FINAL FOCUS TEST BEAM ALIGNMENT
- - A DRAFT PROPOSAL -

G. E. FISCHER, R. E. RULAND

Stanford Linear Accelerator Center

Stanford University, Stanford, CA.

1. Introduction

1.1. GENERAL OUTLINE OF THE FINAL Focus TEST BEAM

In its present form, the Final Focus Test Beam (FFTB)[1] is a transport line designed to transmit 50 GeV electron beams of SLC emittance (3 x 10^{-10} radian-meters) straight through the central arm of the Beam Switchyard (BSY C line) with a final focus point out in the Research Yard but relatively near the end of the switchyard tunnel. The axis of the incident beam coincides with that of the SLAC linear accelerator; the final focus, some 300 meters downstream of the end of the accelerator, is displaced from this axis by about 2 meters horizontally.

1.2. ORIGIN OF GENERAL ALIGNMENT SPECIFICATIONS

Several optical designs for this transport system have been developed and studied by Oide[2]. So that the promise of extraordinarily small final focus spots ($\sigma_x \approx$ 3 micrometers, $\sigma_y \approx$ 60 nanometers) may be realized, focusing elements, (quadrupoles and sextupoles), should be placed on the design trajectory to absolute accuracies of order fractional to several microns in transverse position. These values, calculated for each element as if it alone were out of place, derive from the fact that off axis trajectories are subject the variations of phase advance and dispersion thereby causing growth of the spot's area at the final focus by a factor of $\sqrt{2}$. For reasons that will become more evident later, we will call these values *single element incoherent "jitter" tolerances*.

As early as the fall of 1988, J. J. Murray had taken one of the Oide proposed cases (FFTF34)[3] and analysed the effects of permitting much larger (perhaps surveyable) imperfections in the position and strength of all magnets and beam position monitors and found that the system was "correctable" without a "significant" (no more than say x 30%) loss of performance (effective luminosity). Other cases (for example FFTB59) are currently under consideration and appear to exhibit similar sensitivity to imperfection. Further detailed work on "tuning the beam" was performed by Oide (Ref. 2)which showed that initial alignment errors could be as large as 30 μ in the vertical and 100 μ in the horizontal directions. We will use these values as a guide in the following discussion. Clearly, the better (ie. smaller) such "standard tolerances" achievable, the higher will be the probability of achieving the goals of this project with the minimum of tuning. For the moment we will define the range 5 to 10 micrometers in transverse displacement error as the "specification" for the "ab initio" tolerances for this alignment proposal. The much smaller stability values originally calculated by Oide, which we have called jitter[4] are "operational tolerances" which, if exceeded, call for operational orbit correcting and retuning of the beam.

1.3. SCOPE OF THIS PROPOSAL

The hardware, methods and procedures outlined in this proposal are dedicated to measuring the placement of mechanical objects with respect to certain defined geometric axes. We wish to emphasize that the problems of locating (a) the effective magnetic axes of focusing elements, (b) the effective electrical center of beam position monitors and (c) even the effective axis of the incident beam relative to mechanical reference surfaces are treated elsewhere[5] In the following we consider only the problem of measurement. The task of mechanical repositioning of elements on-line, although implied, is not yet addressed.

2. Concept

2.1. OUTLINE OF METHOD

The narrow forward geometry of the FFTB lends itself to the method of "survey by offsets". The main task is, therefore, the establishment of an absolutely straight line whose axis can be related to that of the linear accelerator, the agency which provides, presumably with little or no steering, the beam's input direction to the system.

Fortunately, the original planners of the SLAC BSY provided just such a straight line[6] which was used to layout the geometry of the energy defining slits in the A and B lines, as well as providing a C line reference. As will be shown later, with some reconfiguration and additions, the BSY laser alignment system should have adequate resolution and accuracy to serve as the primary reference line, independent of tunnel monuments that may shift with time or the effects of atmospheric refraction. Moreover, this laser based system can be used while the beam is in operation, thereby providing the means for on-line check on the straightness of the reference line and hence indirectly on the coordinates of components.

The steepest angle the beam trajectory makes with respect to the reference line is of order 20 milliradians. This means that offset measurements between the trajectory and the reference line must be made at "s" and "z" distances known to better than 0.1 millimeters if the error introduced in transverse measurements is to be kept less than 2 microns. For the long simple longitudinal distances of this problem, 0.1 mm accuracy can be reached using an "electronic distance meter" (Kern Mekometer ME5000) or with certain restrictions the interferometer calibrated "distinvar wire"[7]

Figure 1 depicts a crossection of the BSY C line tunnel taken at a point sufficiently downstream so that the FFTB trajectory has diverged from the laser reference line. We discuss, in following sections, the details of the components and their expected performance.

