SLAC-PUB-270
February 1967

PRECISION ALIGNMENT OF A LARGE BEAM TRANSPORT SYSTEM*

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Summary

The beam criteria for the SLAC beam switchyard and the effect of these criteria upon alignment tolerances and placement of components in the switchyard are discussed. The methods developed in the shop and in the field for meeting the stringent alignment tolerances are also covered.

Introduction

The ability of a beam transport system to perform according to the designer's specifications depends on how well the installation meets the alignment tolerances. The alignment of a large beam transport system is described in this paper with particular reference to the SLAC beam switchyard.[1,2]

The purpose of the beam switchyard is to deliver the electron beam from the Stanford two-mile linear accelerator to the experimental areas. The switchyard consists of an elaborate system of bending magnets, magnetic quadrupole lenses, protection devices and diagnostic instruments. These elements are primarily divided into two transport systems leading to the two experimental areas. The two systems, labelled A and B for their respective experimental areas, have a common origin in the beam line from the accelerator. A list of the most pertinent design parameters is contained in Table I. The problems of alignment are primarily those of meeting the requirements set forth in Table I.

The switchyard layout is shown in Figure 1. The beam size and position is defined by collimators C-0 and C-1. A pulse magnet bends the beam by 0.5° toward either the A or the B system. The basic optics of both systems is shown in Figure 2. The doublet (Q-1 Q-2) forms a double image of the beam on the plane of symmetry where the slit defines the resolution of the beam. The bending magnet M-1 disperses the beam for energy resolution at the slit. The symmetry quadrupole Q-3 recombines the different momenta so that after passing through the second set of bending magnets M-2, the beam will be achromatic. The symmetry quadrupole Q-3 has little effect on the vertical divergence of the beam because the vertical size of the beam is quite small there. The quadrupole doublet (Q-4 Q-5) can be used to produce a nearly parallel beam or to get a small spot on some target.

Alignment Requirements

Each basic transport configuration in the switchyard lies on a different plane. The exit beam lines are required to be horizontal, referenced to local gravity, in the experimental areas. The accelerator axis points downward by 4.74 milliradians to the local gravity vector at the beginning of the switchyard. Exit beam lines for the A and B systems and the common accelerator line define the two planes in which the A and B system beams lie. These tilted beam planes are shown in Figure 3. A major part of the alignment

TABLE I
Parameters for the Transport System of the SLAC Switchyard

	Electron-Photon Area-A	Secondary Beam Area-B
Maximum energy	25 GeV	25 GeV (expands easily to 40 GeV)
Input conditions: Beam radius	0.3 cm	0.3 cm
Angular divergence	$< 10^{-4}$ rads	$< 10^{-4}$ rads
Energy spread	< 2.6%	< 5.2%
Total bend	24.5°	12.5°
"Resolution"	0.1%	0.2%
"Dispersion" at slit	0.15%/cm	0.3%/cm
Isochronicity (3000 Mc RF)	< 10°	< 10°
Achromatic	Yes	Yes

* Work supported by the U.S.Atomic Energy Commission

effort is targeting each component so that it can be aligned in its respective tilted plane.

The tolerances reported in Reference 1 were calculated using the error analysis features of TRANSPORT[3], a computer program written especially with this problem in mind. Two criteria which most limit placement tolerances are energy resolution (see Table I) and the apertures of switchyard elements downbeam from the element being aligned.

The most restrictive translational alignment tolerance is ± 0.025 cm for the horizontal position of either element of quadrupole doublet (Q-1 Q-2). This tolerance is based on the requirement that the beam must be centered at (Q-1 Q-2) or else the doublet will bend the beam and affect the accuracy of the energy measurement.

The most restrictive rotational alignment tolerance is ± 0.1 milliradians for rotation about the beam line axis for magnets in the first bending group, M-1. This rotational tolerance is necessary, because the vertical component of the bend must be small enough to allow the beam passage through the magnet aperture of the second bending group, M-2 and necessarily, the beam must pass within ± 0.06 cm of the vertical center of the symmetry quadrupole, Q-3.

Although most of the other tolerances are numerically larger, some of these are just as difficult to achieve. For example, the switchyard is about 300 meters long and some longitudinal tolerances are 0.4 cm, or about 1 part in 10^5.

