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Author

Gunn, J.

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J. Gunn, T. Lauritzen, R. Sah, and P. F. Pellisier

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A PRECISION SURVEYING SYSTEM FOR PEP*

J. Gunn, T. Lauritzen, and R. Sah, Lawrence Berkeley Laboratory
P. F. Pellisier, Orinda Control Systems, Orinda, CA.

Summary

A semi-automatic precision surveying system is being developed for PEP. Reference elevations for vertical alignment will be provided by a liquid level. The short range surveying will be accomplished using a Laser Surveying System featuring automatic data acquisition and analysis.

Introduction

The PEP storage ring and its injection lines will consist of nearly a thousand beam elements which will be placed in about 2.5 kilometers of tunnel. Therefore, the PEP project provides a good opportunity to consider new concepts in survey and alignment.

Traditionally, particle accelerators have been surveyed and aligned using conventional optical methods; and the instruments used have been theodolites, optical-tooling levels, jig transits, etc. These methods have provided adequate accuracy for most applications, but their use is very time-consuming and therefore, costly. As a result, various laboratories have worked on the development of new instruments and survey methods, such as the Distinvar instrument developed at CERN[1]. Some fully automatic surveying systems [2,3] were considered for PEP, but they were not found to be sufficiently promising to pursue vigorously. Instead, we have chosen to develop a semi-automatic precision surveying system.

Alignment Accuracy

An accurate alignment of the beam elements in a particle accelerator is crucial, because quadrupole magnets which are displaced transverse to the particle beam contribute unintended dipole fields which deflect the beam. A colliding-beam machine like PEP is especially vulnerable to alignment errors, because the strong quadrupoles which are placed near interaction regions tend to produce very large closed orbit distortions. The relative alignment of nearby magnets, especially the alignment of successive quadrupole magnets, must be much more accurate than the overall alignment of the machine as a whole.[4] Therefore, the long range surveying (over distances of hundreds of meters) will be considered separately from the short range surveying (over distances of tens of meters).

Long Range Horizontal Surveying
(Surface Survey)

The control of the long range horizontal alignment of PEP will be provided by 12 primary survey monuments in the PEP tunnel, one monument being placed at each end of the six straight sections. These primary monuments will be located precisely through the following procedure: a network of 8 surface monuments have been installed and surveyed on the PEP site; vertical shafts will be drilled from the surface to the PEP tunnel at the primary monument locations; and the primary monuments will be located relative to the surface monuments by surveying through these vertical shafts.

A preliminary survey of the PEP site[5] proved to be accurate to ± 1 mm, which was quite satisfactory. However, we plan to resurvey the site during the construction period, in case some monuments shift slightly in position.

Long Range Vertical Surveying
(Liquid Level)

The long range vertical alignment of PEP will be 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.[6] It consists of a series of "wells" or half-filled water containers, which are connected to each other by a water-filled pipe. If the liquid level is properly designed and operated, the water surfaces in the various wells will be at the same elevation to an extremely high accuracy.

Liquid Level Design

Figure 1 is a photograph of a liquid level well. It consists of a container of clear acrylic plastic, which is half-filled with water during normal operation (the well in the photograph is shown unfilled). A short length of flexible plastic tubing connects the bottom of the well to a water line, and another length of tubing connects the top of the well to a vapor return line. Bolted to the top of the well is a digital depth micrometer (0.01 mm least count) with its rod replaced by a long pointed stainless steel probe. To take a reading, the probe is advanced until it just touches the water surface, the contact being sensed visually or with an electrical resistance measurement. The micrometer reading is then a measurement of the height of the top of the well above the water surface. Simultaneously, the center of the tooling ball at the top of the micrometer is 250 mm above the water surface.

Two prototypes of the liquid level have been tested successfully. Numerous design concepts were incorporated in the fabrication of these prototypes. Water was chosen as a working fluid because of convenience, low cost, low coefficient of thermal expansion, and low viscosity The effects of air pressure gradients were eliminated by building a sealed system with a vapor return line with only one external vent. Surface tension effects were minimized by using large wells (2" diameter) and by adding commercial algae control solution. Temperature gradient effects were controlled by minimizing the overall depth of the water. Lastly, the time required to recover from disturbances was minimized by using large water lines (1 inch diameter) and a low viscosity fluid. The damping time for a 2200 meter liquid level for PEP will be about 6 minutes.