2.2. Placement Resolution of a BSY Laser Alignment Fresnel Lens.

The concept of the SLAC laser alignment system is depicted in Figures 2 and 3. The idea is disarmingly simple. If all lens centers lie along a perfectly straight line, all will focus the divergent light from the source onto the same spot in the far focal plane. If some lens is off a defined axis by an amount Δx, y , the focal spot is displaced by an amount

$$\Delta x', y' = \frac{(r+s)}{r} \times \Delta x, y \tag{1}$$

in which "r" is the distance from the source to the lens and "s" is the distance from the lens to the focal plane. By making r small with respect to s very large optical levers can be effected.

The resolution in the measured $\Delta x', y'$ is also related to the size of the image. The diffraction limited full width at half maximum w of the central image is given as:[8]

$$w = \sqrt{5}/\pi \left(\frac{\lambda s}{D} \right) \tag{2}$$

in which λ is the wavelength of the light (normally red light of wavelength 632.8 nanometers), and D is the effective diameter of the lens.

If we were to use the configuration of the *existing* BSY system, we note that the source is near the far eastern end of the BSY tunnel but the focal plane is at far western end of the accelerator located over two miles away. This arrangement has the advantages of sharing a common detector with the accelerator laser alignment system and high sensitivities due to large lever arms.

Inserting values typical of the BSY target coordinates, r = 299' , s = 10,637', D = 5.5"/12" = 0.46', we find a calculated width w of 10.5 mm.

Assuming for the moment that the detector is able to locate the center of the image to 1/l00th of its size*, and applying the lever arm of Equation (1), the resolution to which the position of the lens can be located is: about 3 micrometers. Depending on axial target coordinate in the BSY, this value varies between 2 and 9 μ. Of course it should be realized that in order to use the presently existing BSY equipment for the new transport line, the existing lens holders and the laser station will need to be relocated. The foregoing was a sample calculation to show that resolutions consistent with requirements are achievable.

2.3. Repeatability of BSY Laser Target Insertion

The efficacy of the method depends on the ability of inserting BSY type lenses, one by one, with repeatabilities of position to better than the suggested resolution. Since it has been known for some time that some of the hinge mechanisms along the accelerator suffer from a lack of repeatabilty, a test was performed on a spare BSY lens actuator. This device (shown in Figure 4) was mounted within the working aperture of a large, three axis, coordinate measuring machine and exercised by hand. The results of many insertions demonstrate a repeatability in the vertical direction (radial with respect to the shaft roller bearing) with a full width of about 1.5 microns. The horizontal spread (in line with the axis of the hinge shaft) is about 7.5 microns but can most probably be improved by a addition of a spring. These tests do not prove that the other 20 or so units installed in the BSY will perform entirely satisfactorily, (tests will have to be performed), but lead one to the notion that they too can be used.

2.4. Coordinate transfer from center of Fresnel lens to new tooling outside the vacuum enclosure

Having established that lenses can be inserted into the laser line of sight in a repeatable way, the coordinates of the lens axes (See Figure 5) must be transferred to new reference tooling located outside the vacuum enclosure. The original tooling, a K & E mirrored target for x and z, and a tooling ball for the y coordinates were meant to be used in connection with the "standard optical alignment" methods employed 25 years ago. Such methods will not suffice for micron accuracies or permit the monitoring of positions while the beam is in operation. New tooling

* This value depends in detail on the type of detector employed and will be discussed in Section 3.5

is required and the aforementioned CMM will be used to locate their coordinates. distances with micron accuracies. It should be added that these CMMs, equipped with optical probes (TV microscopes) can be used to examine the fresnel lenses for asymmetric errors of construction that would lead to systematic errors in the positions of their laser light images.

2.5. Coordinate transfer from the laser tooling station to a component tooling station

Figure 1 shows a possible "offset arm" to relate the coordinates of the tooling on a quadrupole, for example, to that on a laser station. We have not decided exactly what form of measurement will prove to be the most appropriate. The suggestions listed below should be followed up experimentally and developed into reliable and cost effective solutions.

Horizontal What ever reading mechanism is proposed, it seems useful to provide a mechanical, albeit floating, bridge to support the instrumentation across the, up to two meter, span.

