MASTER

LBL-12006

CONF-810211--1

Lawrence Berkeley Laboratory

UNIVERSITY OF CALIFORNIA

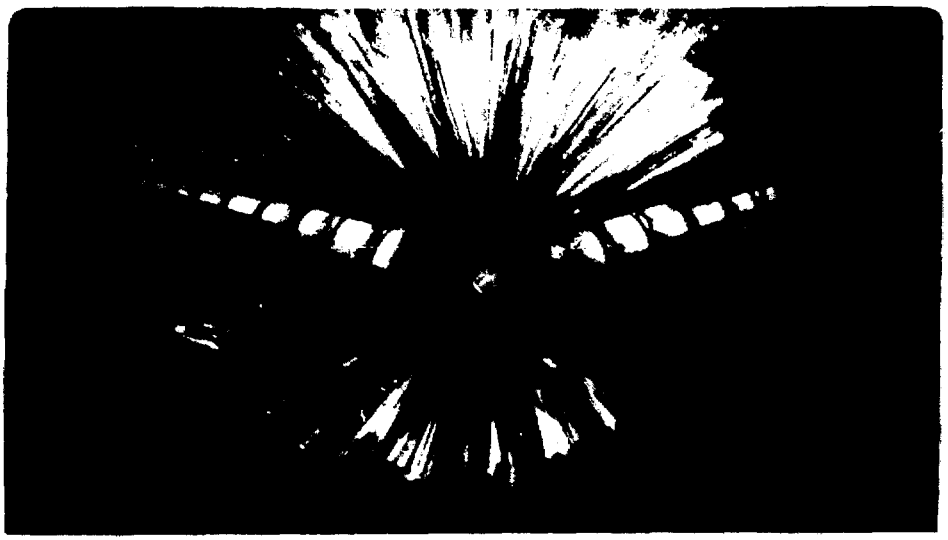
Accelerator & Fusion Research Division

To be presented at the 1981 American Society of Photogrammetry and the American Congress on Surveying and Mapping Convention, Washington, D.C., February 22-27, 1981

THE RECENT HIGH PRECISION SURVEYS AT PEP

R.C. Sah

December 1980



Prepared for the U.S. Department of Energy under Contract W-7405-ENG-48

DISTRIBUTION OF THIS DOCUMENT IS UNLIMITED

THE RECENT HIGH PRECISION SURVEYS AT PEP*

R. C. Sah
Lawrence Berkeley Laboratory
Berkeley, CA. 94720

BIOGRAPHICAL SKETCH

Richard Sah received his Ph. D. in particle physics at Harvard University in 1970. He immediately joined Lawrence Berkeley Laboratory as a post-doctoral fellow and worked several years in both particle physics and particle accelerator development. After a short period working on ion implantation accelerators in industry, he returned to Lawrence Berkeley Laboratory in 1975 as a staff physicist, and he has been the leader of the PEP Survey and Alignment Group.

ABSTRACT

The task of surveying and aligning the components of PEP has provided an opportunity to develop new instruments and techniques for the purpose of high precision surveys. The new instruments are quick and easy to use, and they automatically encode survey data and read them into the memory of an on-line computer. When measurements of several beam elements have been taken, the on-line computer analyzes the measured data, compares them with desired parameters, and calculates the required adjustments to beam element support stands.

INTRODUCTION

The Positron Electron Project (PEP) is a joint project of Stanford Linear Accelerator Center and Lawrence Berkeley Laboratory. PEP is a $78 million construction project funded by the U. S. Department of Energy, and it consists of an electron-positron storage ring which is used to perform colliding-beam particle physics experiments at center-of-mass energies up to 36 GeV. The storage ring is approximately circular in shape and has a circumference of 2200 meters. It consists of a vacuum chamber in which counter-rotating beams of electrons and positrons collide, and many hundreds of electro-magnets are used to guide the beams around the storage ring and to focus the beams to a small transverse size. In addition, RF power is supplied at a number of cavities to accelerate the particle beams. The electrons and positrons are provided by the two-mile-long SLAC linear accelerator, and two "injection beam lines" transport these particles to the PEP ring. The precise alignment of all the PEP technical components was the responsibility of the Survey and Alignment Group, and this difficult task provided an opportunity for the development of substantial new instrumentation.

