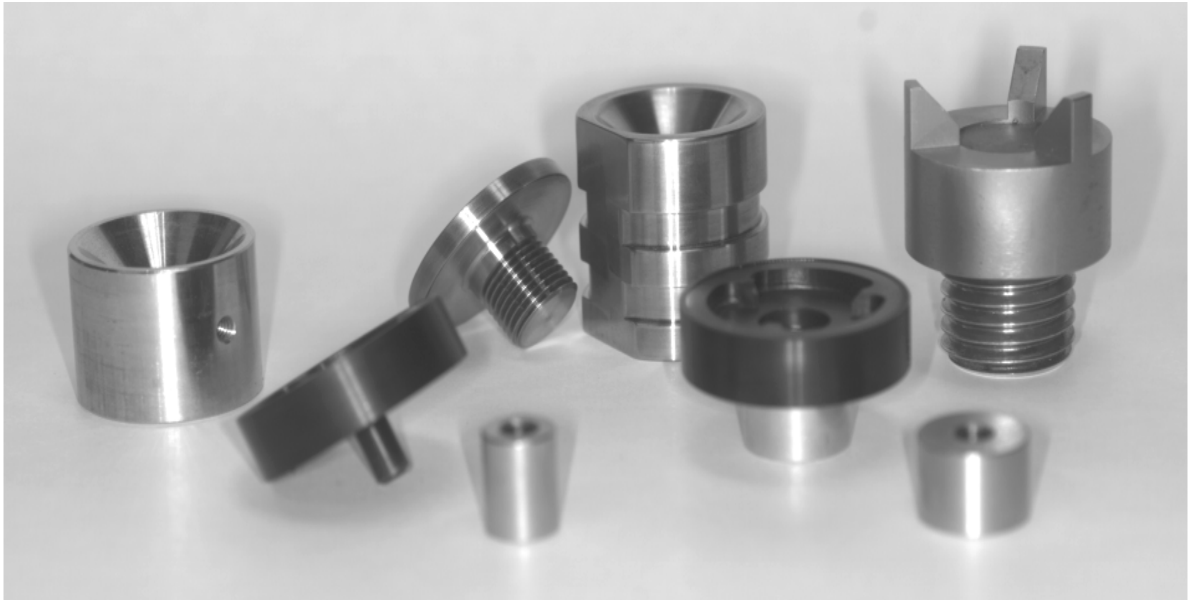

Fig. f711_e *Sphere receptacles: floor, component, and wall bracket fixed mount versions, removable centered version*

7.1.2 Network Lay-Out

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

7.1.2.2 Synchrotron Network The synchrotron network geometry is dictated by the machine lay-out. Additionally, the geometry should permit observing each target point from 3 different stations. The free stationing method requires a greater number of reference points. However, 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.

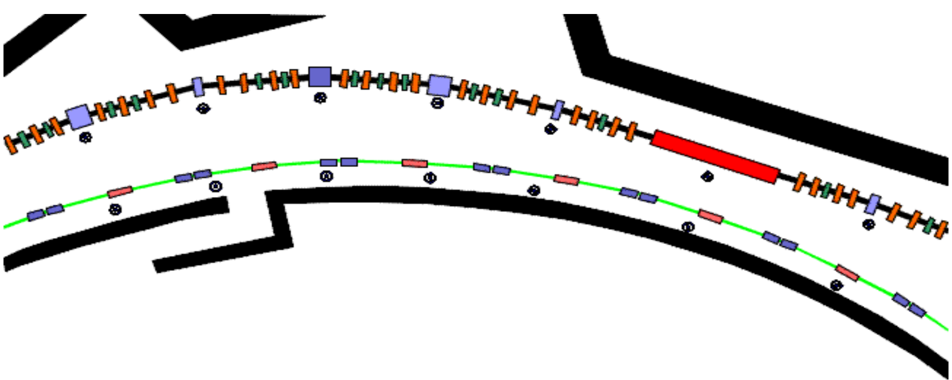

Fig. f7122_a *Section of synchrotron network*

7.1.2.3 Beamline Network The beamline 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 beamlines. Re-surveys will require opening some of these windows. Along a beamline, floormarks, 5 on each sides, spaced equally, make up the principle structure of the network. The two narrowly spaced beamlines off a SC bend will be treated as one single beamline with the typical 10 reference points. Where the separation between beamlines 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.

