SLAC – PUB – 3543
January 1985
(A)

THE ALIGNMENT OF STANFORD'S NEW ELECTRON–POSITRON COLLIDER*

HORST FRIEDSAM, WILLIAM OREN,
MATTHEW PIETRYKA–PRESENTER,
RAINER PITTHAN, AND ROBERT RULAND
Stanford Linear Accelerator Center
Stanford University, Stanford, California 94305

ABSTRACT

The Stanford Linear Accelerator Center (SLAC) is in the process of building a new particle collider, the SLAC Linear Collider (SLC). This paper gives a brief introduction to SLAC and an outline of the surveying activities underway for the alignment of the SLC. The precise horizontal and vertical networks on the surface and in the tunnel are discussed, along with the instrumentation required. The close confines of the sloping, curving tunnels and the sub-millimeter relative positioning tolerances make for an interesting project.

INTRODUCTION

The Stanford Linear Accelerator Center is a national fundamental physics laboratory designed, built, and operated by Stanford University under contract with the Department of Energy. It is located on a hilly, 480 acre piece of Stanford's "academic lands" just West of campus proper. Scientists from the U.S. and abroad use SLAC's giant machines to study the most fundamental particles and forces constituting matter.

Since its establishment in 1962, SLAC has built three machines, one linear and two ring-type. SLAC's namesake, the linear accelerator (linac), was the first machine built. Completed in 1966 after four years of construction, the linac stretches 10,000 feet from West to East. Its components are housed in two parallel structures separated by 25 feet of compacted earth and connected by vertical shafts. The beam tube resides in an underground 10 foot by 11 foot concrete box tunnel. The high power klystrons and supporting electronics occupy a 17 foot by 30 foot sheet metal structure on the surface. Radio frequency waves generated by the klystrons and fed to the 4 inch copper waveguide tube below, can now accelerate electrons to 35 billion electron volts (GeV). Upgrades will boost output to 50 GeV by 1986. Special magnets in the beam switchyard (BSY) area at the East end of the linac steer the beam to one of several study areas.

The second machine, the Synchrotron-Positron-Electron Asymmetric Ring (SPEAR) took less than two years to build and was completed in 1972. SPEAR's above-ground, 600 foot oval ring is fed with accelerated positrons and electrons from the linac. These particles rotate around the storage ring in opposite directions and collide at two interaction regions with a maximum of 8 GeV energy,

---

* Work supported by the Department of Energy, contract DE-AC03-76SF00515.

Presented at the 1985 ASP–ACSM Annual Spring Meeting,
Washington, D.C., March 10–15, 1985

where special detectors collect data. Also, special "windows" allow the study of synchrotron radiation produced in this tight ring.

The third big project, the Positron-Electron Project (PEP), commenced in 1976 and was completed in 1980. It is also a storage ring machine fed by the linac, and was built in a horizontal plane in a 12 foot wide tunnel. PEP's 2 kilometer circumference provides collision energies of 30 GeV at its 6 interaction regions.

The next machine, the SLAC Linear Collider (SLC), is now under construction. A true linear collider would simply have two linacs pointed at each other. One would accelerate electrons and the other positrons, and the particles would collide in the middle. A very attractive feature of linear colliders is that they are much cheaper to build, per GeV, than ring-type colliders. Indeed, the price of a linear collider bears a linear relationship to design energy, while for ring colliders the relationship is quadratic. The SLC will not be a "true" linear collider in that only one linac, the existing one, will be used. Both positrons and electrons will be accelerated to 50 GeV and then separated and brought around to a collision point. The particles will be used only once and then dumped, so there is no need for circulation mechanisms.

THE SLAC LINEAR COLLIDER

The shape of the completed SLC will be like a stethoscope with the straight part being the existing linac and the curved parts being the new North and South collider arcs. The diameter of the loop formed by the arcs will be about 1 kilometer. Because of the location of existing facilities and local geology, the floor of the arc tunnels will not lie in a plane. Beginning at the linac with its −0.005% slope, the floors will fall at a maximum −7% and then rise at +10% before leveling out near the interaction point. The average depth of the 10 foot by 10 foot arched ceiling tunnel will be over 60 feet with a maximum of 110 feet. The walls and ceiling will consist of shotcrete over steel ribbing, while the floor will be of poured concrete.