Laser Reference Line

An extension of the accelerator laser alignment system[4,5] provides a reference line throughout the first half of the switchyard. The function of this extension is to establish alignment targets whose position is considered known to within ± 0.05 cm for all the transverse positions. These well located target positions are then used to position the components in the beam lines. Figure 4 shows a laser alignment target stand and a portion of the vacuum pipe through which the laser beam travels.

The extension has a separate laser located at the end of a 25 cm diameter vacuum pipe which extends 250 meters from the end of the accelerator. Twenty alignment positions are along this extension, each of which has a retractable laser target whose position can be determined by an operator at the beam injection end of the accelerator. The targets are similar to the targets in the 60 cm diameter pipe which is used for the accelerator system. The 25 cm switchyard pipe is tangential to the bottom of the accelerator pipe at the coupling between pipes. The offset is required because of the size of the collimators (see Reference 6) which prevent use of a 60 cm light pipe throughout the switchyard. However, the reference line is centered in the pipe at the beam injection end, 3000 meters upstream, so there exists a slight slope to be compensated for in measurements.

Earth Curvature Effects

The earth curvature at SLAC, 1.511×10^{-7} radians/meter, was determined through the use of astrogeodetic methods by the U. S. Coast and Geodetic Survey. Curvature, if disregarded in surveys over large distances, can result in significant errors in the placement of components having small alignment tolerances. The possible error in elevation from the beginning of the switchyard to the end stations is 5 mm, due to a change in local gravity reference.

Two machine programs[6] were written which compute the pitch and roll angles made by any component with the local gravity vector at that component's particular location. In addition, the programs compute the necessary tape distances required by alignment crews to position switchyard elements. The field crews are supplied with alignment values which correct for their using local gravity as reference and for sighting from a plane above the beam component planes.

Targeting

All instruments and magnets in the beam switchyard are processed through a special optical tooling shop before installation. The shop technicians mount tooling balls and targets on the exterior of the component to allow accurate placement of that component during installation. Figure 5 shows the location of the different targets, tooling balls and mirror stage assembly placed on a quadrupole magnet. The center of the mirror in the mirror stage is scribed with a target. The field bullseye target and the center of the mirror are used by the field alignment crew to point the component in the correct direction. The proper attitude is obtained by utilizing the mirror stage. Elevation of the component is fixed with the tooling ball mounted on the mirror stage assembly.

In the shop, the first step is to locate the mechanical center of the component by using special jigs designed for this purpose. The tooling balls and targets for use in the field are then placed at specified positions relative to this mechanical center.

Next, alignment angles are turned into the components by use of a clinometer having an accuracy of two seconds. These are the angles by which a component must be rotated about its X and Z axes from a level position to be properly tilted for installation in the switchyard. The computer programs mentioned above were used to compute the values of the alignment angles for the beam switchyard components. The angles turned are checked by measuring the before and after tilted positions of four tooling balls placed upon each corner of the components which allows computation of the turned angles.

Once the angles are turned, a mirror stage assembly is secured to the component at a specified location from the mechanical center. A mirror stage assembly is shown in Figure 5. It is placed by use of an overhead jig transit positioned from tooling bars in the laboratory. After the mirror stage assembly is bolted into place, the mirror in the assembly is set level by auto-collimation from the overhead transit and locked in place. The correct tilt of the component is guaranteed in the field by auto-collimating on the mirror with a transit through holes in the shielding blocks on the second level. The tilt is independent of curvature effects as local gravity reference is used in the shop and in the field to level the mirrors.

Placement of Components

The elements were positioned in the field by placing them in the proper position relative to wires stretched between bending magnet group vertices. These vertices were established using the laser line as the basic reference line. Figure 6 shows a plan view of the stretched wires in the beam switchyard area.

These wires are stretched between stands placed on the shielding blocks, which are about three meters above the beam pipes. Figure 7 shows the relative positions of the field alignment crews and the beam switchyard elements. Optical instruments, jig transits, and sight levels are used to place the components properly relative to the stretched wires.