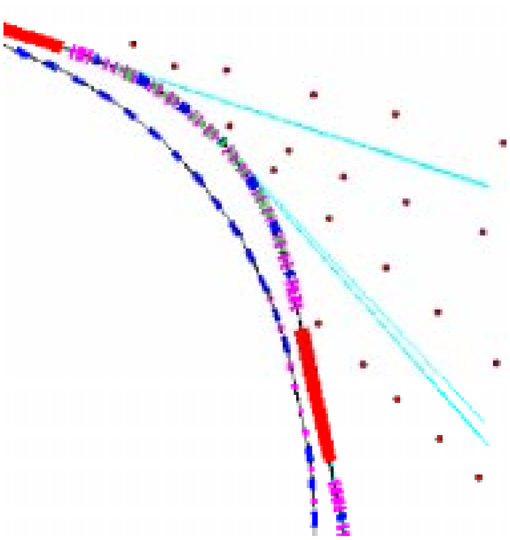

Fig. f7123_a Beamline network incl. Synchrotron, injector network

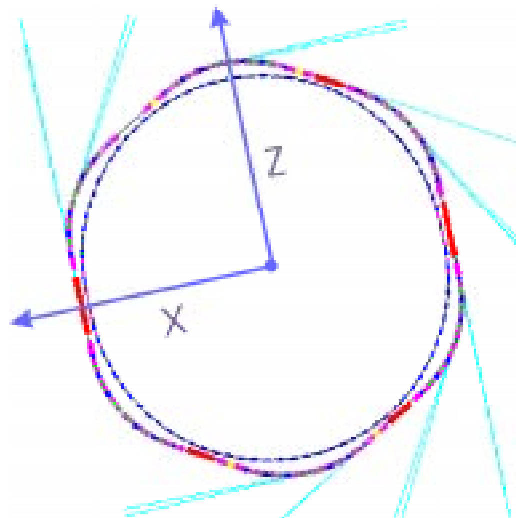

Fig. f713_a Survey coordinate system definition

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 building. 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).

7.1.5 Network Survey

If the measurements were to be carried out today, fall 1996, the primary instrumentation for the network observations would be a laser tracker (fig. f715_a) /theodolite combination. However, some interesting instrument developments are becoming available within the next 2-3 years. Leica just released a new total station optimized for industrial metrology, the TDM5000 (fig. f715_b). It has integrated motorized horizontal and vertical drives, can be equipped with automatic target centering, and is superior to the presently available total station, the TC2002, in both angular and distance resolution. Furthermore, Leica has already announced the TDM6000, which is a TDM5000 with significantly improved distance measurement resolution. The TDM6000 will obliterate the need for laser trackers for static measurements.

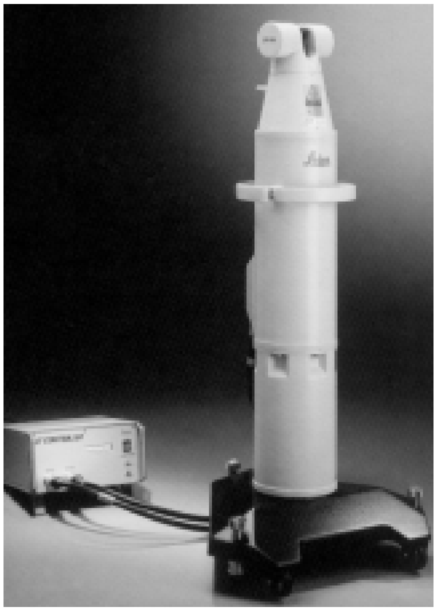

*Abb. f715_*a *Leica Tracker Smart310*

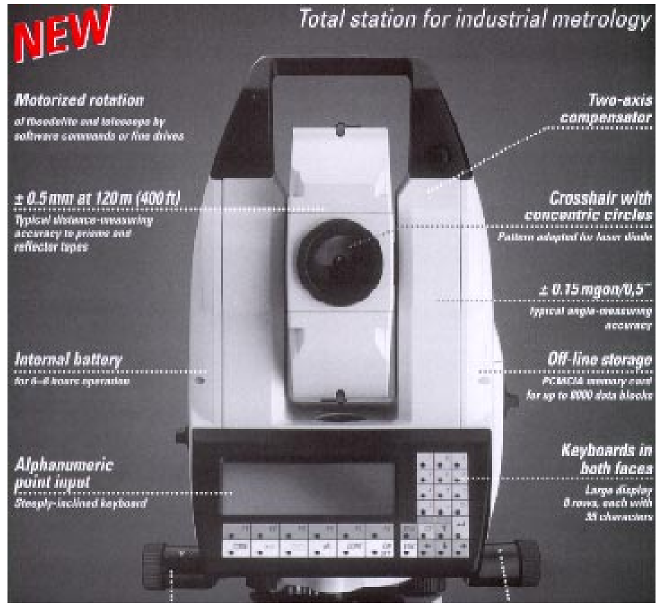

*Abb. f715_*b *Total Station TDM5000*

The laser tracker/total station would be placed close to the intersection of the diagonals of each reference point quadrilateral (see fig. f715_c). From there, 6 points in a forward direction and 6 points in backward direction would be measured. The measurement procedure should include 3 sets of direction measurements to the same 12 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

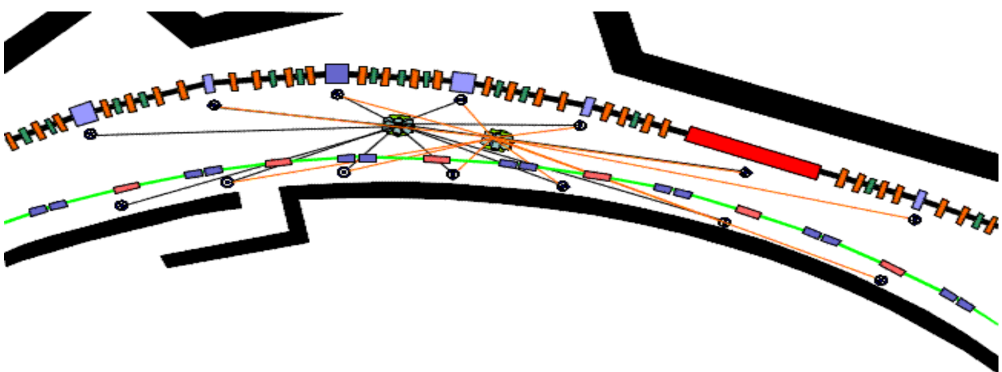

Fig. f715_c TC2002/TDM5000 observation plan schematic

strengthen the elevation determination, all reference points should be observed with a standard high precision double-run level procedure. A Leica N3 level in combination with 2 double scaled half-centimeter rods is recommended. Today's electronic levels are not as accurate as the N3 and are very lighting sensitive; however, the situation should be re-evaluated later. Fig.f715_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.