1. Interferometry

Perhaps the most accurate absolute measurement of distance between the tooling on the component and that on the reference housing is by means of standard metrological interferometry. Over a flight path of two meters, the distance uncertainty should remain below about 1 micron in spite of the combined errors due to temperature, pressure and humidity of the intervening air as well as the uncertainty in the instruments' stabilized wavelength and its ability to resolve fringes[9] It must be pointed out however that this technique is relatively expensive and not too well suited to being employed in the field. This is particularly true if used in multiple widely separated areas or for remote reading during beam operation. We believe, however, that the tooling and the "arm bridge" should be designed so that initial standardization and recalibration of other instrument types be possible by this method.

2. Invar rod method

It is entirely possible to suppose that the arm bridge carry a fixed calibrated invar rod, one end of which is fastened to the tooling on one side, the position of the other end read by sensing elements having micron resolution. Since these elements have to read stably over relatively short distances (say 1 mm to 1 cm), a wide variety of radiation resistant instrument heads come to mind. Among these are the SONY Magnascale and high precision LVDTs, magnetic or capacitance proximity gauges.

3. Plain rod method

The expense of Invar rods can be traded against the necessity of measuring the average temperature of an ordinary metal transfer rod. What is gained in capital cost is lost in computer read instrumentation channel cost and extra laboratory calibration. This tradeoff has not yet been evaluated.

Vertical We propose to transfer vertical coordinates by means of hydrostatic levels whose liquid containing tubes are carried by the bridge and whose wells are fixed to the tooling at each end. By keeping the riser heights below, say one centimeter, temperature effects will be minimized. We have not yet chosen the fluid or method of height read out. Mercury has been used with excellent results[10]. The difficulties of using water with a high precision capacitance read out appear to have been solved by Roux[11].

Although we do not need to consider the effects of perturbations of the local gravity vector on the average geoid at SLAC over the short offset distances involved, it should be pointed out that very careful attention most be paid to the coordinate systems of the linac and of the BSY laser systems. They are neither parallel to each other nor normal to the local gravity vector at any point along their length. For this reason carefully machined shim blocks are called for to compensate for the resulting height differences of the various components along the beam line.

2.6. ROLL, YAW AND PITCH

So far we have described the precision measurement of the transverse and, to a lesser accuracy, the longitudinal coordinates of components. A solid is, however, defined by six parameters. Assuming for the moment we can mount the coordinate tooling to reference the nodal point of a component, (the effective electrica. center) studies have shown that we do not need to measure pitch and yaw with extreme accuracy (Milliradians are sufficient). For this reason we presume that they can be set up by more conventional means. The roll angle (θ_z) tolerances are under investigation. Fortunately there exist today remote reading tiltmeters of sufficient accuracy, near zero angle, to solve this problem.

3. Recent Experiences with the BSY Laser Alignment System

The BSY system has been in disuse since the onset of the SLC construction program in summer 1984. At that time high-power slits were removed to make room for the Arc transport system and some target stations are therefore no longer in service. To the best of our knowledge the system was not used till February of this year when a new laser was installed.

We are pleased to be able to report the following observations:

1. The Fresnel targets of all but one of the remaining 17 target stations could be inserted on demand.
2. With the exception of the last target (No.20), the widths of the images observed over 10,000 ft downstream, were consistent with those calculated. The last target is so close to the source, it is suspected that the finite phase space of the laser adds to the image size.
3. Relative to the double target at the end of the accelerator (Station 30-9), a very cursory look indicates that Stations 12, 13, 14, 15, 17, 18, 19 appear to be on a straight line to within about 0.1 mm. Since it is very unlikely that the mountings have been realigned in the last 5 years (perhaps two decades), this observation speaks for the remarkable stability of the downstream part of the Beam Switchyard Tunnel floor and of the original laser target housings. Target 16 is misaligned by about 1mm. We note that it is mounted on an stand made of bolted together dexion angle steel.
4. Figure 6 is a photograph of the image from a BSY Fresnel lens. This picture shows that the far wings of the pattern can be used to determine the relative roll of target stations.
5. The image plane of the observation station has been equipped with a new form of position readout. The oscillating image differentiating scanner has been replaced by a modern CCD camera shown in Figure 7. In its first form, suitable for image widths below 1 cm, the light falls directly on the array. The image is digitized on a gray scale and may be enhanced by a series of filter-programs resident on a local PC. The computer and its digitized output are shown in Figure 8. Various algorithms have been written to find the “center” of the image. Tests are under way to determine the best methods. For images larger than those easily accommodated, a simple demagnifying lens is called for. It goes without saying that the whole panoply of todays computer aided image enhancement techniques may be employed to rapidly find centers of images to better than 1/100th of their width. During recent exercises with the main accelerator laser alignment, system using targets in Linac sectors 1

and 2, early results in a semi-automated data acquisition mode resulted in overall position repeatabilities in the 4 micron range.