Traditionally, particle accelerators have been aligned using optical surveying instruments such as precision optical levels and jig transits. It was recognized very early that these instruments would provide adequate accuracy for PEP alignment, but that their use would create a serious staffing problem. The problem was that the PEP construction project represented a one-time-only survey and alignment

*This work was done with support by the U.S. Department of Energy under Contract W-7405-ENG-48.

task, in which about a thousand components needed to be aligned precisely. This task would require tens of thousands of measurements by a large crew of surveyors for about 15 months; but once PEP was completed, a much smaller crew would be required for re-surveys. It was indeed the difficulty, inefficiency, and cost of hiring and training a large crew of surveyors which led to our undertaking instrumentation development for PEP alignment.

The major new concepts which we developed and implemented were the following:

(1) Develop surveying instruments which are easy to use. This minimizes technician training requirements as well as improves the speed and accuracy of surveying measurements.
(2) Automate the acquisition and analysis of survey data by the use of computers. This concept improves survey speed and accuracy; and the survey information can be used more efficiently.

Unquestionably there were substantial risks in embarking on a difficult and costly program of development and innovation. However, we believe the cost savings (mainly in survey technician labor) during the PEP construction project has more than compensated for this development effort.

PEP ALIGNMENT REQUIREMENTS

The alignment tolerances on the PEP technical components are based on various requirements concerning the accuracy with which one must steer the particle beams. That is, the electro-magnets which are used in controlling the beams have to be very accurately aligned if they are to perform their functions properly. Of the 700 or so magnets used in the PEP project, all but a handful fall into the following three types: dipole magnets which "bend" the particle trajectories and guide the beams around the storage ring; quadrupole magnets which focus the beams, keeping them small in transverse size; and sextupole magnets which deal with various non-linear effects.

Although all the PEP components must be aligned reasonably well for proper functioning (typically to ±1.0 mm accuracy), the quadrupole magnets present the most difficult alignment requirement. A quadrupole magnet acts as a focussing or defocussing lens; and, if a quadrupole is misaligned transversely to the beam direction, it acts as a dipole magnet to deflect the beam. The result of these inadvertent and undesired deflections is to displace the trajectories of the stored electron and positron beams, causing a "closed orbit distortion". These orbit distortions may seriously degrade the operation of the storage ring; and, if the distortions are very large, it may be impossible to store any beam at all. In fact, beam monitors, orbit correction programs, and beam steering magnets have been incorporated in PEP to deal with residual misalignments of magnets. Even so, the alignment tolerances of PEP quadrupoles are quite severe. Over short distances along the beam line, on the order of 10 meters, the quadrupoles must be aligned transversely to an accuracy of ± 0.2 mm or better. Over long distances the alignment tolerance can be relaxed considerably, because the particle beams are not very sensitive to smooth, long-range distortions of the beam line. Over distances of hundreds of meters, the PEP storage ring must be aligned to an accuracy of about ± 2.5 mm.

SURVEYING METHODS

Table 1 shows the surveying methods which were selected for various aspects of the PEP project.

TABLE 1: SURVEYING METHODS

	LONG RANGE	SHORT RANGE
HORIZONTAL	SURFACE SURVEY ± 2.5 mm/350 m	LASER SURVEYING SYSTEM ± 0.2 mm/10 m
VERTICAL	LIQUID LEVEL ± 0.1 mm/1000 m	LASER SURVEYING SYSTEM ± 0.2 mm/10 m

The long range surveying task consists of providing accurate reference points around the PEP ring, and the techniques are global in the sense that they can be used over distances as large as the entire PEP project. The short range surveying task is concerned with the alignment of components within a small portion of PEP, and the components are aligned relative to previously established reference points.

The long range horizontal alignment of PEP is based upon a network of primary survey monuments on the surface of the site. Twelve secondary monuments in the PEP tunnel are then tied to this surface network by surveying through vertical shafts from the tunnel to the surface. The 90 tertiary survey monuments in the PEP tunnel are located by surveying within the tunnel. The surface survey was performed by a survey team of the National Geodetic Survey, and electronic distance-measuring instruments were used. The site survey was accurate to about ± 1.0 mm, and all the survey monuments were located to ± 2.5 mm or better. Reference elevations for the long range vertical alignment of PEP are provided by a specially developed instrument, the "liquid level" (Gunn, 1977).