The actual beamline arcs will consist, essentially, of about 1000 combined function magnets. These magnets, measuring roughly 20 by 20 by 250 cm, steer, focus, and correct the passing electron or positron bunches. Groups of 20 magnets called achromats are the building units manipulated to form the arcs into the desired three-dimensional shape. A cursory glance at an achromat reveals what appears to be a segment of the arc of a simple circular curve. Actually, the magnets are built with a 270 meter bending radius and adjacent magnets are connected by 10 cm tangents called drift spaces. If the plane of an achromat is tilted, a change in elevation, as well as horizontal position, results as its length in traversed. Therefore, the arcs are composed of many achromats whose planes are tilted to provide the necessary changes in horizontal and vertical position.

From the physics point of view, the key characteristic of an achromat is that a particle bunch exits with physical properties (like its cross-section) equal to that when it entered. Thus, the electron and positron bunches can pass from achromat to achromat to their final destination unchanged. For the SLC, electrons and positrons will arrive at the end of the linac in bunches of 5×10^{10} particles with cross-section of about 30 microns and energy of 50 GeV. This bunch will be maintained around the arcs until the final focus region is reached. In the final focus area, the bunches will be squeezed and focused down to a cross-section of about 1 micron and directed at each other at the collision point. A perfect head-on collision between two particles will give an energy of 100 GeV.

TOLERANCES

Proper function of the SLC will require both high absolute accuracy and extreme relative accuracy in the positioning of magnets. Since the SLC arcs are "add-ons" absolute accuracy is an expression of the relationship between new components and the existing linac. The relationship of the SLC to the National Net is of no consequence. The high absolute accuracy is particularly important in the "timing" of the particle bunches so that collision occurs in the proper location within the detector. However, in magnetic particle transport systems, high relative positioning of neighboring elements, or smoothness, is the highest virtue. Comparatively large shifts in absolute position are tolerable as long as the system remains very smooth so that particle path disturbances remain negligible. Some key placement specifications are as follows:

- the absolute accuracy of a magnet position relative to its theoretical position must be ±10 mm.
- the ends of two neighboring achromats must align within ±0.4 mm.
- the ends of two neighboring magnets within an achromat must align within ±0.1 mm.

DESIGN COORDINATE SYSTEM

The three-dimensional positions of the arc magnets are specified by a program called TRANSPORT (Brown 1973). The right handed coordinate system used in TRANSPORT has its origin at station 100+00 on the East end of the linac beamline and defines reference axes as follows (see Fig. 1):

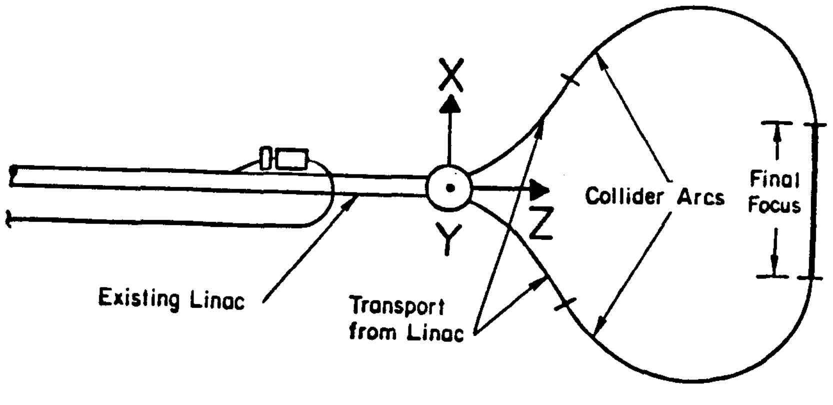

Fig. 1. The TRANSPORT Reference System.