The tooling balls placed on the components in the optical tooling shop were either placed on the component in such a manner that they would be under the stretched wire or offset a known distance from the stretched wire. This is illustrated in Figure 8. Invar tapes were then used to position components relative to magnetic vertex points by measuring to the mirror center on the components.

Tape Bench Facility

The distances along the stretched wires required for the placement of components were measured using tapes scribed at the tape bench facility which is located in one of the accelerator tunnel accessways. The facility is shown in Figure 9. The tapes are scribed in their field positions, i.e., the horizontal correction for catenary sag is compensated for by scribing the tape in the sagged condition. The facility uses a master tape, which is a steel tape calibrated and certified by the National Bureau of Standards.

The beam switchyard field tapes are invar. Invar was chosen primarily because of its low thermal expansion characteristics. The stability of invar under load, i.e., tendency to creep, was investigated and was found that under light tensile loads (10 pounds) the average stress level was 2000 lbf/in^2 which did not cause any measurable creep even when the tape was under load continuously for 10 days with an average ambient temperature of 21.1° C. In the field, the invar tape is supported in the same manner as on the tape bench.

The techniques used allow scribing accuracy to within .076 mm and the stability of the tapes after field use has been excellent. After use the tapes show deviations of less than .076 mm from the originally scribed length.

Acknowledgement

The several authors of this report wish to express their appreciation to all the people who, by their encouragement or active participation, helped in this project.

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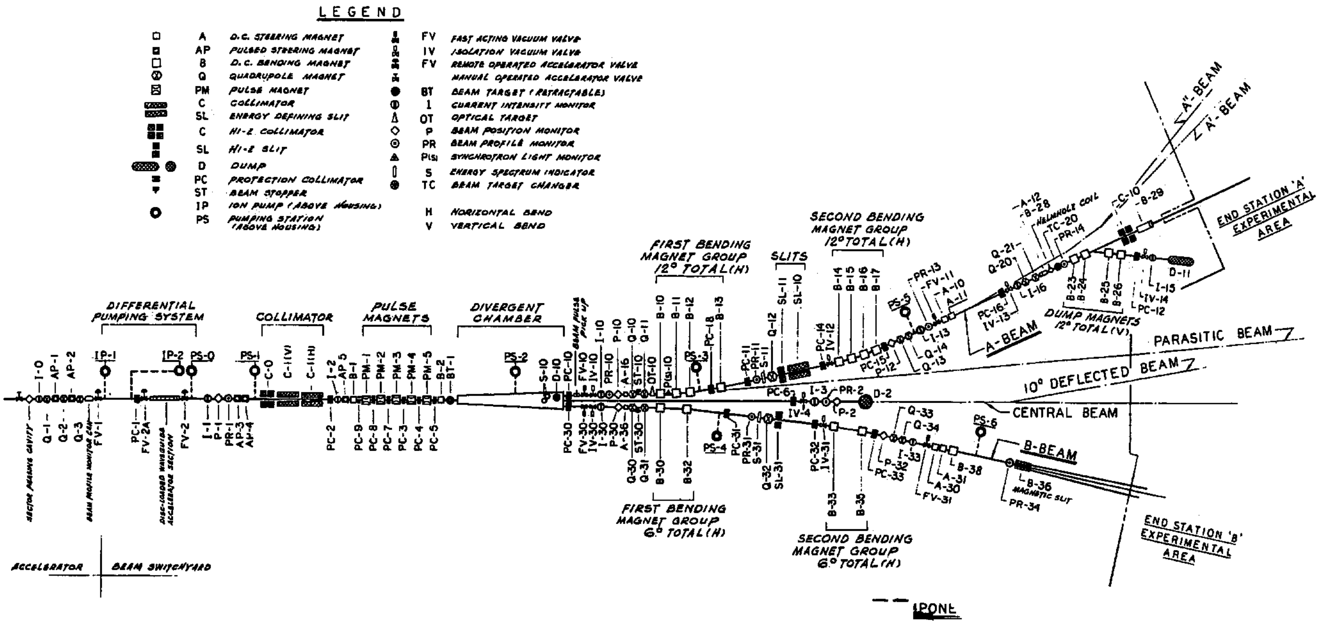

Fig. 1. Component layout of the beam switchyard for the two-mile linear accelerator.