The Laser Surveying System is a specially designed system for aligning components within a small portion of the PEP ring. This system utilizes lasers, electronic instruments, and an on-line computer; and it greatly speeds up and simplifies survey and alignment. Both the liquid level system and the Laser Surveying System will be discussed more fully in subsequent sections of this paper.

During the construction of PEP, about 20 thousand survey measurements were made in about 15 months. This represented a truly formidable quantity of data to be recorded and analyzed manually, but it was a trivial amount of data for a computer to handle. Therefore, a substantial development of software (computer programs) was undertaken in order to computerize all the analysis of PEP survey data. In fact, the vast majority of measurements, all those taken with the Laser Surveying System, were automatically recorded by a computer. This automation of data acquisition and analysis was the foundation of the survey and alignment of PEP.

One management concept which was particularly important to the successful alignment of PEP was that of "vertical integration". That is, all tasks related to PEP alignment were done by the Survey and

Alignment Group. For instance, we had a hand in all the following areas: computer simulation of alignment errors, computer simulation of closed orbit measurement and correction, beam monitor system design, orbit correction system design, setting of alignment tolerances, design of alignment fiducial fixtures, design of survey instruments, analysis of survey data, and design of support stands for PEP components. This policy of "vertical integration" permitted the development of a consistent and cost-effective concept for PEP alignment.

LIQUID LEVEL

The long range vertical alignment of PEP is based upon reference elevations provided by a liquid level, a simple device which locates the same elevation (i.e., points on a gravitational equipotential surface) at widely separated locations. The PEP liquid level is a permanently-installed instrument which runs around the entire circumference of PEP. This instrument consists of a series of "wells" or half-filled water containers which are connected by a water-filled pipe. During operation, the water surface levels in the various wells lie at the same elevation.

Figure 1 is a photograph of a liquid level well. It consists of a glass container which is half-filled with water. A short length of flexible plastic tubing connects the bottom of the well to a water pipe, and another length of tubing connects the top of the well to a vapor return pipe. Bolted to the top of the well is a digital depth micrometer with its rod replaced by a pointed stainless steel probe. Elevation readings are taken by advancing this probe until it is seen to touch the water surface. At that setting, the micrometer reading is a measurement of the height of the top of the well relative to the surface of the water. When the readings have been completed, the data are used to set the micrometers so that the tooling balls at the tops of all the micrometers are at the same elevation.

It was found that the water level in the wells tended to drift slowly because of temperature changes. Therefore, simultaneous readings are always taken at two wells, in order to measure their relative elevations. Although the resolution of each reading is $\pm$ 0.01 mm, systematic errors degrade its accuracy to about $\pm$ 0.07 mm. Tests with liquid level prototypes (Gunn, 1977) showed that slope measurements can be made to an accuracy of $\pm 2 \times 10^{-7}$ radians or $\pm$ 0.04 arc seconds. Experience with the PEP liquid level shows that measurements can be made quickly and easily to an accuracy of $\pm$ 0.1 mm or better.

LASER SURVEYING SYSTEM

The PEP Laser Surveying System is a semi-automatic special purpose system for surveying PEP Components within a short section of the storage ring (typically 25 meters). Lasers and electronics permit quick and easy measurements, and totally computerized data acquisition and analysis take the manipulation of numbers entirely out of the hands of the human operator. The use of computers not only permits greater speed and accuracy but also permits certain simplifications. For instance, the positions of survey monuments must be accurately measured, but the monuments do not have to be placed in any specific location. The reason is that it is easy for the computer to deal with the measured positions of every individual survey monument, and there is little advantage in insisting that