$+Y$-axis	upward along the gravity vector at station 100+00
$+Z$-axis	easterly, perpendicular to gravity and in the vertical plane of the linac
$+X$-axis	northerly, perpendicular to gravity and the Z-axis.

The program gives three coordinate values and three sequential rotations for selected points along the arcs. The rotations are yaw (θ), pitch (ϕ), and roll (ψ) about the Y, X, and Z axes respectively.

GEODETIC REFERENCE SYSTEM

Gravity surveys at SLAC conducted during linac construction revealed no significant gravity anomalies. This fact, combined with the small area covered by the SLC net (less than 2 square kilometers), allow use of a sphere as a geodetic reference surface for vertical and horizontal surveys. The chosen sphere is defined by the mean radius of curvature of Clarke's ellipsoid at the origin of the TRANSPORT coordinate system. This sphere, a so-called Gaussian sphere, has the same tangent plane as the ellipsoid at this one point. The sphere is considered to be tangent to the TRANSPORT plane at station 100+00.

The primary consideration for the vertical surveys is the transformation from sphere-approximated geoid heights to the TRANSPORT plane. This correction amounts to almost 8 cm in the worst case. Orthometric corrections and discrepancies due to path differences are negligible due to the small size of the site and full monumentation of the net.

The first adjustment of the horizontal position net combines GPS vectors and conventional observations. A three-dimensional solution at ground elevation is used to make best use of the GPS data. After adjustment, the determined positions are reduced to the TRANSPORT plane. All later adjustments are carried out in the plane because of computational ease. Thus, distances and angles must be reduced to the plane before adjustment. On a couple steep lines, the correction to be applied to an angle due to deviation of the local gravity vector with respect to gravity at the origin of TRANSPORT approaches 20 seconds.

DATA HANDLING

The huge amount of data to be collected makes automatic data flow essential. Use of an electronic field book makes data entry faster and more reliable, allows easy checking of observations, and makes transfer to the data base fast and efficient.

The SLC project uses hand-held Epson HX computers as electronic fieldbooks. Programs written in Basic prompt for input and control the observation sequences. The Epson features a micro printer in addition to a minicassette for data storage. Field data is passed to IBM PCs for error correction and storage. Finally, files are passed to an IBM mainframe for adjustment.

A comprehensive set of adjustment and propagation programs is used to plan surveys and process data. A group of programs based on the recent theory of free nets is used to test observation schemes and net configurations. Other programs check and establish input files for the least squares adjustment routines. Also available is a program for the simultaneous adjustment of GPS vectors and conventional measurements. Deformation analysis algorithms are necessary to monitor monument movements in the months between network surveys.

ALIGNMENT DESIGN

To position the approximately 1000 magnets in the arc tunnels, a network of nearby reference marks is necessary. Even with directions and distances with standard deviations of ±0.3 mgon and ±0.05 mm, respectively, error analysis shows that a tunnel traverse alone could not supply reference points with the required accuracy. Therefore, a surface control network with vertical penetrations will support the tunnel traverses. Vertical support, also, will be supplied through the penetrations to check the accrual of systematic errors in the tunnel leveling. The required accuracy of a horizontal tunnel position supplied by the surface net is ±5 mm.

CONNECTION TO DESIGN COORDINATE SYSTEM

The proper location and orientation of the new SLC components with respect to the existing beamline is of utmost importance. A Macrometer^{TM} survey performed by Geo-Hydro picked up four positions along the linac and five net points to provide a very strong directional tie and x-coordinate connection. Traverses run from alignment fixtures in the BSY near linac station 100+00 to penetrations in the North and South arcs supply z-coordinate connection and an independent directional check. Differential levels run from the same area out through two access tunnels to the surface vertical net give y-coordinate ties.

