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Precision Fiducialization of Transport Components*

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Abstract

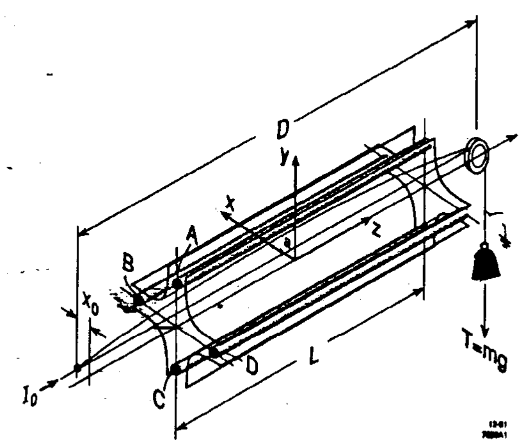
We have constructed an apparatus that simultaneously locates, to micron tolerances, the effective magnetic center of focussing lenses, as well as the electrical center of beam position monitors (BPM) imbedded therein, and once located, for transferring these coordinates to specially mounted tooling frames that support the external retroreflectors used in a laser tracker based alignment of the beam line. Details of construction as well as experimental results from the method are presented.

1. INTRODUCTION

The Final Focus Test Beam (FFTB) is a transport line designed to test both concept and advanced technology for application to future linear colliders. It is currently under construction at SLAC in the central beam line. Most of the quadrupoles of the FFTB have *ab initio* alignment tolerances of less than 30 microns, if the planned for beam based alignment tuning procedure is to converge.[1] For such placement tolerances to have any meaning requires that the coordinates of the effective centers, seen by the beam particles, be transferred to tooling (that can be reached by mechanical or optical alignment methods) located on the outside of the components to comparable or better values. We describe below the execution of a new method [2] to accomplish this fiducialization for magnet-beam-position-monitor packages and discuss our experiences with the apparatus to date.

2. CONCEPT OF THE METHOD

Consider the arrangement shown schematically below.



A thin wire, stretched more or less parallel to the mechanical axis of the lens, but displaced from this axis in the horizontal plane by an amount x_0, is set to vibrate at frequency ω. The voltage generated in a loop containing the vibrating wire will be proportional to two terms:

$$E(t) \;\alpha\; \{k\,L\,a\,\omega\,(\,x_0 \cos(\omega t) \;+\; a \sin(2\omega t)\,)\}$$

in which kL is the gradient-length of the lens and "a" is the amplitude of the oscillation[3]. The first term, occurring at the driving frequency and proportional to x_0, will be null if the wire oscillates about average positions at which no net flux is cut, that is about a point which is in the longitudinal middle of the lens and on the magnetic axis. We will call this location the *nodal point* because a whole family of lines intersect there; each obeying the zero-net-flux-cut condition. The sensitivity of the device to wire displacement can be made quite high by choosing a relatively high driving frequency. Noise reduction is achieved by observing the output through the use of a synchronized lock-in detector. The second term, which is proportional to a^2, never vanishes. It can be used to monitor the amplitude of the resonantly swinging wire.

After nulling the fundamental signal in both horizontal and vertical planes, the coordinates of the wire position may be measured with respect to precision tooling at both ends of the physical magnet. If the magnet is installed on the physical beam line in such a position that the beam particles simulate the wire then, by definition, the component is properly aligned[4].

3. DETAILS OF THE APPARATUS

3.1 The Wire:

The frequency of the lowest vibrating mode is given by: $f = 1/(2D)\mathrm{sqrt}(T/\mu)$ in which D is the distance between suspension points, T is the tension and μ the mass per unit length. To keep the frequency high it is useful to employ a very fine wire tensioned to just below its breaking point. A 35 micron gold plated tungsten wire, often used in drift chamber applications and having 2.2×10^{-5} kg/m, is used. The tension is provided by a 0.150 kg mass and transmitted over a jeweled bearing pulley to maintain constancy of force. For D=1.6 meters, the frequency is 81 Hz. The sagitta between support points is given by: $\delta y = \rho X^2/8T$, in which $\rho = \mu g$ is the weight per unit length and X=D/2, the half-length of the suspension. Under these conditions the overall sag of the wire is 12 microns. If the height of the wire is measured close to its entrance and exit of a half meter long magnet, the effective sag correction is about 1 micron. The mechanical detail of the wire shakers is shown in figures below. The orthogonal loudspeakers couple the motion of their cones to the wire via a plastic rod.