Two Prototypes

Following the successful test of a 54 meter long prototype, a 1 kilometer long prototype was constructed and tested. Figure 2 is a schematic diagram of this prototype inside the SLAC accelerator housing. The vertical scale is exaggerated in this diagram, in order to show clearly the 1/2% slope of the linac. Figure 3 shows how the prototype was folded back upon itself so that it could fit in a 500 meter section of the SLAC accelerator housing; there were 7 wells. The liquid level prototypes worked extremely well. They were fast and easy to operate, and their dynamic response agreed with calculations.

Simultaneous Readings

It was found that, because of temperature effects, the water level in the wells tended to drift slowly (a typical rate was 0.02 mm per minute). Therefore, simultaneous readings must be taken to measure the

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relative elevations at two wells. In practice it proved to be easy to take readings of two wells simultaneously (within 15 seconds or less), so water level drift was not a problem.

Precision

The precision of liquid level readings was excellent. The water level could easily be read to ± 0.01 mm. Well number 1 was taken as a reference, and water level readings were taken at all the other wells, relative to well 1. It was found that the largest errors occurred in the relative readings of wells 5 and 1, which were the farthest apart. Even for that case, the precision was better than ± 0.04 mm. Further measurements were taken to try to find temperature and tidal effects, but no clear signals were seen. Over a period of many weeks, the precision of liquid level readings was found to better than ± .05 mm, which corresponded to a slope error of $\pm 1.0 \times 10^{-7}$ radians over a distance of 500 meters.

Accuracy

The accuracy of the liquid level prototypes was somewhat difficult to measure, for the lack of a better instrument against which one could compare. The accuracy of the 54 meter prototype was checked with an optical level, and the liquid level was found to accurate at least to the resolution of the optical level, about $\pm 2 \times 10^{-6}$ radians or about ± 1/2 arc-second. Since wells 1 and 7 were located next to one another in the 1 km prototype, their readings were also checked with an optical level. They agreed to ± .03 mm, corresponding to a slope of $\pm 0.3 \times 10^{-7}$ radians over a distance of 1 km. However, since wells 1 and 7 were next to one another, some cancellation of errors was possible; and another check was needed. The SLAC electron accelerator is aligned with a laser alignment system in which a laser beam passes through an evacuated pipe; the laser provides an extremely accurate straight line, although the slope of the line is unknown. The 1 km liquid level prototype was compared to the laser alignment system by the following procedure: the tooling balls on the liquid level micrometers were all set to be at the same gravity equipotential, and then the height of each tooling ball was compared to the height of a laser target. Since five measurements were made, a least squares fit was made to determine two parameters (the slope and intercept). If we define x(i) to be the horizontal position of the i th measurement, then the expected height of tooling ball i (relative to the laser line) is

$$y(i) = I - S \cdot x(i) - \frac{x(i) \cdot x(i)}{2 \cdot R}$$

where I and S are the intercept and slope at x = 0; and R is the radius of the earth, taken to be 6367 km. Figure 4 shows the residuals of the least squares fit, with [y(observed) -y(fitted)] plotted against x. The liquid level and the laser alignment system agreed so well that the slope S of the linac was determined to within $\pm 1.8 \times 10^{-7}$ radians. It is interesting to compare the residuals (typically 0.05 mm) with the sagitta of the earth's curvature over 500 meters (about 5.0 mm).

Conclusions

The tests of the prototypes show that a liquid level can locate a gravity equipotential surface with a slope error less than $\pm 2 \times 10^{-7}$ radians; which is at least 10 times better than optical leveling methods. This accuracy will minimize vertical alignment errors and closed orbit distortions in PEP. Furthermore, using the liquid level will minimize costs by speeding up surveys.

Short Range Surveying
(Laser Surveying System)

A Laser Surveying System (LSS) is being developed for the short range surveying of PEP. It features automatic data acquisition and data analysis, which will assure rapid surveys and reduce potential errors. The on-line data analysis will also permit a new alignment sequence: normally magnets are aligned while they are being surveyed, but we plan to survey the magnets, calculate the required adjustments, and then make the changes. Separating the survey and alignment functions will allow both to proceed at maximum speed.

