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A Proposal for the Alignment of the Superconducting Super Collider (SSC)*

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A. Tutorial Information

1. General. This proposal deals with both organizational and technical problems which are important for the precision survey and alignment of an engineering structure of the large size and the tight tolerances of the Superconducting Super Collider.

2. Organizational Tutorial. In this spirit, if we take a systemic approach, it is important that the geodetic and alignment engineering is integrated into the design and accelerator engineering at a very early stage. Naturally "Alignment", which for short we will use instead of "Geodetic and Alignment Engineering", is not the center of all activities as shown in the diagram below. However, it is an important end-user; an end-user, which may be the last to complete work in the tunnel and upon whom depends a timely turn-on and well-functioning of the accelerator. This diagram, therefore, should be interpreted as representing the required communication channels which must be built into the organization.

Accelerator Physics < – – – >		< – – – – – – > Civil Engineering
	Alignment Engineering	
Magnet Design < – – – – – – >		< – – – > Mechanical Engineering

Decisions which have impact on alignment and, therefore, must have input from alignment, include:

- alignment stay-clears in space
- beamheight above floor
- alignment fiducials on the cryostats (magnets)
- FODO cell pattern
- magnet support
- mechanical adjustments
- distance between adjacent penetrations from surface to tunnel
- tunnel width

We make this point so strongly because of a fundamental difference between alignment and most other construction and installation activities: alignment is a labor-intensive process, which often has to be repeated after turn-on. Thus, the operational cost of repeating the alignment, and the down-time it takes to do it, have to be kept in mind during design.

Another reason to build the input of alignment into the organisation is the following: the critical path network (CPN) for an accelerator project will typically not have many nodes which depend on installation alignment until the design of items important for alignment is frozen. With other words, alignment is a driven, and not a driving, activity. It is, therefore, important to have other organizational means to identify and correct developments which are detrimental to a smooth alignment process.

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3. Technical Tutorial. Although one often speaks of survey and alignment, they are different processes, which should be kept apart in the design and performance of the work.

Definition.	
Survey	— finds out where things are
Alignment	— moves them to where they belong

Traditionally most of accelerator alignment has been done with optical tooling techniques, using spirit or split-bubble levels to determine the elevation of magnets, and jig transits to measure off-sets to a baseline established with the jig transit. While these methods are very versatile and fast to set up they have several disadvantages:

a. The actual alignment takes place under control of the operator at the instrument, who will verbally instruct another person in which direction to move the object (magnet, collimator, BPM etc.). A third person is necessary to hold and arc a leveling rod or a tooling scale. Obviously the disadvantage in this method is the requirement to keep the highly skilled optical survey crew working beyond the survey proper until the alignment is also done.

b. It also turns out that "shout-and-holler" methods give poor quantitative control over the adjustment movement, since the movement is not independently controlled in a continuous manner. This lack of control may result in many time consuming iterations.

c. After the set-up is torn down no follow-up control is possible. With optical tooling techniques generally no redundant information, which would allow a least square fit, can be taken. Thus blunders in the set-up can not be detected. This may result in a magnet being perfectly aligned with respect to the baseline defined by the jig transit, but being off from the required location in space by many times the tolerances, because the jig transit had not been properly centered over a monument. With traditional methods these errors are not recoverable unless one goes back and redoes the measurements.

d. Most important for deciding the survey method in a large storage ring may be the following argument. It is generally believed that absolute positioning in a ring is not important but that local smoothness is. The concept of absolute positioning with respect to a set of ideal coordinates can not be given up if measurements and mechanical adjustments are not separated in time and function. Local smoothness is defined only when the positions of all local machine elements of a given tolerance are known, and they are known only after the survey. Therefore, the two activities, survey and alignment, must be kept separate in most cases and optical tooling techniques should not be used except for some special applications .

In what follows we will deal with different forms of survey at different places, and with different kinds of alignment for different purposes.

Namely: the survey takes place in two different areas:

1. above ground	<——— transfer ———>	2. below ground

while the alignment is separated in two different steps:

1. installation placement		2. smoothing alignment
	<——— iterations ———>	
(needs surface information)		(does not need surface information)

B. Technical Proposal

1. Survey above ground. With traditional methods (trilateration and/or triangulation) the surface survey would be a costly and time consuming operation. However, since several years a satellite based technique is available, called the Global Positioning System (GPS).[1] Commercial vendors like Texas Instruments or Macrometrics offer (nearly) turn-key receiver systems. The accuracy has improved from several 10^{-5} to $2 \cdot 10^{-7}$ recently, where the biggest improvement came from combining the Very Large Baseline Interferometry stations, whose positions are known to 10^{-8}, with GPS stations in a simultaneous fit to reduce uncertainties in satellite orbits by an order of magnitude. For a project the size of SSC it would be more cost effective to acquire the necessary hardware rather than to contract out the job.

   The GPS system has to be supplemented for short distances by methods based on Electronic Distance Meters (EDM's with an accuracy $< 10^{-6}$) and theodolites.[2] The EDM's, in conjunction with a permanent SSC baseline, will determine and control the local scale factor for SSC during the whole of the construction project. Both types of instruments are also needed for work in the tunnels to place and align the components (see below).