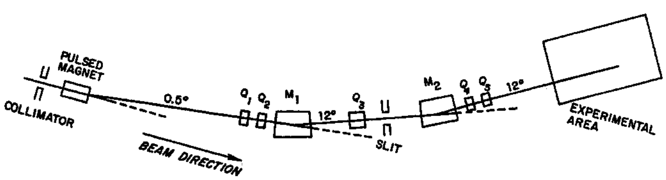

Fig. 2. Schematic diagram of a typical achromatic bending system.

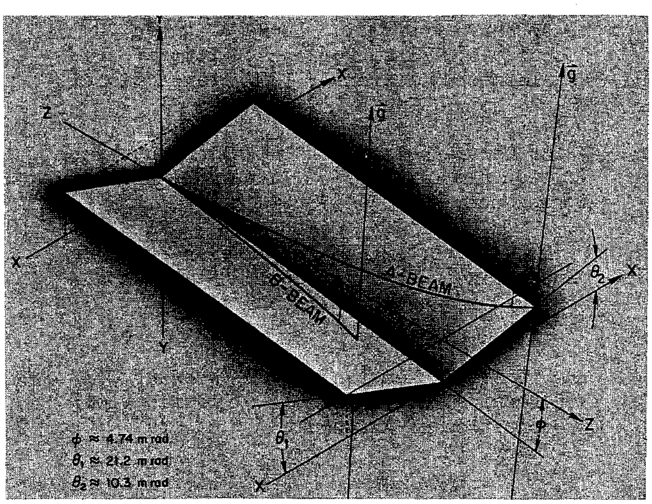

Fig. 3. Tilted planes of A and B Beams in the beam switchyard.

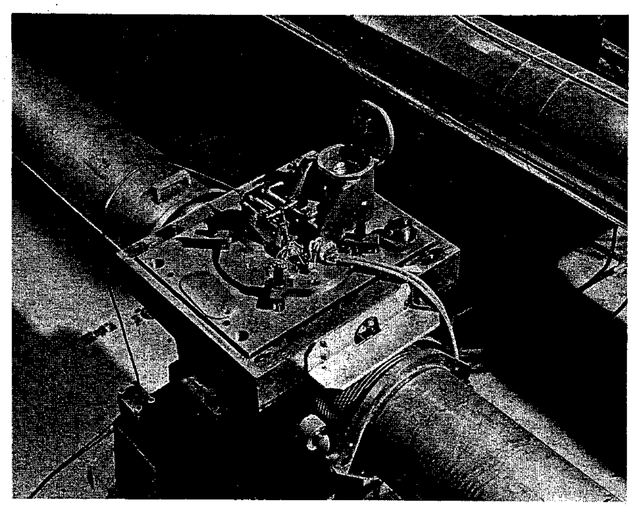

Fig. 4. Alignment equipment on laser target stand.

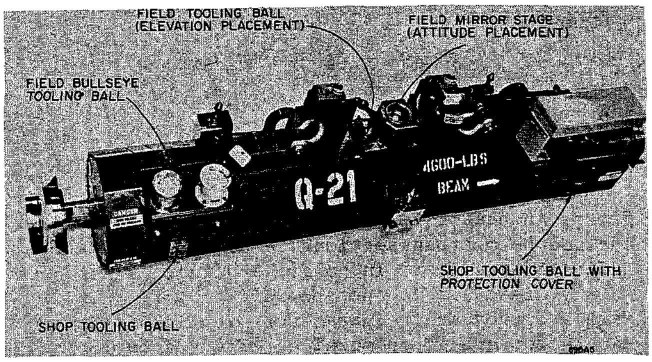

Fig. 5. Alignment equipment on a quadrupole magnet.

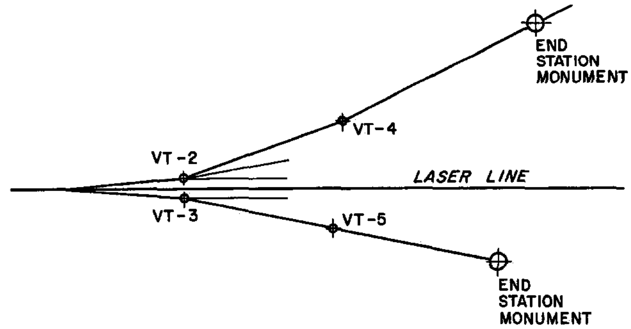

Fig. 6. Stretched wire layout for alignment of beam switchyard area.