SURFACE HORIZONTAL NET

A geodetic network incorporating the penetrations is necessary to provide them with a consistent set of relative coordinates. Thirteen strategically located control monuments and 16 penetrations covering the 1.2 km by 1.2 km area form this net (see Fig. 2). The measurement schedule, determined using free net

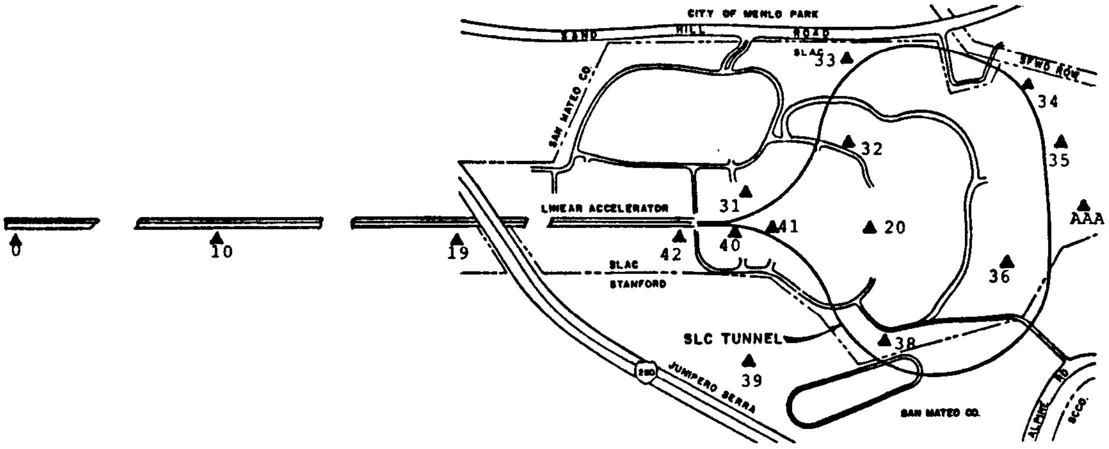

Fig. 2. Surface Horizontal Control Monuments.

error propagation, consists of directions and distances with standard deviations of ±0.3 mgon and ±3 mm respectively. Results of this error propagation show error ellipses with semi-major axes of about 2 mm.

The desired accuracies preclude the use of ordinary ground-level monuments with tripods. Instead, the control monuments must be either massive concrete pillars or welded steel-frame towers, both with independent observing platforms. The reinforced concrete monuments protrude 2 to 3 meters from the ground and extend as much as 7 meters below ground. These pillars have diameters of 75 cm below ground and 45 cm above. Each is equipped with a Kern forced centering plate, and a 60 cm diameter concrete pipe "sleeve" above ground to insulate it from the sun. The towers are drilled and tapped to accept translation stages for precise centering over ground marks. Tunnel positions under penetrations are occupied with special removable stands with translation stages. These stands bolt to the concrete aprons around the surface openings of the penetrations.

Equipment

Of primary importance is a forced centering mechanism which will accept instruments made by Kern, Wild, CERN,[*] and SLAC. It must also repeat centering within 0.01 mm, be insensitive to 15 kg lateral forces, allow integration of a translation stage, and be easy to handle. The chosen design consists of a socket made by CERN[†] and special adapters to fit instruments made by Kern, Wild, and SLAC into these sockets. A socket is composed of three pieces: a sphere with a 30 mm diameter hole through its center; a lower housing with cup-shaped recess for the sphere; an upper housing with a hole in its top that allows the sphere to protrude. The hole in the sphere may be leveled and then locked into place with screws connecting upper and lower housings. A cylindrical shaft topped by a Kern, Wild, or other locking plate may then be guided into the sockets.