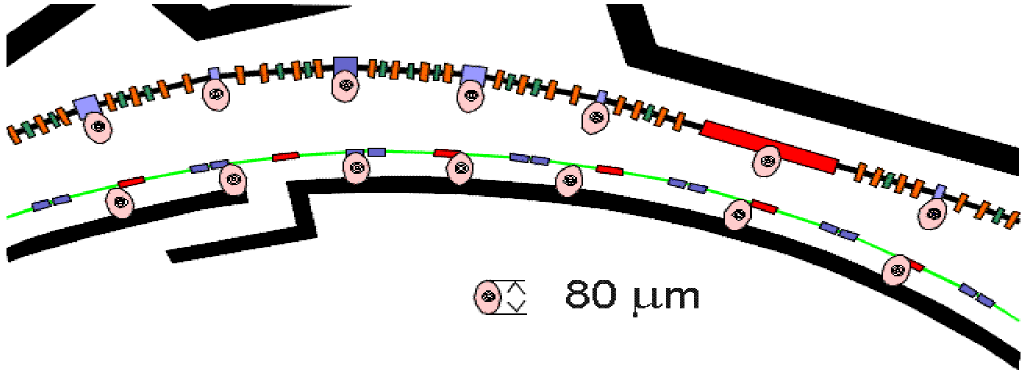

Abb. f715_d Error ellipses for section of tunnel net

7.1.6 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 cannot have only translation parameters, its rotational orientation parameters must also 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, it is assumed 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 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.

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 σx, σy, σz of dipoles, quadrupoles and sextupoles are given in the beam following coordinate system, the relative surveying tolerances σx, σy, σz of BPMs refer to the upstream sextupole, the chamber positioning tolerances are given with respect to the components on one girder, and the global tolerances σX, σY, σZ are given in the global alignment coordinate system.

7.2.2.1 Synchrotron Tolerances The following table t7221_a summarizes the synchrotron tolerances.

	σx [μm]	σy [μm]	σz [μm]	σr [mr]	σX/Z [mm]	σY [mm]
Dipole	250	250	250	0.1	2	1
Quadrupole	150	150	250	1	2	1
Sextupole	150	150	250	1	2	1
SC Dipole	250	250	250	0.1	2	1
Undulator	150	150	250	1	n/a	n/a
V-Chamber					n/a	n/a
BPM	75	75	250		n/a	n/a

Table t7221_a Synchrotron Positioning Tolerances

7.2.2.2 Booster Tolerances The following table t7222_a summarizes the booster tolerances.

	σx [μm]	σy [μm]	σz [μm]	σr [mr]	σX/Z [mm]	σY [mm]
Dipole	250	250	250	0.1	2	1
Quadrupole	150	150	250	1	2	1
Sextupole	150	150	250	1	2	1
BPM	75	75	250		n/a	n/a

Table t7222_a Booster Positioning Tolerances

7.2.2.3 Injector Tolerances The following table t7223_a summarizes the injector tolerances.

	σx [μm]	σy [μm]	σz [μm]	σr [mr]	σX/Z [mm]	σY [mm]
Dipole	250	250	250	0.1	2	1
Quadrupole	150	150	250	1	2	1
Sextupole	150	150	250	1	2	1
BPM	75	75	250	n/a	n/a	n/a
Gun	500	500	1000	n/a	2	1
Accel. Sect.	150	150	250	1	2	1

Table t7223_a Injector positioning Tolerances

7.2.3 Relationship between Coordinate Systems

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

7.3 Fiducializing SLS Magnets

7.3.1 Warm Magnets

It is suggested to design the magnet laminations such that the fiducialization reference can be picked up mechanically. Grooves in the top and bottom part of the magnet facing the aisle side have been used successfully. The following figure f731_a shows a recent examples; fig. 14 depicts the fixturing for the PEPII HER quadrupoles. Alternatively, fixed fiducials in form of bushings welded to the magnet can be used (see above fig. f711_e and fig. f731_b). Should it be necessary to measure the magnetic properties of the quadrupoles and sextupoles, one should consider also determining the magnetic centerline and correlating that information with the fixture supplied reference to the mechanical centerline.