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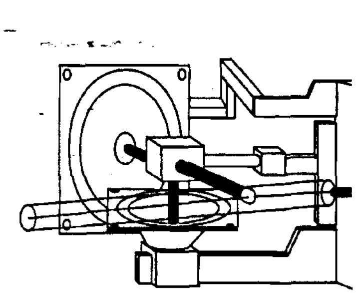
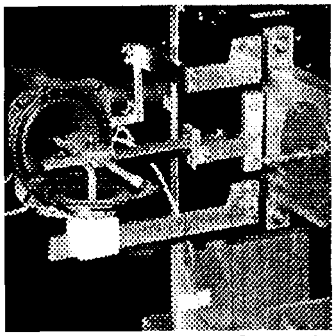



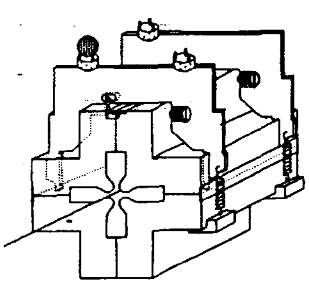
Care must be exercised so that magnetic fields from the speaker driving coils do not couple to the vibrating wire loop. Each end of the wire suspension can be translated in x and y by computer-driven precision stages[5] having 0.1 micron repeatability.

3.2..The Magnets:

Most FFTB quadrupoles[6] are iron-cored magnets having bore diameters of 2.30 cm and 0.461 meter effective lengths. The four solid-core quadrants were precision ground with numerically controlled machine tools. Great care was taken in their reassembly after insertion of the beam position monitors. Slots are machined into the quadrants so that the mating planes are exposed in several places. With 220 amperes in 20 turns, they can produce a gradient of 83 T/m.

3.3 The Fiducial Tooling Support Frames:

When installed on the beam line, the position of a magnet package is defined by its fiducial tooling balls. These 1.5000" diameter spheres also house the retroreflector corner cubes that are used by the "laser tracker"[7] alignment scheme to survey the object. The spheres are demountable; being held in their cups by permanent magnets. Reproducibility of placement is about 1 micron. The effective optical center of the ball is calibrated against its mechanical center to comparable precision. The cups are permanently referenced to the magnet's slot exposed split planes by invar frames as shown in Figures 4 and 5 below. Springs press the frame feet against the precision ground planes of the magnets.




3.4..The Coordinate Measuring Machine:

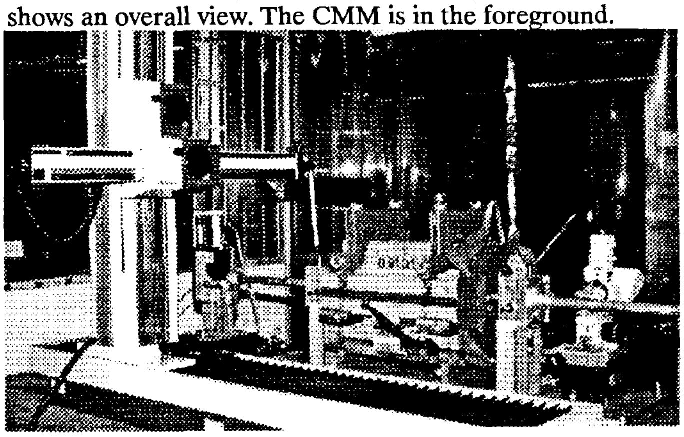
Although the movable stages holding the ends of the wire can be used to move the wire very accurately and thereby perform magnetic measurements, or to find the calibration constants and offsets of the BPM etc., a way must be found to transfer the coordinates of the wire to the magnet's tooling balls, or to its split planes. This is accomplished by the use of a coordinate measuring machine (CMM). This device is nothing other than a highly calibrated three axis positioning stage that carries a touch probe. We have found it convenient to use a horizontal arm model[8] that can access the apparatus from one side only. This configuration leaves the other magnet side free for all the wiring and services in a manner similar to as would obtain in the final tunnel installation. The touch probe technology employed[9] permits repeatabilities in the few micron rms range. The software package provided permits an easy redefinition of the measurement coordinate system. Absolute scale calibrations are made against mechanical reference standards[10] and/or by interferometric methods.