4. The Proposal

From the aforesaid discussion one is led to the notion that technology existing at SLAC demonstrably permits the establishment of a *straight line reference system* from which the coordinates of beam-line components may be determined, monitored and maintained. The proposal, therefore, is to extend such a reference system into the research yard to whatever length is required and to develop the necessary ancillary measurement equipment and software for rapid realignment. We stress the word rapid because the favorable conditions of ground stability observed in the tunnel will not obtain in the yard; a region which will be subject to changes of loading and major diurnal temperature fluctuations.

We propose to equip every focussing element with an associated laser target station. (Current versions of the FFTB optics contain 29 Quads) Flat field bending magnets, which in principle have loose transverse tolerances, will be placed by conventional means. We assume for the purpose of this proposal that sextupoles will be aligned and permanently fixed to their associated quadrupoles in a precision laboratory environment. The mechanical mounting of beam position monitors will be treated in a similar way.

Although there are more modern[12] methods, we believe this proposal is competitive, both technically and financially, for the following reasons:

1. A great deal of the required hardware already exists. This includes: the laser, its mounting, the input mirror box, some 16 Fresnel target actuators and their vacuum housings, some 600 ft of 10" vacuum pipe and bellows joints, the double targets to reference to the accelerator, a detector room with its CCD Camera and precision slide readout.
2. By virtue of the system's very large lever arm, it achieves the type of resolution required.
3. The existing mechanical parts can achieve the required repeatabilities. Engineering designs exist and additional stations can be manufactured from existing drawings.
4. Because it is unlikely that the old BSY lenses will fit into the extended system perfectly, a new program for the so called artwork has already been written. The manufacture of new lenses by chemical machining is today about an order of magnitude less expensive than it was 25 years ago due to advances in microelectronics technology.

5. It is well to remember that in the micron world, steel behaves like butter. The existing designs of the housings attest to their stability and rugged resistance to abuse.

6. No matter what scheme is adopted for an optical reference line, the difficult problems of coordinate transfer must be solved.

At this moment of writing we are not ready to evaluate, with complete confidence, all the ingredients of the error budget for either the resolution or the accuracy of the system. On the basis of other investigators experiences[13] we believe that entering the micron world may present unexpected effects. We believe this fact is consistent with the exploratory nature of the Final Focus Test Beam's mission.

5. Acknowledgements

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REFERENCES

1. For preliminary parameters see, for example, T. Fieguth, "Final Focus Test Beam(s)" presentation to the FF working group, International Workshop on Next Generation Linear Colliders, SLAC Report 335, December 1988 p. 312.

2. K. Oide, "Design of Optics for the Final Focus Test Beam at SLAC", Proceedings of the 1989 IEEE Particle Accelerator Conference, Chicago, March 1989, Vol. 2, p. 1319

3. Computer file MISALIGN OIDE Cl, on disk JJM193, dated November 3, 1988

4. The term "jitter" derives from the notion that high frequency errors are not correctable by conventional means. Since high frequency countermeasures have already been proposed for highly sensitive beams, the term jitter is probably a misnomer and should be more clearly defined.

5. For example "Finding the Magnetic Center of a Quadrupole to High Resolution" G. E. Fischer, J. K. Cobb, D. R. Jensen SLAC-TN-89-01 March 1989 and these proceedings.

6. For a general description of the SLAC linear accelerator laser alignment system see: R. B. Neal “The Stanford Two Mile Accelerator” Benjamin, New York, 1968 Lib. Congress Cat Card 68-23364, Chapter 22, p. 821 - 885, Support and Alignment. This chapter also contains a discussion of the BSY system. More readily available is W. B. Herrmannsfeldt et al. “Precision Alignment Using a System of Large Rectangular Fresnel Lenses”, Applied Optics, Vol. 7, p. 995, (1968)

7. See for example: W .Coosemans et al. “Automation by Microcomputer of Geodetic Distance Measuring Instrument: The Distinvar” CERN 85-16 November 8, 1985.

8. See Reference 6. The BSY system is described in greater detail in “Precision Alignment of a large Beam Transport System” Herrmannsfeldt et al. IEEE Trans. Nucl. Sci. NS-14 No. 3, 903-7 (1967) and additional calculations can be found in SLAC-TN-65-034 April 1965.

