

## THE PEP LASER SURVEYING SYSTEM\*

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### Summary

A Laser Surveying System has been developed to survey the beam elements of the PEP storage ring. This system provides automatic data acquisition and analysis in order to increase survey speed and to minimize operator error. Two special instruments, the Automatic Readout Micrometer and the Small Automatic Micrometer, have been built for measuring the locations of fiducial points on beam elements with respect to the light beam from a laser. These instruments automatically encode offset distances and read them into the memory of an on-line computer. Distances along the beam line are automatically encoded with a third instrument, the Automatic Readout Tape Unit. 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

PEP is an electron-positron storage ring currently under construction at Stanford Linear Accelerator Center (SLAC). It is a joint project of Lawrence Berkeley Laboratory (LBL) and of SLAC. The storage ring and its injection lines consist of nearly a thousand beam elements installed in about 2.5 kilometers of tunnel, so PEP has provided a good opportunity to develop new concepts in accelerator survey and alignment.

Accurate alignment of the beam elements in a particle accelerator is crucial. In particular, the strong quadrupole magnets placed near the interaction regions can create very large closed orbit errors, because misaligned quadrupoles contribute unintended dipole fields which deflect the particle beams. The relative alignment of nearby magnets must be accurate to  $\pm 0.2$  mm (rms) or better, although the long range alignment (over distances of hundreds of meters) does not have to be more accurate than about  $\pm 2.0$  mm (rms).

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. Then 90 tertiary survey monuments in the PEP tunnel are located by surveying within the tunnel.

Reference elevations for the long range vertical alignment of PEP are provided by a specially developed instrument, the "liquid level".<sup>1)</sup> 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. That is, the water surfaces lie on the same gravitational equipotential surface. After readings have been taken, a tooling ball at each well can be set at a specific elevation for subsequent use as an elevation reference. The resolution of the liquid level readouts is  $\pm 0.01$  mm, but systematic errors degrade the overall accuracy to about  $\pm 0.07$  mm. Over long distances, the liquid level can be used to measure slopes as small as  $\pm 2 \times 10^{-7}$  radians, which is at least 10 times better than is possible using precision optical levels.

Each section of the PEP machine which lies between a pair of adjacent survey monuments is called a "sector", and the alignment of PEP beam elements is accomplished relative to the survey monuments at each end of a sector and relative to the tooling ball of a liquid level well within the sector. A sector is typically about 25 m long, and the PEP beam line curves only slightly within a sector because of the roughly circular shape of PEP (350 m average radius). A specialized Laser Surveying System has been developed at LBL for the surveying of PEP beam elements within these sectors.

### Laser Surveying System

Figure 1 is a schematic diagram of the measurement of horizontal offset distances using the Laser Surveying System. The laser itself is a surveying laser produced by Hamar Laser Instruments, Inc. The laser light beam exits horizontally from a rotatable turret on the top of the instrument, so the beam can be swept in an accurate horizontal plane. Making measurements with the laser is simplified by the use of special laser targets consisting of four photocells in an array. Difference signals from these photocells are used to measure the location of the center of the energy distribution of the laser beam, and a resolution of better than  $\pm 0.05$  mm can be achieved. It should be pointed out that the laser targets are always operated in the "null reading" mode in that the beam is always centered on the target during laser target use. This means that no laser target readings must be recorded and that the laser target calibrations are not critical.

For measuring horizontal offsets, 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.

Measuring vertical offset distances follows a similar procedure. 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 measurement of distances along the beam direction is done using an Automatic Readout Tape Unit (ARTU), which is essentially an electronic tape measure for encoding distances.

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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  $\pm 0.1$  mrd.

#### Automatic Readout Micrometer (ARM)

The Automatic Readout Micrometer (ARM) is a specially developed instrument for measuring horizontal offset distances from an accelerator beam element to a laser beam. See Figure 2. One end of the ARM has a socket which fits over a tooling ball on a fiducial fixture. The other end holds a laser target which must be centered on the laser beam. The laser target is mounted on a telescoping tube which can be adjusted so that the ARM is any desired length between 0.87 m to 1.27 m. A "threadless nut" riding on a smooth rotating shaft provides the linear motion for adjusting the telescoping tube. Two large thumbwheels, one "coarse" and one "fine", control the shaft rotation and the tube motion. A special feature of the design is the infinite range of adjustment of the thumbwheels. That is, the thumbwheels can be operated anywhere within the range of operation of the ARM, without ever encountering a limit of thumbwheel adjustment. A second feature is that the "threadless nut" acts as a clutch, so that the telescoping tube can be adjusted by simply pushing on the tube, thus providing an "extra coarse" adjustment for the ARM. Furthermore, the absence of threads on the drive shaft is a safety feature in that minor mishaps cannot result in stripped threads.