3.5 The Wire finder:

The touch probe of the CMM tells the associated computer to read a coordinate when the load on the probe is exactly 7 grams. This force would, of course, deflect the delicate wire. For this reason an auxiliary fixture is employed. A very fine micrometer screw is run up to the vibrating wire such that the wire begins to touch the anvil which shorts the wire to ground. This point can be detected by observing its effect on the second harmonic signal. The procedure is repeated on the opposite side. The wire must have been half way between the two settings. The sensitivity is better than 1 micron. The other end of the micrometer is in the form of a tooling ball that is touched by the CMM. Another method is to use a well calibrated high resolution microscope.

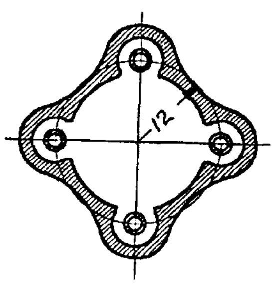
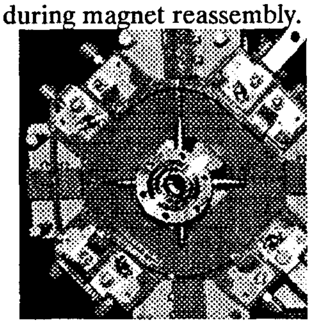
3.5 The Mounting Bed and Environment:

All of the apparatus is mounted on a polished flat, 3.2 ton granite block which is seismically isolated from the ground by soft rubber pads such that its damped vertical resonance occurs at about 2 Hz. The air in the "clean room" enclosure is kept at a slightly positive pressure and is temperature controlled at 20 +/- 0.5 deg.C. The photograph below shows an overall view. The CMM is in the foreground.



3.6 The Beam Position Monitors:[11]

The aluminum extrusion which houses the four stripline electrodes closely follows the magnet's bore and length. The extrusion is installed with no clearance so that the pole pieces clamp the unit in place during magnet reassembly.

The downstream end of the electrode is shorted to the wall. It should also be pointed out that the signal processing, which takes place after stretching, is at a low enough frequency (25MHz) such that the position readings should be independent of the longitudinal (time) characteristics of either the beam, or the simulated beam on the wire, to provide a truly two dimensional characterization of the BPM's geometry. This feature leads us to believe that the BPM nodal point should be near the longitudinal center of the structure. Although we are here concerned with the response of the monitor very close to its center where linear response is expected, in order to obtain high off-axis accuracy, the next order in the expansion will be used.

3.7 The Electronics:

3.7.1 BPM Calibration Electronics:

The operating electronics have been designed to achieve a 1 micron position resolution with a beam intensity of 1×10^{10} particles per bunch with monitor cable (RG-223) lengths up to 280 ft. The signal-to-noise ratio at the ADC is estimated to be about 4500. The calibration electronics for BPM offset determination consists of a 2 ns pulse sent down the same wire at 1000 Hz. The strip line response is measured using a filtered synchronous detector read out by a DVM to 1 part in 5000. The signals of strips A,B,C,D, are read by a single channel whose input is switched to each electrode in turn. Variations of gain or cable impedance therefore do not enter the calculation:

$$\Delta x = k(V_b - V_d)/(V_b + V_d) \qquad (2)$$

For this monitor the value of k, measured directly by displacing the wire, is 5430 microns.