9. For a brief discussion of measurements in the micron range the reader may find it useful to refer to the report “Some thoughts on Linear Collider Alignment and Mechanical Stability” G.E.Fischer and M.Mayoud [CERN-LEP-RF-SU-88-071 March 1988 pages 24-30

10. P. F. Pellissier, Trans. IEEE on Nuclear Science Vol. NS 12, No. 3 p. 19 (1965)

11. D. Roux, Note ALGE 88-04, March 1988, ESRF Grenoble France. and Note ALGE 88-06 November 1988.

12. See, for example, the very detailed proposal: “Magnetic Axis Alignment and the Poisson Alignment Reference System” Lee V. Griffith et al. Lawrence Livermore National Laboratory, UCID 21591 January 31, 1989 used to align an FEL.

13. “Microns, Microns, Everywhere and All of Them Out of Line” W. B. Davison et al. Steward Observatory, University of Arizona, Tucson, Ar 85721 and presented in SPIE Vol. 608 Optical Alignment III, (1986)

BEAM SWITCHYARD CROSSECTION

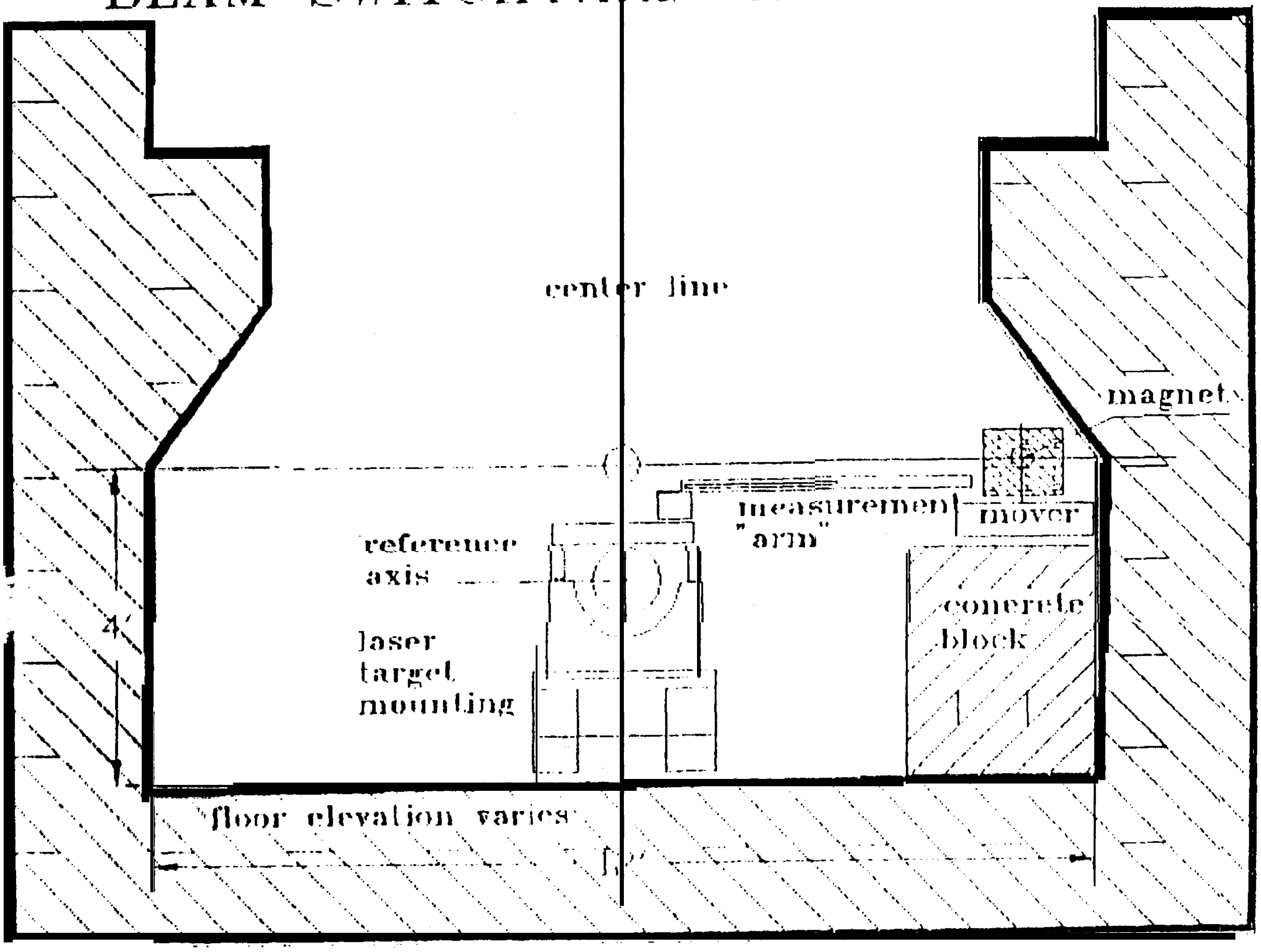

Figure 1.