For observation of directions and distances, a Kern E2 theodolite with attached DM503 EDM is used. The E2 is an electronic theodolite with least count of 0.1 mgon. It features automatic compensation for small mislevelments and a bus interface for data transfer. All observations are recorded on an Epson HX computer. The Epson prompts for input and all data transfer is automatic. For night observation, the Epson controls one of the E2 display screens to show the nominal value of the direction to each successive station, after an initial pointing at each target. Observations are immediately checked for gross errors and the standard deviation of the pointings computed upon completion of a set. The DM503 was hand selected by Kern for SLAC and has a measurement standard deviation less than 2 mm after calibration and environmental corrections are applied. Digital psychrometers and a barometer are used to monitor atmospheric conditions. Centering on towers and over penetrations is accomplished with socket-mounted translation stages and Wild NL optical plummets. The

---

[*] Conseil Européen pour la Recherche Nucléaire (European Organization for Nuclear Research).

[†] For a description of CERN's socket, Distinvar, and offset device, see Gervaise, 1981.

Wild NL has a minimum focus distance of 0.9 meters and relative accuracy of 1:200,000.

VERTICAL SURFACE NET

Elevations are needed for transfer through the penetrations to the tunnel and for reduction of measured distances on the surface. Benchmarks located near each penetration and horizontal control point form a net to satisfy this need. The required accuracy of the elevations of these benchmarks is comparable to the horizontal accuracy of ±2 mm.

To minimize errors and simplify repeated leveling of the net, both benchmarks and turning points are permanently monumented. The benchmarks consist of sections of threaded 5/8 inch rebar driven to refusal and topped with a stainless sphere. The turning points are either railroad spikes in asphalt or 3 foot sections of rebar in natural ground. Turning point spacing is such that maximum sight distance is 20 meters and sights are balanced to less than 0.2 meters. The average number of setups between benchmarks is 12, and to double-run the entire net requires about 700 setups.

Equipment

All observations are made with new Wild N3 levels and calibrated 0.5 cm Kern rods. The N3 is not affected by magnetic influences, has a minimum focusing distance of 0.5 m, has the required accuracy, and may be calibrated at SLAC. The rods are equipped with digital temperature sensors attached to the invar in three places keep track of rod scale temperatures. All observations are recorded and checked by an Epson HX.

HORIZONTAL TUNNEL POSITIONS

The reference points used to lay out magnets are established by traversing from penetration to penetration. The relative accuracy of neighboring traverse points must be ±0.2 mm. Traverse point spacing was determined considering this ±0.2 mm specification and the fact that highest relative magnet accuracy occurs within an achromat. Free net simulation indicates four traverse stations per achromat are necessary, or a spacing of about 17 meters. Directions to ±0.3 mgon and distances to ±0.2 mm per 100 m are required.

Equipment

Ideally, tunnel monuments would consist of permanent wall-mounted sockets, but this is not possible due to the inconsistency of the shotcrete walls. Therefore, floor-mounted stands must be used. They must be removable because the tunnel is narrow, rigid enough to withstand the lateral load applied by the mechanical measuring device, and provide repeatability in position of ±0.02 mm. Special tripods over floor marks meet these needs. The floor marks are brass plugs with optical tooling targets recessed into their tops. The tripods are about 1 meter tall and made of welded, 7.5 cm diameter heavy guage aluminum tubing and 2.5 cm thick plates. After bolting these tripods to the floor over floor marks, translation stages and CERN sockets are mounted and centering performed with a Wild NL optical plummet.

Directions are measured with Kern E2s using special short-distance targets. Results are tabulated immediately at each station by the Epson HX so that additional observations can be made if necessary. Distances are measured using CERN's Distinvar. The Distinvar uses lengths of 1.65 mm diameter invar wire as a comparison standard. The actual length of each wire used must be determined before and after each use on SLAC's laser interferometer calibration bench. This calibration capability, along with the Distinvar's ability to apply 15 kg of tension with an accuracy of one part in 10,000, results in distance measurements with a standard deviation of ±0.05 mm.

VERTICAL TUNNEL POSITIONS

Vertical reference points in the form of 1/2 inch by 2 inch stainless round-head rivets are epoxied into the floor every 20 meters. Elevations of these marks are determined using the same instruments and procedure used for the surface net. Special 2 meter and 1 meter rods are necessary because of the arched ceilings and other tight spots in the tunnels. Independent supporting elevations are passed through the penetrations by making simultaneous N3 observations on both ends of suspended, calibrated invar tapes.