3.7.2 Vibrating Wire Electronics:

With the quadrupole excited to full strength, the rms voltage from the vibrating wire loop should be about 17 microvolts for a displacement of 35 microns; in practice slightly lower because the wire suspension is not infinitely long. Such voltages are easily measured by modern spectrum analyzers. Far higher sensitivity may be attained, however, by detecting the signal synchronously with a lock-in amplifier[12], whose trigger is derived from the loudspeaker driver signal. The method is to find the correct observation phase with a large signal and then find the magnetic center wire position by noting the coordinate at which the signal changes sign. By fitting a sequence of observations, the resolution of center crossings is about 0.2 microns. 'Zero drift' of the lock-in then becomes important.

4. RESULTS

4.1 Magnetic center with respect to split planes:

4.1.2 Repeatability of Measurement:

Using the microscope method of locating the wire, six measurements of centers repeated with a rms of 2.3 microns in y and 5 microns in x. The nodal points were measured by observing a family of lines cutting zero flux which were found to intersect within 2mm of the longitudinal center of the iron and with a transverse spread of about 1 micron. The micrometer touch method has even better repeatability but there exists an as yet unexplained systematic offset in the results between the two methods.

4.1.3 Variation of center with magnet temperature:

It was found that, as the magnet warmed up after turn-on, the vertical center rose about 10 microns as its mounting expanded. The time constant of the magnet is estimated to be about 4 hours. This expansion was anticipated and will be corrected in service with the magnet supported on a magnet mover having micron resolution. However the fiducialization is performed with respect to the invar tooling frame which should be independent of magnet temperature.

4.1.4 Variation of center with magnet current and ramp rate:

It was found that the centers of these solid core magnets did not move more than a fraction of a micron when currents were ramped **up** at the extreme rate of about 100A/sec up to currents well into saturation. However by ramping **down** rapidly at this speed, center changes of up to 2 microns could be produced. It remains to determine if these changes persist when slower more controlled ramp rates are used.

4.1.6 Variation of center with magnet dis-and re-assembly:

A series of six measurements of the magnet center taken before and six after BPM insertion showed that the magnet returned to its original shape with centers within about 2 microns (ie. within the repeatability errors) with respect to its split planes.

4.2 Electric BPM centers with respect to the magnetic centers:

The electrical centers measured in the first two BPMs as installed in the magnets were less than 50 microns in x and y from the magnetic centers. We consider this entirely acceptable, given the mechanical construction tolerances of the aluminum extrusions.

ACKNOWLEDGEMENTS

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1 J.Irwin et al. "The Optics of the Final Focus Test Beam", SLAC-PUB-5539 May 1991, and in IEEE Trans. of Nuclear Science, Proc. of the Part.Acc. Conf. San Francisco 1991.

2 G.E.Fischer, J.Cobb, D.Jensen. SLAC-TN-89-01 March 1989

3 A more rigorous derivation of this voltage, including xy coupling and sag effects of the wire can be found in SSC Internal Report MD-TA-209 by Z. Wolf and P.Pellisier Dec 13,1991.

4 Minor correction would have to be applied if the real beam does not traverse the magnet in a symmetric way. Further, the optics are insensitive to pitch and roll errors at the milliradian level.

5 PM 500 Series, Newport Corp. 18235 Mt.Baldy Circle, Fountain Valley, CA 92708 U.S.A.

6 These lenses were constructed for the collaboration by the Institute of Physics, Novosibirsk,USSR.

7 The laser tracker is a theodolite mounted laser interferometer that automatically tracks the position of the reflector from one position to another to microns in radius and 5 microradians in angle. The device is made by the Cheasapeake Corp. in Lanham, Maryland U.S.A. The alignment process is described in SLAC-PUB- 5326 Dec 1990.

8 Mitutoyo C Series 806-10 MTI Corp 18Essex Rd.Paramus NJ 07652

9 Renishaw Model TP2-5W with sapphire probe tips etc.

10 Kolb-Baumann Step Gauge, Aschaffenburg, D-8750, calibrated by the P.T. Bundesanstalt, Labor 5.21, Bundesalle 100, D-3300 Braunschweig.

11 High Resolution BPM for FFTB, H.Hayano, J.L.Pellegrin, S.Smith, S.Williams . SLAC-PUB- 5691, Dec.1991

12 Princeton Applied Research, Model 5207 Lock-in Amplifier.