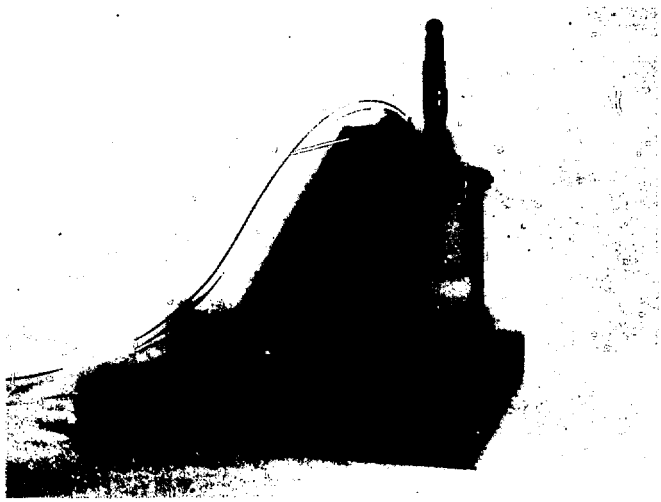
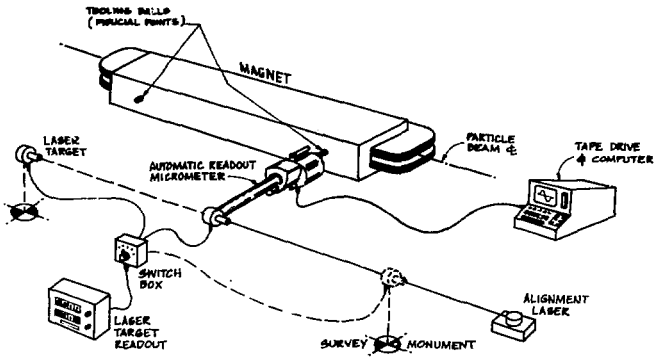


Figure 1. Liquid level "well"

Figure 2. Laser target mounted on optical plummet (left) and alignment laser (right)



MEASURING OFFSET DISTANCES
WITH LASER SURVEYING SYSTEM

XBL 773-7860

Figure 3.

Figure 4. Automatic Readout Micrometer (ARM)

monuments be located at exactly analogous positions around PEP.

Figure 2 shows the top of an instrument stand with a surveying laser (right) and a laser target mounted on an optical plummet (left). The laser is built by Hamar Laser Instruments, Inc., and it provides a narrow beam of light which can be used as an accurate line-of-sight. The location of the center of the light beam can be done easily using a laser target, which consists of an array of four photocells. Difference signals from the photocells are converted electronically to a target offset distance, which is then displayed on a large digital readout. The laser targets are normally used in the "null reading" mode in that the beam is centered on the target. This means that laser target offsets are zero, that target offsets do not have to be recorded, and that laser target calibrations are not critical.

Figure 3 is a schematic diagram showing how offset distances are measured with the Laser Surveying System. First, the laser beam must be accurately aligned over the two survey monuments at the ends of a sector. Laser targets are mounted directly on optical plummets which have been centered over the survey monuments, and the laser beam is then centered upon these targets. Fiducial fixtures are then attached to the accelerator magnets so that tooling balls on the fixtures are accurately located relative to the magnetic centers of the magnets. A specially developed instrument, the Automatic Readout Micrometer (ARM) is then used to measure the horizontal offset distance from a tooling ball to the laser beam line. A push of a button encodes the offset distance and stores it in the memory of the on-line computer.

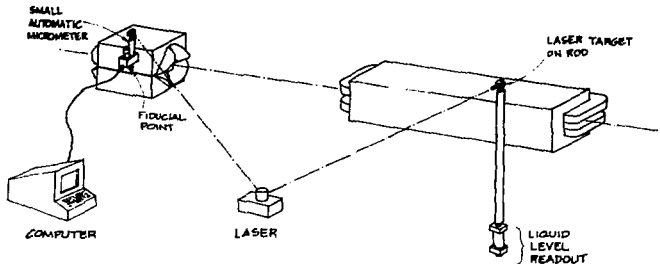
The design of the ARM instrument has been described previously (Lauritzen, 1979). It is a semi-automatic instrument in that it must be adjusted manually to take a reading, but the measurement and recording of offset distance are automated. Figure 4 shows the ARM.

Measuring vertical offset distances follows a similar procedure, as shown in Figure 5. First the alignment laser is accurately leveled, and the beam height is set at a specific distance above the tooling ball of the liquid level well. Then the elevation difference between the laser beam and each magnet fiducial fixture is measured using the Small Automatic Micrometer (SAM). The alignment laser turret is used to sweep the laser beam until the beam is directly above the magnet fiducial fixture, and the SAM is used to measure and to encode the elevation difference. The SAM instrument is shown in Figure 6. The accuracy of SAM and ARM is on the order of ± 0.05 mm.

The measurement of distances along the beam direction is accomplished using an Automatic Readout Tape Unit (ARTU), which is essentially an electronic tape measure for encoding distances to an accuracy of about ± 0.4 mm.