Figure 5 shows the LSS in a typical application, measuring the horizontal offset distances of magnets relative to a line between two monuments. First, two laser targets are placed accurately over the two survey monuments using optical plummets. Secondary monuments will be installed between the primary monuments, so that the distance between adjacent monuments typically will be 25 meters. Next, the laser beam is "bucked in" over the monuments by centering the beam in the two targets, so as to get null readings. Then the Automatic Readout Micrometer (ARM) will be adjusted to the offset distance from the magnet to the laser beam, also giving a null reading. The length of the ARM is then automatically encoded and read into an on-line computer for immediate recording and analysis. Critical components of the LSS have been tested to be accurate to ± 0.1 mm, and the LSS is expected to have an overall accuracy of ± 0.2 mm or better.

Measuring magnet elevations is a very similar procedure. The laser beam is swept in a horizontal plane using the laser turret, until it is over a tooling ball (at a magnet or at the liquid level). Then the ARM is used to encode the elevation of the tooling ball, relative to the laser beam.

The Laser Surveying System is expected to maximize the speed at which PEP can be surveyed. It will require less skill on the part of the operator than conventional optical instruments. The alignment laser and the computer have both been delivered and tested. Major components of the ARM have been ordered, and the ARM is in the detailed design stage. Also, software is being developed for both on-line and off-line data analysis.

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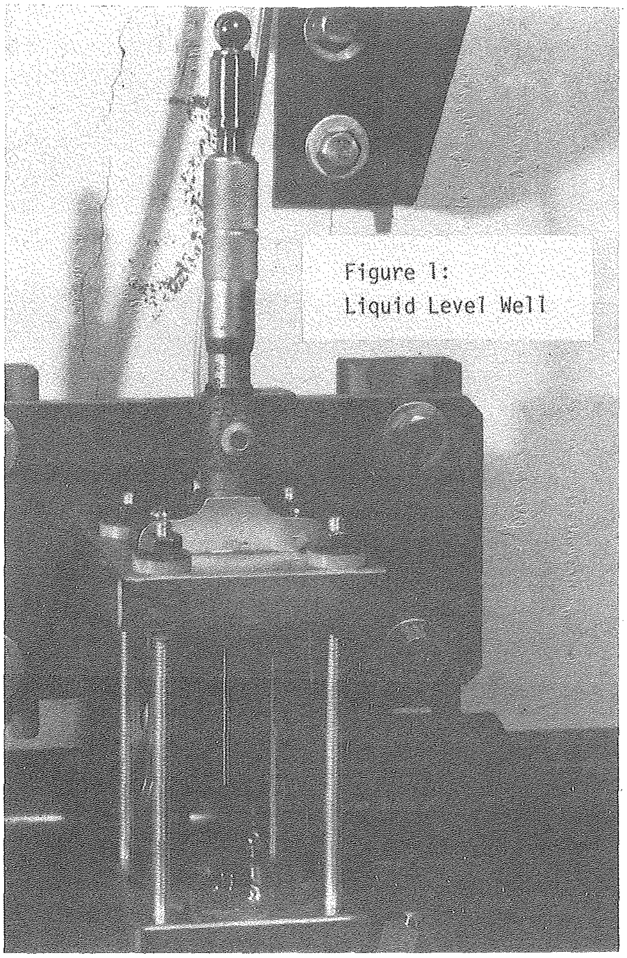