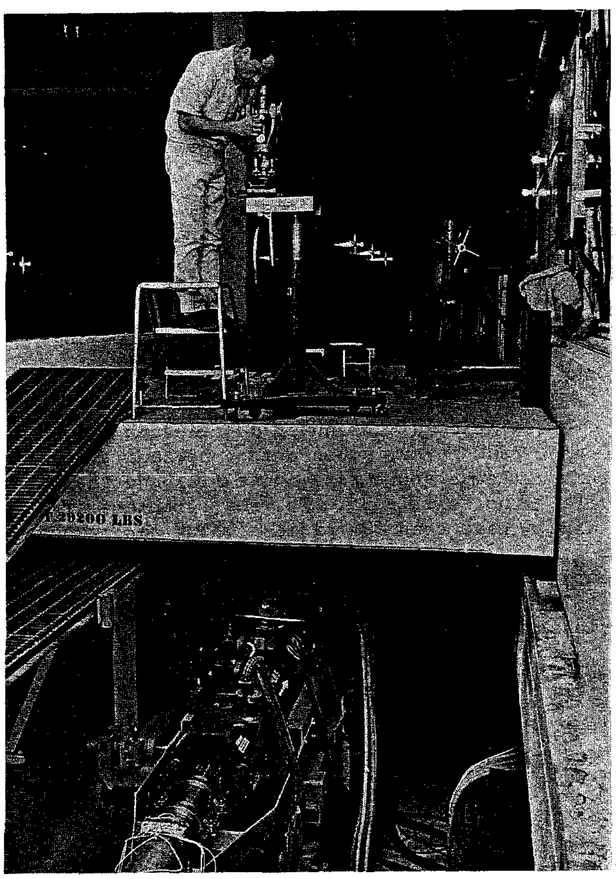

Fig. 7. Alignment of beam switchyard components from second level shielding blocks.

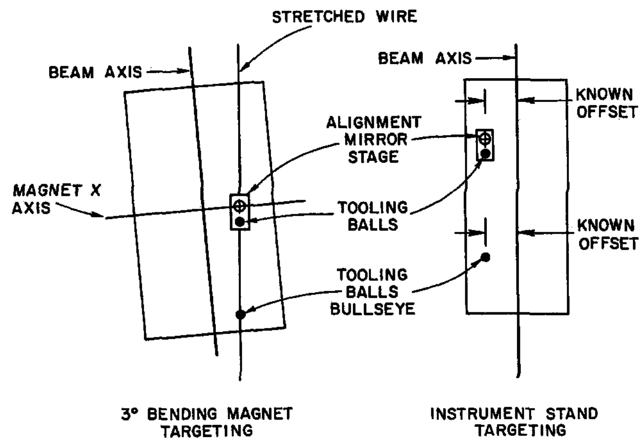

Fig. 8. Targeting on beam switchyard components.

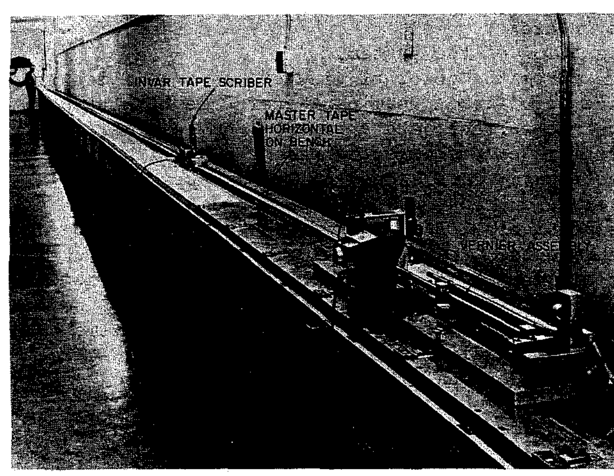

Fig. 9. Tape Bench Facility.