Distance encoding by the ARM is provided by a completely separate mechanism. This second mechanism consists of an Ideal Aerosmith, Inc., incremental digital readout system, which has been remounted within the ARM instrument. This device consists of a steel tape which is pulled over an invar wheel. The wheel in turn is connected to a digital encoder for integrating the tape motion. The position of the laser target is encoded by attaching the end of this tape to the target.

The ARM instrument is quite simple to use. First, the length of the ARM is calibrated on a special invar gauge. Then the laser target is mounted, and one end of the ARM is placed on the tooling ball to be measured. The ARM is supported by a stand while the length of the ARM is adjusted to center the laser target on the laser beam. The ARM is then "arced" or moved back and forth to check it is perpendicular to the beam. When the ARM has been properly adjusted, the push of a button encodes the ARM length and stores it in the computer.

The resolution of the ARM is  $\pm 0.01$  mm and the accuracy is better than  $\pm 0.1$  mm, even when some allowance is made for instrument drift during normal use.

#### Small Automatic Micrometer (SAM)

The Small Automatic Micrometer (SAM) is basically similar in concept to the ARM except that it is a much smaller instrument with a smaller range (0.32 m to 0.37 m). See Figure 3. The SAM is used for elevation measurements. During normal operation, it is first set vertical using a bubble level, and then it is clamped in place using a special support. The laser beam is swept horizontally to the SAM, and the SAM length is adjusted so that the laser target is at the laser beam elevation. The vertical motion of the laser target and the length encoding are provided by an electronic micrometer, which is entirely incorporated into the SAM. Here again, a push of a button encodes the length and stores it in the computer. The resolution of the SAM is  $\pm 0.01$  mm and the accuracy is better than  $\pm 0.05$  mm.

#### The Automatic Readout Tape Unit (ARTU)

The Automatic Readout Tape Unit (ARTU) is also based upon an Ideal Aerosmith, Inc., incremental digital readout system. Here, the tape unit is operated as an electronic tape measure with a 7.6 m range. Modifications to the readout system include the addition of tooling ball sockets both on the body of the ARTU and at the end of the tape, the addition of a rotary dashpot to dampen tape motion, and the addition of a push button for taking automatic readings. Although the ARTU has a resolution of  $\pm 0.01$  mm, the tape sag and other sources of systematic errors limit the accuracy to about  $\pm 0.4$  mm, which is more than adequate for measuring distances along the beam direction.

#### On-Line Computer

The on-line computer is a Tektronix 4051 Graphics System operated as a stand alone computer. The function of the computer is to prompt the surveyors throughout the surveying procedure, to record survey data, to compare these data with desired values, and to calculate immediately the required adjustments of the stands of the accelerator beam elements.

First, a set of Fortran programs are run to create input files. These programs produce a detailed description of the PEP ring, organized by sectors. The Tektronix 4051 is then operated as a computer terminal to record this input data on magnetic data tape cartridges. At some subsequent time when the surveying is being done, the 4051 is operated as a stand alone 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.

The elaborate use of computers in the Laser Surveying System has a number of important advantages. The automatic data acquisition avoids instrument reading errors and recording errors. The data analysis is fast and requires a minimum of labor. The power of computer programs permits flexibility in locating surveying monuments; that is, monuments may be placed only approximately at their nominal locations even though they must be surveyed accurately. Complex accelerator magnet lattices or lattice changes can be accommodated relatively easily. Lastly, the use of calibrated shim stacks in the magnet stands permits the efficient utilization of the survey data. Instead of adjusting magnet stands through many iterations as is commonly done, the Laser Surveying System calculates in detail the required corrections which are then carried out exactly. Only a very few iterations are required.

#### Logistics

The entire Laser Surveying System including all the instruments and instrument stands are carried by an electric vehicle and a trailer which can be driven directly into the PEP tunnel. See Figure 4. All the electronics including the computer are mounted on the vehicle and are powered by the vehicle batteries using an inverter. This scheme has proven to be extremely convenient because it minimizes transportation delays on the PEP site.

## Conclusions

A highly computerized Laser Surveying System has been developed for the PEP project. The system has completed the initial debugging and is being used in the routine alignment of beam components. Automatic data acquisition and data analysis provide high surveying speed and minimize operator errors.

## References

1. J. Gunn, T. Lauritzen, and R.C. Sah, "A Precision Surveying System for PEP", IEEE Trans. on Nuclear Science, NS-24, No. 3, 1367 (June 1977).