Measurements of beam element rotations about an axis along the beam direction are done using an electronic tiltmeter, which permits rapid "roll angle" readings. These readings are not automatically encoded and must be entered manually on the computer keyboard. The tiltmeter is normally operated at a sensitivity range which permits readings accurate to ± 0.1 mrd.

The entire Laser Surveying System including an on-line computer is carried by an electric vehicle and its trailer. Figure 7 shows an elevation measurement within the PEP tunnel. Visible in the



MEASURING MAGNET ELEVATIONS
WITH LASER SURVEYING SYSTEM

Figure 5.

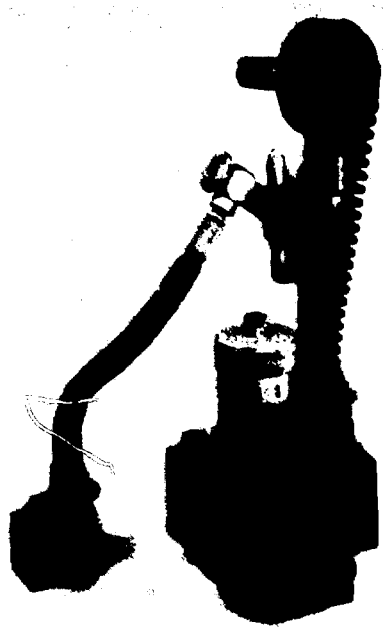


Figure 6. Small Automatic Micrometer (SAM)

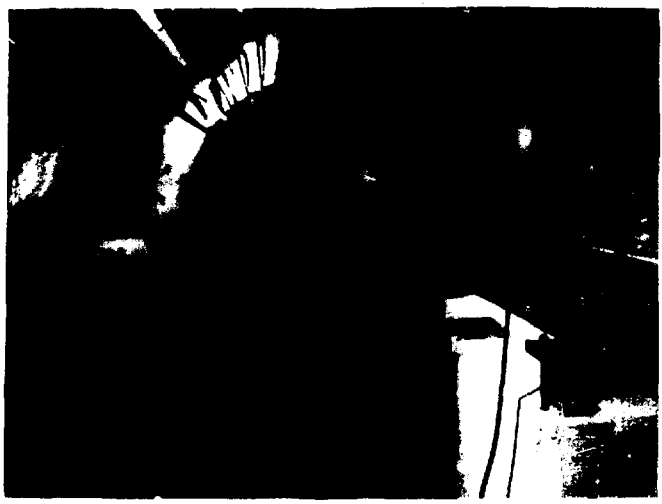


Figure 7. Making an elevation measurement at PEP

Figure 8. Adjusting a stack of calibrated shims in a support stand

photograph are the electric components, and on the top of the vehicle is the laser target readout which the technician monitors as he adjusts SAM.

SURVEY DATA ANALYSIS

A set of FORTRAN computer programs have been written to perform the preliminary data analysis for PEP survey and alignment. These programs calculate the desired locations of PEP components and analyze survey data concerning the monuments, in order to produce input data tapes which have a detailed description of the PEP storage ring and of all the survey monuments. At a later time when surveying is being done, a Tektronix 4051 Graphics System is used as an on-line computer under the control of a BASIC program named MEASURE. This program prompts the operator in an interactive fashion, reads the input tape to see what is to be aligned, records and prints the new survey data, and calculates the required corrections. The program MEASURE was carefully written to provide very complete guidance to the operator, in order to make the surveying procedures as easy as possible. The measured data are also recorded on an output tape for future reference.

An important benefit of an on-line computer is the efficient utilization of survey data. After a group of components have been completely surveyed, MEASURE calculates the exact support stand adjustments which are required. The use of stacks of calibrated shims in the support stands permit these adjustments to be made accurately, and very few iterations are required. See Figure 8.

CONCLUSION

The components of PEP were aligned quickly and efficiently using newly developed instruments and methods. When PEP was first operated in mid-1980, the accuracy of the survey and alignment was confirmed by the ease of correcting the residual beam orbit distortions.

REFERENCES

Gunn, J., Lauritzen, T., and Sah, R. C. 1977, A Precision Surveying System for PEP, IEEE Trans. on Nuclear Science, Vol. NS-24, No. 3, PP. 1367 - 1369.

Lauritzen, T., and Sah, R. C. 1979, The PEP Laser Surveying System, IEEE Trans. on Nuclear Science, Vol. NS-26, No. 3, pp. 4140 - 4142.