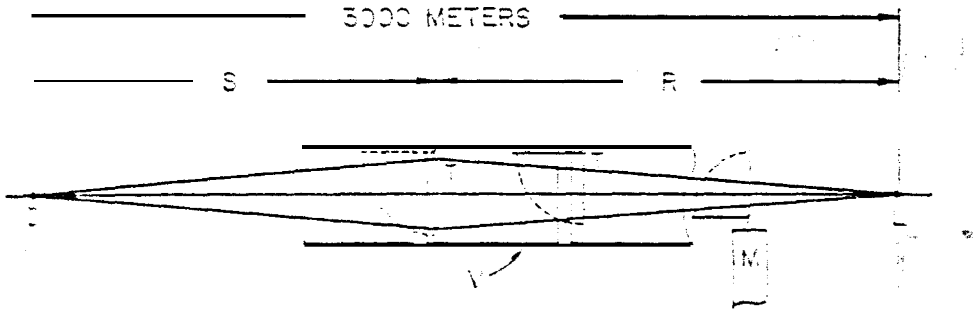

Figure 2. Schematic illustration of the SLAC alignment system. A typical target *T*, which is actually a rectangular Frensel lens, focuses the laser light source *L* to an image at the detector *D*. There are 294 alignment targets and three monument targets such as at *M*, which are attached to deep pillars. *V* is the 60-cm diam vacuum pipe, 12 m long.

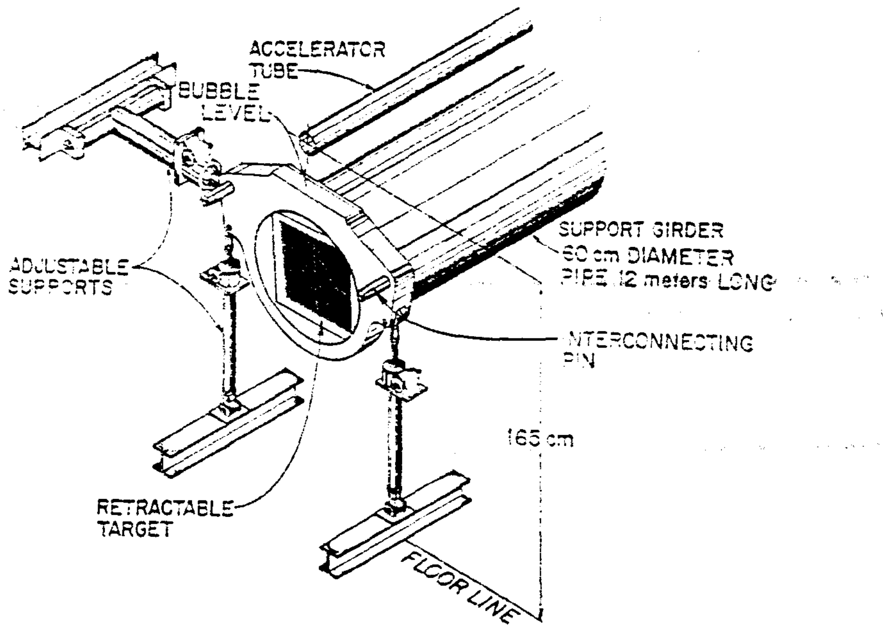

Figure 3. The mounting arrangement at the target end of each accelerator support girder. The target is shown in the inserted position. When retracted, the target is positioned horizontally along the top of the pipe.

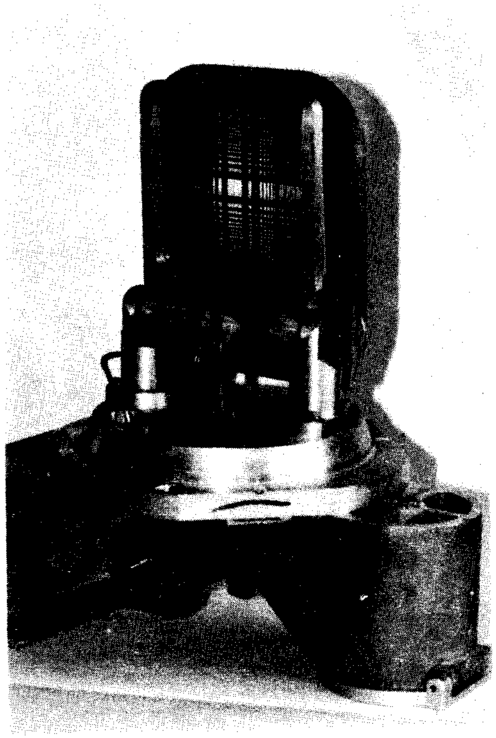

Figure 4.