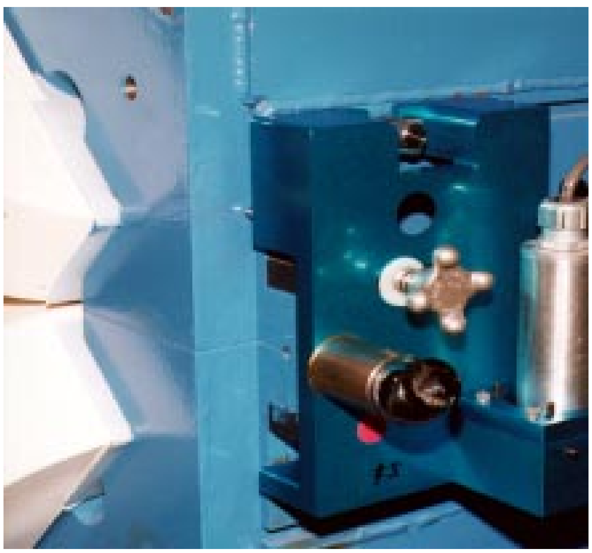

Fig. f731_a PEP II Quadrupole Fixture

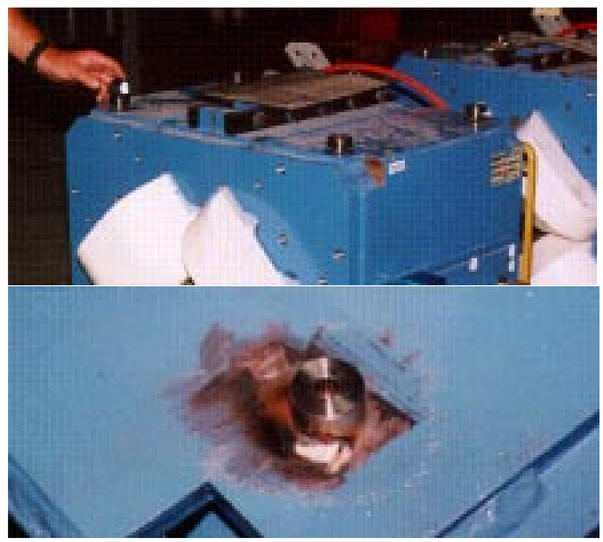

Fig. f731_b Bushing Fiducial

7.3.2 SC Magnets

The fiducialization of SC magnets is always difficult. While the relationship between the yoke and fiducials on the skin can be established before the magnet is cooled down, any direct access to the yoke usually becomes impossible when the magnet is cooled down. An electro-mechanical yoke motion monitoring system based on capacitive displacement sensors has been developed for the CERN LHC SC quadrupoles. For testing the stability of the yoke/skin relationship of SSC quadrupoles, optical quality windows had been designed into the magnet's insulation layers so that any motion of the yoke could be monitored optically. However, both these methods are costly and have heat transmission disadvantages.

7.3.3 Simultaneous Fiducialization of Sextupoles and 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. Because of the required vacuum chamber design, BPMs will be implemented as button sensors integrated into the chamber. This arrangement will make it extremely difficult to mechanically determine the positions relative to the sextupoles. It is therefore suggested to consider an arrangement which is capable of measuring almost simultaneously the magnetic center of the sextupole and the electrical center of its BPM, and to determine their positional relationship. Such setup was built at SLAC for the fiducialization of FFTB quadrupoles and their BPM counterparts. The setup (see fig.f733_a) and measurement procedure are described in Fischer[7].