   The advantages of GPS are: (a) no lines of sight are necessary, (b) monuments can be put on locations which are desirable from a geodetic point of view and do not have to be determined from the topography of the site, and (c) the measurements are more than a magnitude faster than with traditional methods. The GPS output is in the form of three-dimensional coordinates U,V,W in the satellite coordinate system which must be transformed into global spheroidal coordinates and further into a local system.

   Problems of conceptual and theoretical nature which have to be solved are:
   • determination of the transformation parameters needed for transformation of the GPS output into the local spheroidal coordinate system,
   • transformation of the geodetic surface measurements into the spheroidal coördinate system.
   To do the latter, the local geoid has to be determined by measuring the deviation from the vertical with a Zenith camera.[3] This determination should be contracted out to a University Institute specializing in this type of research.

   Because of the size of SSC the general reference surface must be an spheroid, i.e., all measurements have to be translated into spheroidal values. To avoid costly errors and multiple coordinate systems, machine lay-out coordinates which are normally given in a plane coordinate system, should be translated into geodetic spheroidal coordinates at a very early stage. For this purpose a model and the necessary software has to be developed. Therefore, it seems mandatory that the conceptual work starts about two years before construction contracts are let.

2. Survey Below Ground. Refraction due to the temperature gradients in a tunnel are the cause of systematic errors in tunnel surveying. The same small error will add up with each measurement and will eventually lead to very large deviations from the desired location. Even for an accelerator of 1 km diameter such errors, if unchecked, can lead to several cm horizontal closure error.[4] This systematic error must be controlled using either gyro theodolites (which determine true north), penetrations, or a combination of both.

Simulations for SSC, using the SLC GEONET geodetic program system, [5] show that penetrations spaced 3 to 5 km along the SSC, plus gyro theodolite measurements, will keep the systematic error within self-consistent boundaries with respect to the desired accuracy of component placement and the overall distortion the machine will accept.

a. Transfer of Surface Coordinates. The surface coordinates are transferred to the tunnel with INVAR tapes (vertical) and plumbing (horizontal). For the plumbing several methods are available: (a) optical plummets with an accuracy of 1:200,000, (b) pendula with oil damping, and (c) inverted pendula. They all have their specific advantages and disadvantages so that a specific choice depends eventually on the accuracy needed and the circumstances of work.

However, it should be understood that for SSC any of these methods will fulfil the requirements. This is so because the penetrations control only the long wave length deformation of the ring. The more important local smoothness is determined by the network in the tunnel. In the end it is the requirement of local smoothness (0.5 mm over 200 m) which determines the long wave component to be not more than a few cm over 3 to 5 km.

b. Establishing the Tunnel Net. Once global (surface) coordinates are known in the tunnel, coordinates of the tunnel net can be calculated. Measurements to determine the relative position of tunnel control points (horizontal) and benchmarks (vertical) can be done independently of the transfer, that is to say even before the transfer has been made.

The vertical tunnel net is not expected to pose any specific problem, except that some 10,000 marks have to be measured. Non-automatic split bubble levels with INVAR rods will be used.

The horizontal tunnel net has to be established by traditional methods of measuring distances and angles, albeit with modern technology. For the concept proposed here it is crucial that distance measurements can be done fast and non-mechanical. This precludes the use of the CERN DISTINVAR,[6] which exerts a pull of over 30 pounds on the points to be measured, and the cumbersome use of INVAR wire. Thus angle measurements will be done with electronic theodolites, and the distance measurements with 2-color electronic distance meters (to be developed). Presently available EDM's are already achieving accuracies just below 1 mm with single-color techniques.

The total error budgets for vertical and horizontal measurements can be kept in limits by measuring short distances in leveling, by using a dispersiometer, and by additional gyro theodolite measurements for the horizontal control.

c. Installation Alignment. The tunnel net is needed for initial placement of components. It may or may not be needed for the precise alignment, depending on the mechanical construction of magnets (cryostats), and support and adjustment systems. For achieving local smoothness it is more advantageous to place both instruments and targets for the survey on the magnets, but the cryostat design may preclude this method.

To place the magnets in their rough (3 to 5 mm) position the same technique used in the tunnel net is employed by measuring angles and distances. For the initial installation horizontal and vertical placement can be done in one step by measuring distances and horizontal and vertical angles from a known theodolite position in 3-dimensional space.

d. Smoothing Alignment. For the more accurate smoothing survey horizontal and vertical measurements have to be separated. Therefore, precise leveling has to be done here.

The horizontal position could be determined by measuring directions and distances but due to the long target distances (100m m) the horizontal refraction may make this method too inaccurate. A non-optical off-set measurement is preferred.

CERN has developed a NYLON off-set techniques. where a stretched NYLON wire is used as a baseline.[7] Off-sets from the magnets to this wire determine the location of the magnets. For NYLON wire length of up to 90 m, rms-deviations of less than 0.1 mm have been determined. It seems possible to use this method for placement of the SSC quadrupoles and bend magnets, but it will require some effort to extend its range from 90 to 200 m.