Figure 1:
Liquid Level Well

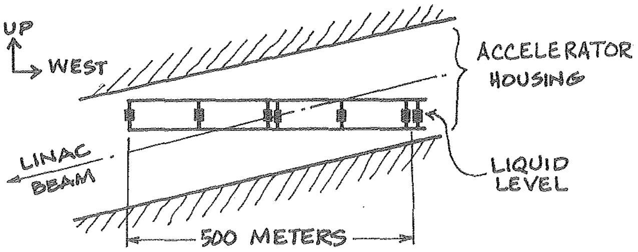

FIGURE 2: 1 KM LIQUID LEVEL

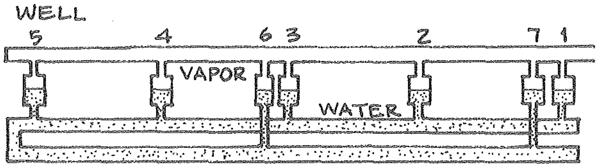

FIGURE 3: LIQUID LEVEL CONNECTIONS

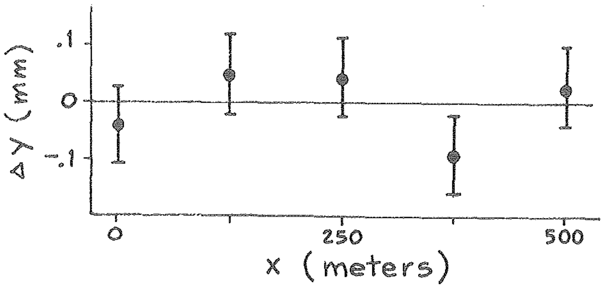

FIGURE 4: RESIDUALS OF L. SQ. FIT

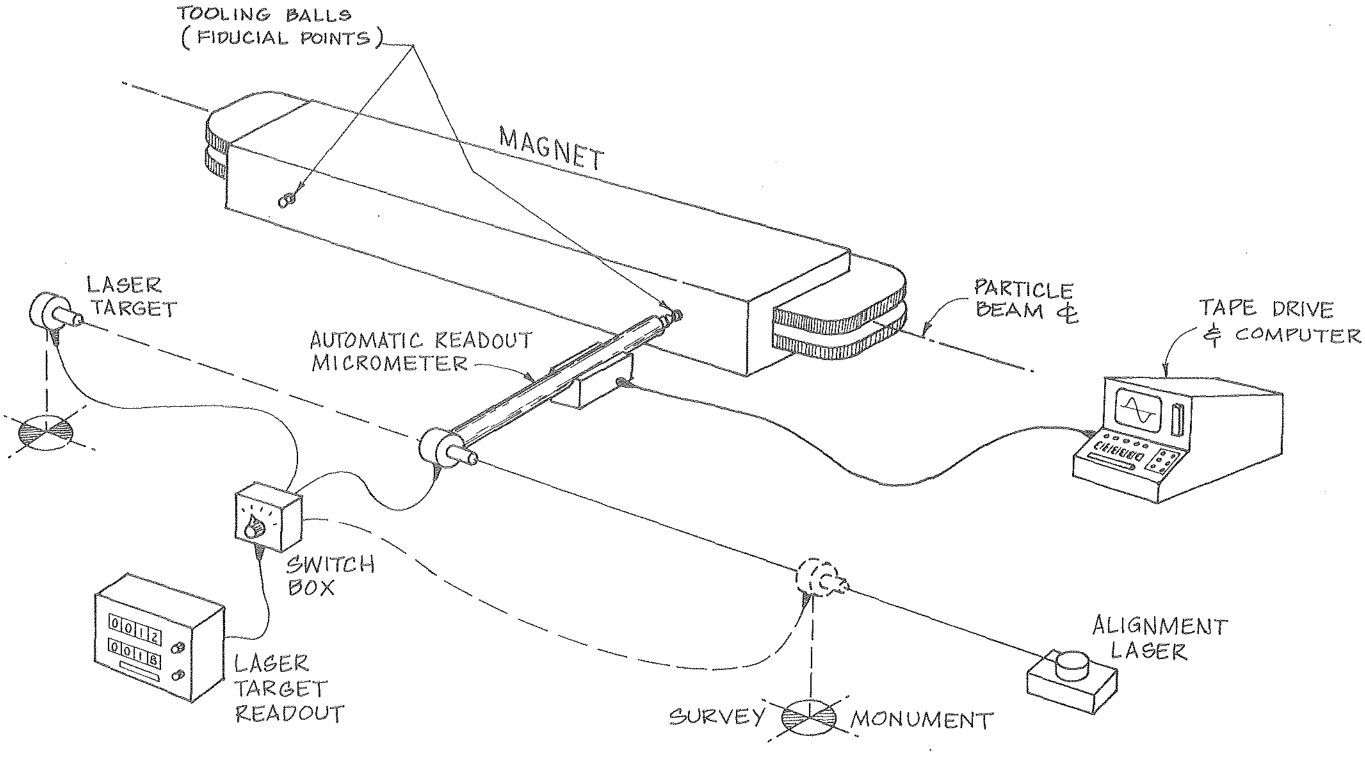

Figure 5:

MEASURING OFFSET DISTANCES
WITH LASER SURVEYING SYSTEM