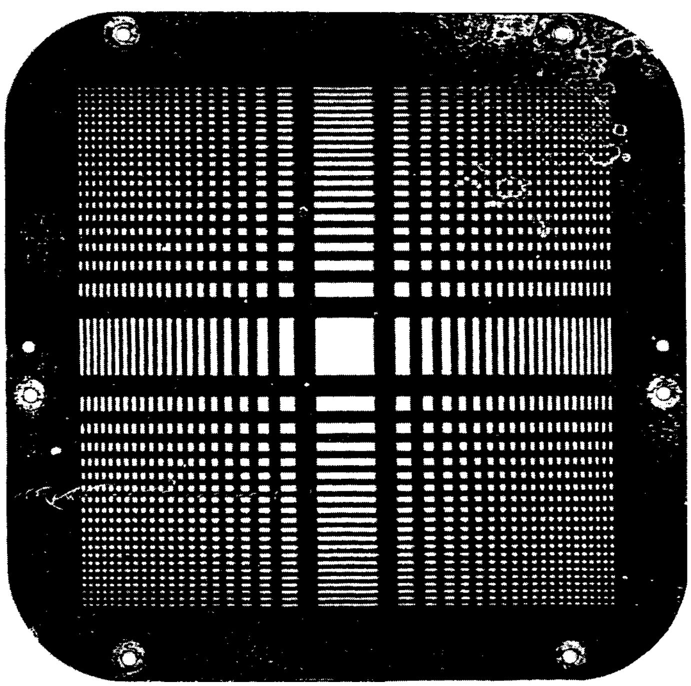

Figure 5.

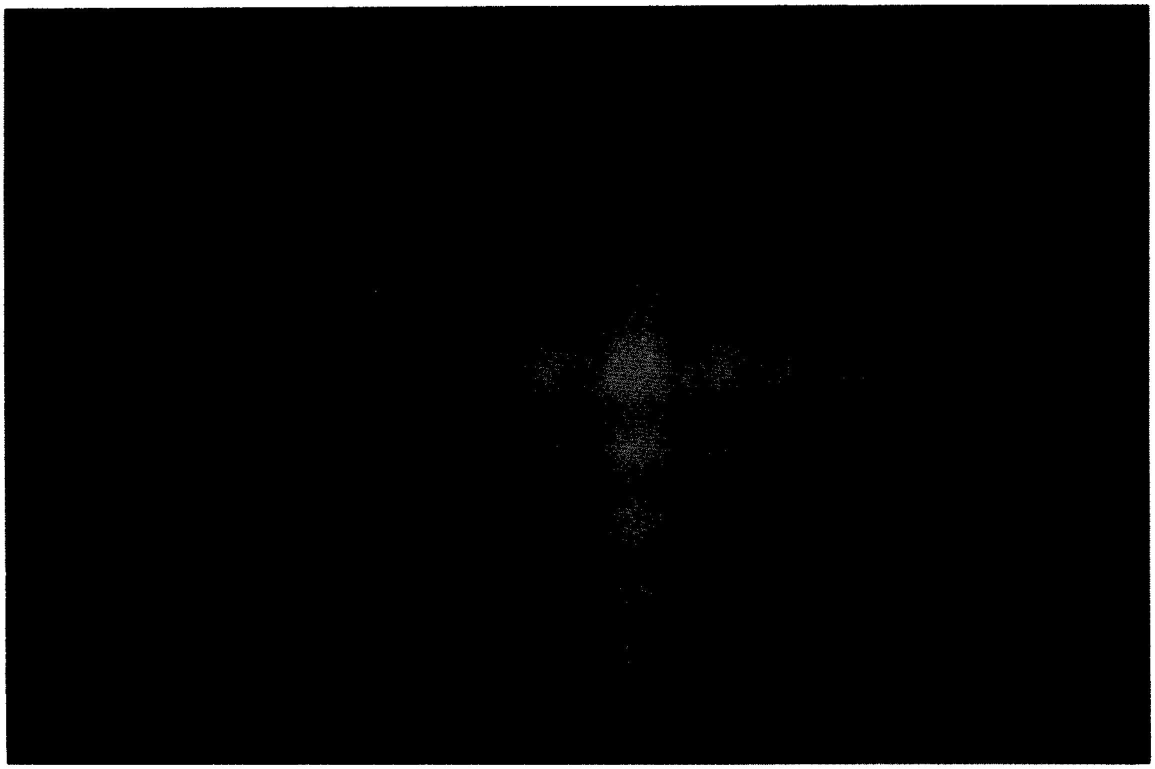

Figure 6.