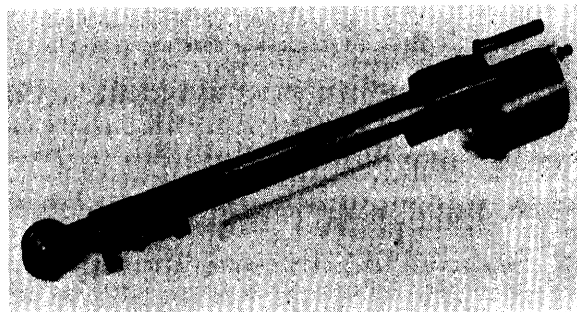


Fig. 2. Automatic Readout Micrometer

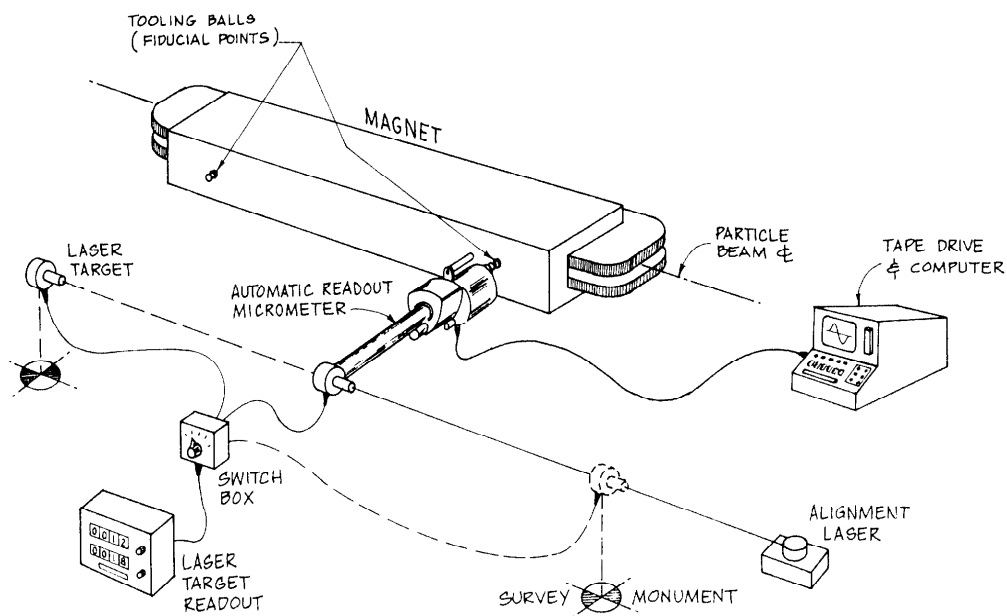


Fig. 1. Measuring Horizontal Offsets with the Laser Surveying System

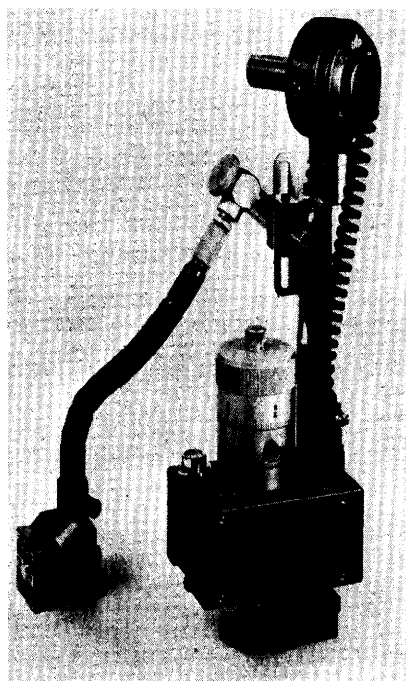


Fig. 3. Small Automatic Micrometer

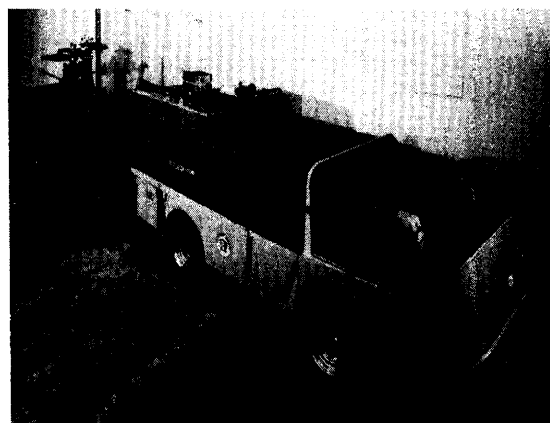


Fig. 4. Electric Vehicle and Trailer