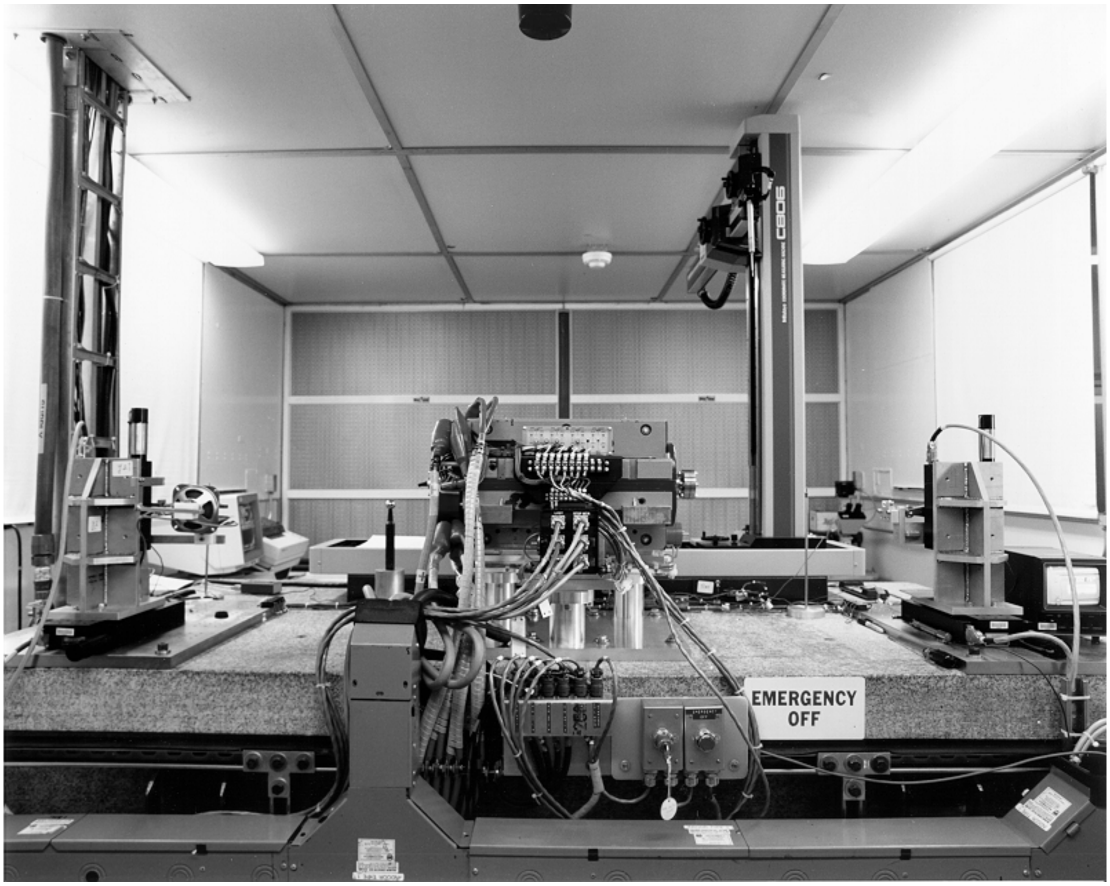

Fig. f733_a Simultaneous fiducialization set-up of FFTB quadrupole and BPM

7.4 SLS Absolute Positioning

Common to all parts of the machine, free stationed TDM5000/6000s, or a laser tracker, oriented to at least six 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

7.4.1.1 Internal Alignment of SLS Synchrotron Girders At today's state of fabrication technology, it should be possible to build steel box type girders, which are dimensionally stable, rigid, and which will not experience permanent deformations during transport. It should furthermore be possible to machine the magnet mounting buttons à la MAX II into a perfect plane. However, I would not recommend to hardmount the components into place. Even if one can convince oneself that the above assumptions are correct, meaning that the mounted magnets would be in perfect relative alignment, there are several reasons to preserve some degree of alignability. Most important here is that if beam based alignment would identify a magnet offset, there would be no easy way to adjust for that. Also, the beam height is about 80 cm above girder; this combined with a footprint of the magnets' standoff/mount of about 40 cm generates a amplification factor of two, translating machining errors in the parallelity of the magnet mount surfaces into x offsets. To allow for vertical adjustments, I would recommend to reduce the nominal height of the magnet mount by e.g. 3 mm and fill this gap with a prefabricated shim inserted between magnet and mount. A lateral adjustment could be preserved by slotting the mounting holes of the magnet standoff in the x direction. An adjustment jig could be referenced to one or two pins which would be press-fitted into additional precision holes drilled into the girder at the same time when the magnet mounting holes are established. This method would still preserve the adjustability of selected components while not require any optical alignment for the internal alignment of components on a girder.

7.4.1.2 Synchrotron Lay-out Survey. It is recommended to fabricate a standard template including all anchor holes for a girder 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 Prealignment of Girder Supports and Adjustment Systems The SLS girders will be supported by motorized adjustment systems. For the alignment concept it is transparent what kind of motorized adjustment system will be used. An example for a successful implementation is the SLAC cam shaft system. Its design doesn't compromise the rigidity of the supports and consequently, doesn't have a resonance in an undesirable frequency range. This system comes in two vertical slices. The bottom piece consists of a mounting plate which holds a mechanical adjustment system and the shafts and stepping motors. The top part is integrated into the movable object (magnet, girder) by mounting the kinematic cams to the object. The object is held onto the cams by gravity. The magnet movers need to be augmented with a mounting system that allows them to be prealigned to within 2-1 mm of their nominal position. The least expensive method is to key the movers to a mounting plate. This plate is then mounted to the floor with four standoff screws grouted/epoxied into the concrete. The adjustment of this plate is accomplished in 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 in a simple level operation. Next the magnet mover mounting plate is set on the nuts and a set of washers and nuts is then screwed on the bolts to fasten down the plate. However, the top nuts remain only hand tight at this point. Then a total station with a „free station Bundle" software package is used to align the plate to within 2-1 mm of its nominal position; the plate is moved into place by tapping. Finally, the bolts are tightened and the magnet mover can be attached after it is verified that the mechanical adjustment system has been set to mid-range. Once the movers are set to mid-range, the girder to which the cams have been mounted can be installed by simply setting it onto the movers' shafts.

7.4.1.4 Alignment of Girders into Global SLS Coordinate System In this step the girders will be moved to their nominal positions under the control of a laser tracker/total station. A tracking instrument would be the most productive tool to control the alignment operation. Usually one would use reference marks attached to the girder and known in the girder coordinate system to control the girder's position. However, these marks should not be used here because they cause a strong violation of Abbe's Principle. The violation occurs because of the vertical separation between girder reference marks and beam height. A small rotation of 0.1

mrad would already induce an error in the x-coordinate of 80 µm. This error can be reduced to an insignificant amount if one uses reference marks on magnets instead. It is therefore suggested to use reference marks on the dominant magnet(s) to align the girder and marks on a different magnet to check the alignment.

Since the roll tolerance of the dipoles is the most stringent roll tolerance of components on a girder, dipole reference surfaces should be used to adjust girder roll. A bridge type fixture in combination with an electronic inclinometer would be the preferred method.