Once the position of the ends of the quadrupoles and bend magnets are known they will be moved to their desired location under the supervision of computer controlled electronic dial gages, strictly separating survey and alignment.

Finally, when the end supports of the bend magnets have been adjusted, the 3 middle supports of the 17 m long structure can be adjusted relative to the ends by a simpler and faster method using standard alignment scopes.

C. Summary of Technical Data and Requirements

1. Surface Net.

Parameters to be determined:

- Scale: dual wavelength EDM, 2 mm/10 km
- Deflection of the vertical: Zenith camera, 0.5 arcsecond
- U,V,W: Dual wavelength GPS receivers, 1 cm/30 km

Equipment availability:

- EDM: available instrument plus 2^{nd} wavelength
- Zenith camera: available, contract job 1 – 2 years
- GPS dual wave length receivers: available, delivery 1 – 2 years

Software:

- Partially available, needs expansion, modification and unification

2. Surface–Tunnel Connection

Penetrations:

- Spacing: 3 to 5 km
- Diameter 80 cm

Equipment:

- Position: optical plummet, available
- Height: INVAR tape set-up, custom made

Accuracies (absolute):

- Surface point: 1.5 cm position, 3 cm elevation
- Tunnel point: 2 cm position, 3 cm height

3. <u>Tunnel Net</u>

Monumentation:

- Position: removable monuments over floor marks every 400 m
- Height: rivets in floor every 40 m

Measurements:

- Distance: dual wavelength EDM, 0.5 mm/400 m
- Direction: electronic theodolite, 0.1 mgon, gyro theodolite, 0.3mgon
- Height: Level, 0.5mm/km

Accuracies:

- Absolute: 2 cm position, 3 cm elevation
- Relative: 1mm position, 1mm elevation

Equipment:

- EDM: available, needs modification
- Theodolite: available
- Gyro: available needs automatization
- Level: available
- Electronic fieldbook: available

Software:

- Partially available, needs modification

4. <u>Lay out Survey</u> (Bolt anker location, support system without magnets, magnets

Method:

- Directions and distance from 2 tunnel net stations

Measurements:

- Distance: EDM, e.g. KERN 503 2mm/100m
- Direction: electronic theodolite
- Height: vertical angles/level

Accuracies:

- Absolute: 2.5 cm position, 3.5 cm elevation
- Relative: 3mm position, 3mm elevation

Equipment:

- EDM: needs modification
- Theodolite: available
- Level: available
- Electronic fieldbook: available

Software:

- Has to be developed

5. Smoothing Survey

Method:

- Off-set NYLON measurement magnet to magnet
- Differential leveling magnet to magnet
- Bend straightening with alignment scope technique

Measurements:

- Off-set: NYLON off-set device, 0.2 mm/200 m, 0.1 mm/100 m
- Height: level, 0.5 mm/1 km

Accuracies:

- Position: 0.3 mm quad to quad
- Height: 0.3 mm magnet to magnet

Equipment:

- Offset device, CERN development, needs improvement
- Level: available
- Electronic fieldbook: available

Software:

- Modules available, need modification

D. Cryostat Alignment Reference

The alignment of the magnetic centerline of superconducting magnets can be only as good as the transfer from the steel stamping to reference marks, e.g. tooling balls, on the outside of the cryostat.

This transfer is mostly being done with optical tooling techniques. As in the case of survey and alignment of beam line elements in the tunnel, optical tooling techniques might not be the best of available methods because they are time consuming and do not give result in permanent original records suited for blunder detection even at a later date.

This matter should be given serious consideration. Quality control (with respect to alignment) of more than 10,000 superconducting magnets is not trivial.

Off hand we would propose photogrammetry to do the job, but other methods like coordinate measurement machines might also be feasible.[8] The photogrammetric method works similar to taking pictures of a bubble chamber event. Photographs from different directions are taken, digitized on an automatic digitizer and computer analyzed. The photograph is the permanent record and might also be used for other trouble shooting at a later date.

E. Summary of Cost Breakdown

Survey and alignment of SSC is estimated to cost approximately between $25M and $30M, depending on some assumptions and methods of cost accounting. This cost does not include benefits and other overhead like relocation, secretarial support, and other incidental cost. This estimate assumes that the working conditions are optimal, especially that there is a minimum of physical interference with the survey and alignment procedure in the tunnel. It also assumes that alignment fiducials and support and adjustment systems of the magnets have been developed with the approval of the alignment group, with other words that they are functional and not a modern version of hammer and wedge.

Approximately one third of the cost is spend for equipment, fixtures, and outside contracts. The other two thirds is needed for salaries of engineers of various kinds, and survey technicians. The total head count at the peak load is just below 100 people.

One of the biggest difficulties in getting SLC aligned will be to find enough qualified survey professionals and to keep them over a long enough time on a rather monotonous, albeit difficult, job.

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