ARC MAGNET SURVEYS

Surveys for installation of arc magnets will occur in four phases. Phase 1 involves positioning a pattern of bolt holes on the floor for the magnet pedestals. A pedestal is required every 2.5 meters and the holes must be located within ±15 mm of their planned positions. Phase 2 brings the pedestals to ±3 mm of their theoretical positions with respect to the traverse monuments. Phase 3 uses the precise adjustment mechanism on top of each pedestal to refine its positioning to ±0.5 mm. Phase 4 is the final smoothing step which provides the necessary ±0.1 mm relative magnet positioning.

Phase 1, pedestal bolt positioning, will be performed by an independent contractor. SLAC will provide him monuments and coordinates for positions under penetrations to control his traverses. Coordinates will also be supplied for the beamline position over the center of the pedestals, called the vertex points, projected to the floor perpendicular to the sloping beamline. Distances and directions will be laid out with theodolites and calibrated invar tapes.

Phase 2 will be performed by SLAC after survey and adjustment of the E2-Distinvar arc traverses. In this phase, a special target mounted on the pedestal top will occupy the position of the vertex point. Two E2 theodolites equipped with laser eyepieces will be set up over the two nearest traverse points. Horizontal and vertical angles computed by an HP 110 portable computer will be turned to the theoretical vertex position with the E2s. The pedestal will then be moved until the target resides at the intersection of the two laser beams.

Phase 3 involves measuring horizontal and vertical directions to the target at the vertex point for computation of its actual position. The small corrections needed will be effected with the precise adjustment mechanism and monitored with electronic dial gauges.

Phase 4, smoothing, will be performed after magnet installation and achromat by achromat since the smallest relative accuracies occur within an achromat. Two measurements will be made in this phase, offsets in the plane of the achromat and elevation differences. The offset observations are made by an automatic device which senses the distance from some point of interest to a nylon line stretched between two fiducials. Offsets up to about 1 meter can be measured with an accuracy of about ±0.05 mm. Offsets up to about 1 meter can be measured with an accuracy of ±0.05. The elevation differences will be observed with an N3 level and 1 meter rods.

CONCLUSION

In early January of 1985, 1000 meters of the South arc tunnel will be turned over to SLAC and pedestal bolt surveys will begin. Pedestal installation begins in March, and the first magnets should be in place by June. As presently planned, the SLC will collide its first beams in the Fall of 1986.

REFERENCES

Brown, K.L., Carey, D.C., Iselin, Ch., and Rothacker, F., *TRANSPORT, A Computer Program for Designing Charged Particle Beam Transport Systems*, SLAC-91 (1973 Rev.), NAL 91 and CERN 80-04.

Coosemans, W., Mayoud, M., Menant, E., and Roux, D., *Processing of the CERN Ring-Shaped Geodetic Networks*, CERN-CAST, 1977.

Dupen, D., *The Story of Stanfords Two-Mile-Long Accelerator*, SLAC-62, 1966.

Fischer, G., *SLC-Arcs*, in: Stanford Linear Collider Design Handbook, Stanford, 1984, pp. 3-3 → 3-72.

Friedsam, H., Oren, W., Pietryka, M., Pitthan, R., and Ruland, R., *SLC-Alignment Handbook*, in: Stanford Linear Collider Design Handbook, Stanford, 1984, pp. 8-3 → 8-85.

Gervaise, J., *High Precision Instrumentation Developed for CERN*, CERN-SPS/SU/81-1, ACSM Proceedings, February 1981.

Lõffler, F., *Geodetic Control Networks at PETRA*, SLAC Translation 0199, 1982.

Richter, B., *An Informal History of SLAC-Part III: Colliding Beams at Stanford*, SLAC Beam Line, 1984.

SLAC Linear Collider Conceptual Design Report, SLAC Report 229, 1981.