7.4.1.5 Quality Control Survey Once the above step is completed in at least one arc, the girder positions are mapped. If the positional residuals exceed the tolerance, one can step back into the alignment process using the quality control map to quantify the position corrections which need to be applied (fig. f7415_a shows the simulated absolute and relative position accuracies for girder components).

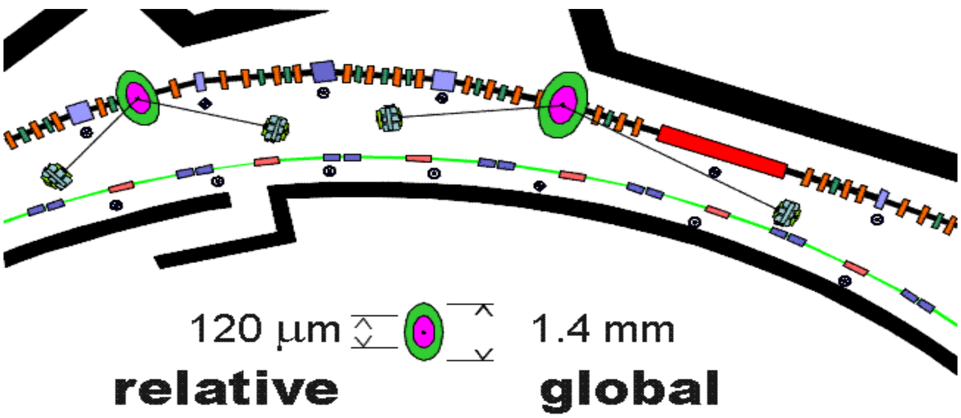

Fig. f7415_a Simulated error ellipses of component fiducial point absolute/relative accuracy

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 Global 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. Here at the SLS, the global shape will be determined by a very narrowly spaced field of control points. Additionally, many systematic error sources are eliminated by moving from the traditional forced centered set-up to the free stationing method. Also, the relative alignment of components on girders is guaranteed to a high degree of accuracy through mechanical means and verified by optical QC. Therefore, at this point, a smoothing operation for the synchrotron is not considered a must, rather an option depending on the analysis of absolute positioning data.

However, if one wanted to improve the relative alignment, instead of a traditional smoothing approach, one could use a different measurement configuration, which is specifically designed to strengthen the determination of the x coordinates of components on adjacent girders. This can be accomplished by setting up a theodolite/TC2002/TDM5000 as close as possible to a girder and measuring horizontal directions to points on components on the adjacent 6 girders, 3 upstream and 3 downstream. By moving the instrument station from one girder to the next, one obtains a traverse with an excellent determination in the x direction (see fig. f751_a). The vertical coordinate would be determined by leveling in a similar configuration. The analysis of this data set would clearly identify weaknesses in the relative transverse alignment.

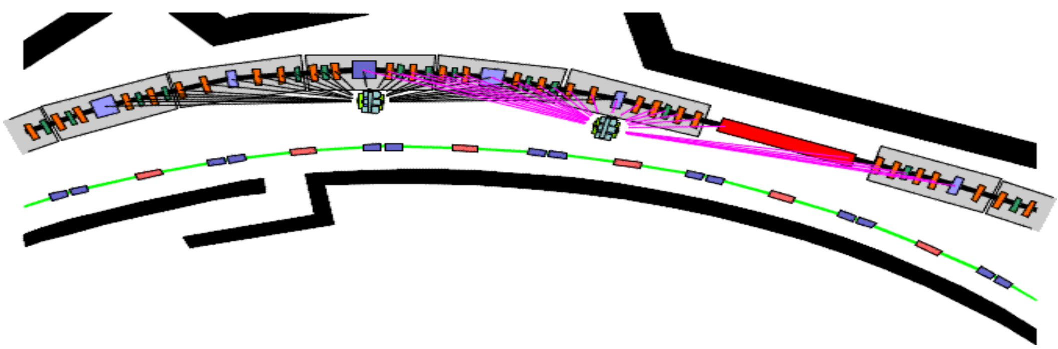

Fig. f751_a Smoothing observation plan

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 smoothing operation is not a must, it should be kept an option depending on the analysis of absolute positioning data.

7.6.0 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. Some particularly important instruments and procedures are in explained in Appendix B.

7.6.1 Hardware

(Only main instruments are listed, necessary attachments and accessories are not specified)

7.6.1.1 Angle and Distance Measurements

Leica TDM5000/6000 with target centering
Optional:
Laser Tracker (Leica or SMX)

7.6.1.2 Elevation Measurements

Zeiss Ni001
Leica N3
Zeiss Digital Level

7.6.1.3 Tilt Measurements

Whyler Inclinometer
Machinist Precision Levels, Set

7.6.1.4 Monumentation, Fixturing

1,5“ sphere receptacles
Magnet Fiducial Fixtures
Mounting Hole Templates

7.6.1.5 Miscellaneous Tools

7.6.2 Data Flow, Data Analysis Hardware

7.6.2.1 Data Analysis Computer

PC, 200Mhz Pentium Pro, 32 MB RAM, 2x2 GB Harddisk

7.6.2.2 Field Computer

Paravant

7.6.3 Data Flow, Data Analysis Software

7.6.3.1 General Office Software

7.6.3.2 Survey and Alignment Software

Bundle based data analysis package
Simulation
Outlier Detection
Database

Industrial Measurement System
Transformation
Ideal Coordinates

7.6.3.3 Field/Data Collection Programs

Horizontal Direction
Vertical Angle
Simultaneous horizontal, vertical and distance
Distance
Level
Set-out

7.6.4 Instrument Calibration

The survey and alignment instrumentation need 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 Institut at the ETH Zürich runs a first class calibration facility and accepts contract work.