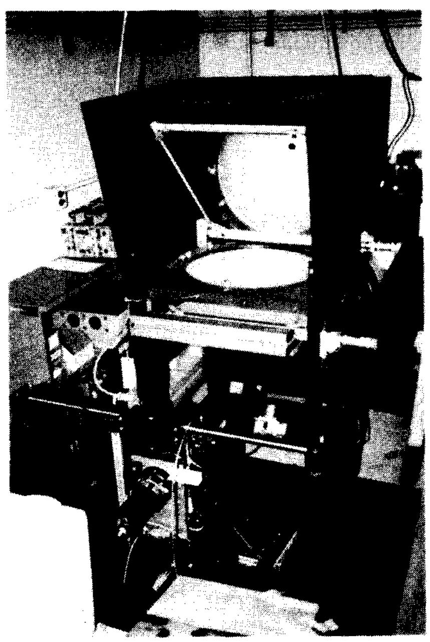

Figure 7.

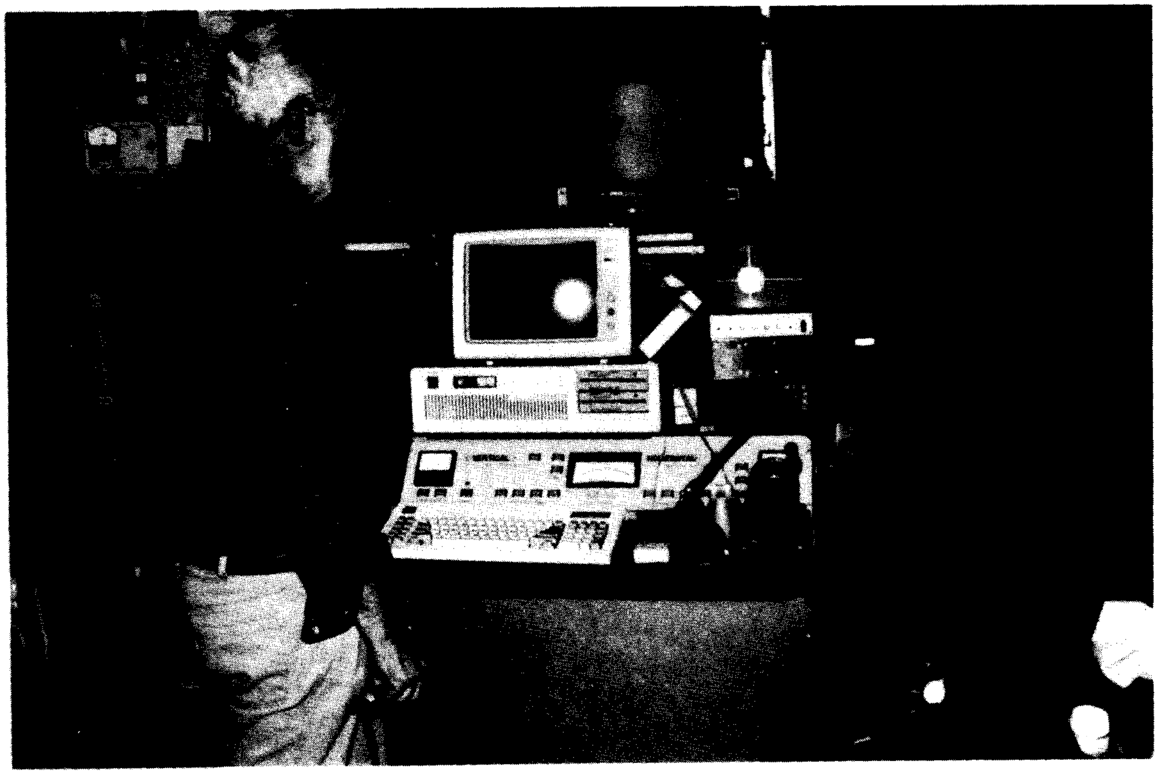

Figure 8.