7.7.0 Position Monitoring System

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.

7.7.1 Absolute Systems

Absolute systems allow the direct measurement of a particular displacement.

7.7.1.1 Vertical Motion

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 ESRF HLS and the „Aachener Schlauchwaage“ are widely used to monitor the motion of accelerators or of water dams.

7.7.1.2 Horizontal Motion

Horizontally, the situation is different, because there is no natural reference. Additionally, the geometry of circular machine doesn’t lend itself to absolute systems based on straight line references.

7.7.2 Relative System

In a relative system, the displacement of an individual component cannot be measured directly, rather it is the integration and propagation of the displacement measurements of many components.

7.7.2.1 Vertical Motion Monitoring

Hydrostatic leveling systems can be setup as relative system. However, this doubles the number of sensor stations without gaining much accuracy. On the other hand, most of the systems designed to monitor relative horizontal motion can be used just as well to measure relative vertical motion, or could easily be expanded to survey in two dimensions.

7.7.2.2 Horizontal Motion Monitoring

7.7.2.2.1 Overlapping Wires Since a single straight wire doesn't deal with a circular machine very well, one can shorten the sagittas by using many short wires instead. These short wires need to overlap to allow a propagation of measurements over the whole system.

Many different wire systems have been implemented. Besides application specific details, they differ mostly in the wire pick-up method. Basically, three different methods are being used: optical pick-ups, inductive pick-ups, and capacitive pick-ups. The advantages - disadvantages of the three different pick-up methods are summarized in table t77221_a.

	Compatible to magnetic fields	Insensitive to radiation damage	Good resolution	Inexpensive
optical	**X**	**X**	**X**	**X**
inductive			**X**	**X**
capacitive	**X**		**X**	

Table t77221_a Advantages/Disadvantages of wire pick-up

7.7.2.2.2 Train Link The name „train link" comes from the fact that the girders are connected like a train. The coupling has been implemented in different ways:

The KEK ATF damping ring girders will be monitored with a laser diode (LD) - position-sensitive detector (PSD) set-up. As can be seen in fig. f77222_a, a laser diode is mounted on the upstream end of girder n. Its beam is split equally into two beams, each bend away from the original direction by about 30 degrees. On girder n+1, again the two beams are each split into two where the second beam emerges at a right angle. All four beams are monitored by PSDs. The x, y translations can be taken directly from the PSD readings. The z translation can be calculated from opposite sign x readings. Roll is a function of opposite sign y readings, while pitch and yaw are correlations of different scale readings in the same plane on the two PSD associated with each beam, respectively.

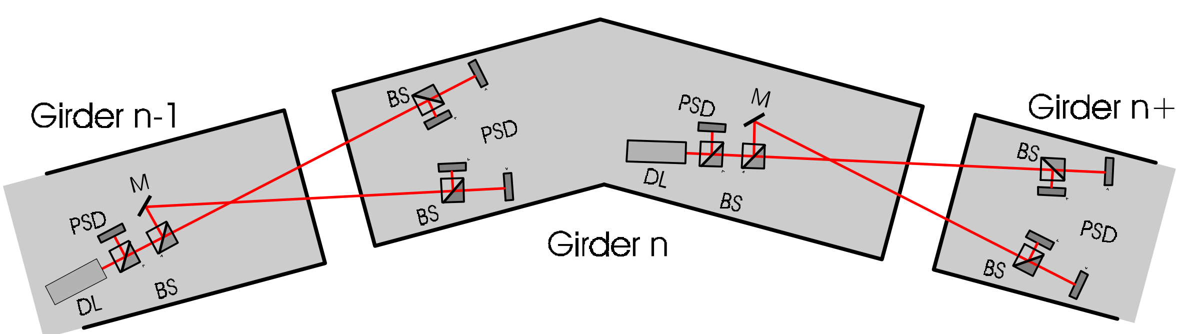

Fig. t77221_a Six degree of freedom laser diode - position sensitive detector set-up

A similar train link connection can be established with inductive or capacitive displacement sensors. On the upstream side of girder n two metal rod are attached equivalently to the above set-up. Instead of PSDs on girder n+1 there are displacement sensors in the same configuration.

With a CCD camera/ image processing approach, the link is established by mounting a CCD camera on girder n. The opposing end of girder n+1 carries a target array of four ellipses (see fig. f77221_b). With well known image processing principles, one can deduce from the elliptical parameters all degrees of freedom.

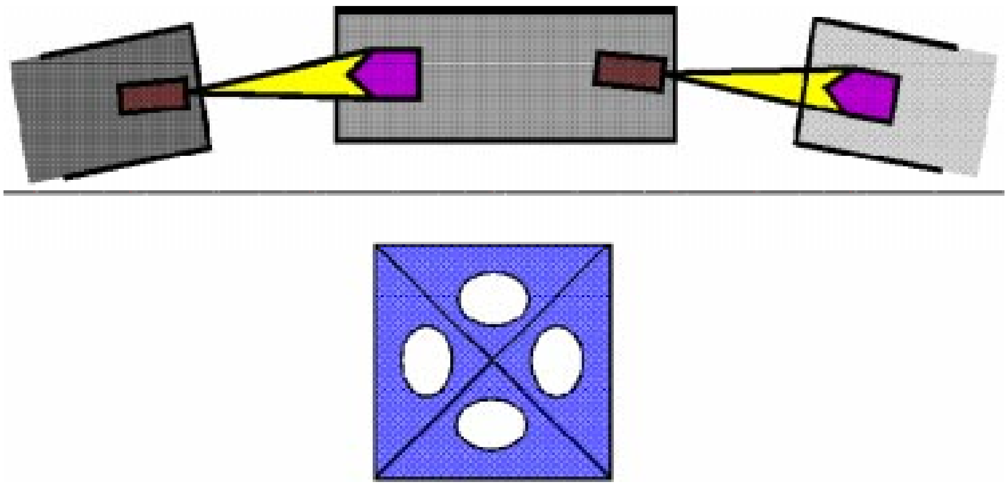

Fig. f77221_b Target for „train link" with CCD camera/ image processing approach

7.7.2.2.3 Laser Beam Reference with Multiple Position Sensors 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[8]. 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 (fig. f77223_a). It is reported that the a positional accuracy of 20 µm was achieved.

7.7.3 Proposed Method

In the vertical dimension a hydrostatic leveling system like ESRF's HLS will accurately monitor relative and global vertical position changes. To also acquire horizontal motion

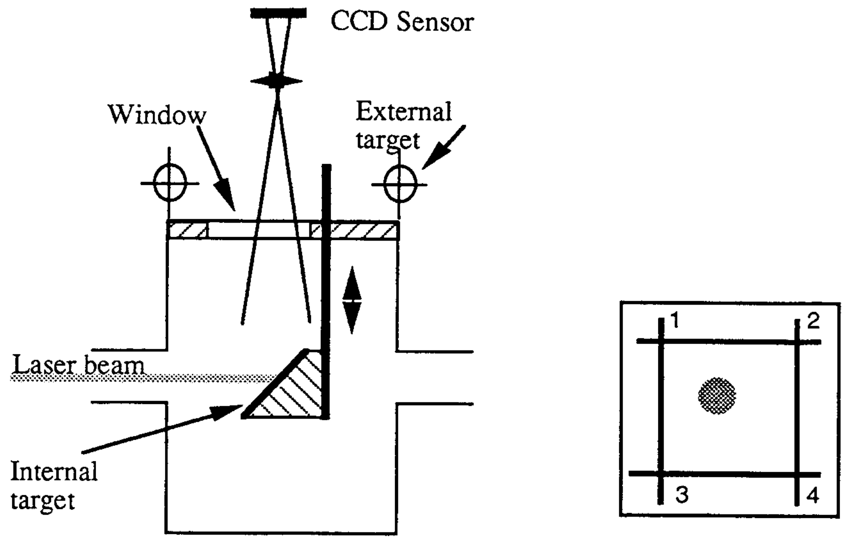

Fig. f77223_a CERN scheme for parasitic use of beam pipe for above monitoring system

information, the hydrostatic level system needs to be augmented by a train link or wire system.

While train-link systems do not provide strong information on global position changes, they are very sensitive to local motions. Because of the ring's mechanical lay-out, there is no contiguous girder train around the ring. Hence, a pure train link lay-out cannot be implemented, rather a combination of several methods will be required. Inside the sextants, which will have a contiguous girder train, a configuration based on the LD/PSD or displacement sensor system should work fine. The straight sections then could be bridged by wires on both sides of the girder/undulators. These wires should be attached to the downstream second last and upstream second girder with two sensors monitoring the downstream last and upstream first girder on each wire. Alternatively, one could continue the girder train with faked girders, represented by just a rigid steal frame wrapped around the undulators.

The hydrostatic leveling system could easily be extended to include the beamlines. Assuming three sensors per beamline, this would add another 33 sensors. It is much more difficult to extend the horizontal reference system into the beamline area. The most direct approach, setting up a wire parallel to the individual beamline'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. However, the CERN scheme should be directly applicable. It should be possible to use the photon beamline vacuum pipes to produce a reference bridging the shielding wall.

Notes and Bibliography

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

[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 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; there is no efficient method to determine the offset vector. This error, 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 setting up the instrument over a known point, the instrument's position is 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 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 veered about 0,5 m off the design trajectory.

[6] The " character indicates inches; 1 in = 2,54 cm, hence the diameter of the 1,5" sphere is equivalent to 3,81 cm.

[7] Fischer, G.E., et al.: Precision Fiducialization of Transport Components, in: Proceedings of the 3rd European Particle Accelerator Conference, Berlin, 1992, SLAC-PUB-5764

[8] Petersson, H., Quesnel, J.P.: Improvement of the Alignment Process of Superconducting Magnets and Low-β-Sections, in: Proceedings of the Third International Workshop on Accelerator Alignment, Annecy, 1993, pp. 189-196.