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A DYNAMIC ALIGNMENT SYSTEM FOR THE FINAL FOCUS TEST BEAM*

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0. ABSTRACT

The Final Focus Test Beam was conceived as a technological stepping stone on the way to the next linear collider. Nowhere is this more evident than with the alignment subsystems. Alignment tolerances for components prior to beam turn are almost an order of magnitude smaller than for previous projects at SLAC. Position monitoring systems which operate independent of the beam are employed to monitor motions of the components locally and globally with unprecedented precision. An overview of the FFTB alignment system is presented herein.

1. INTRODUCTION

The primary objective of the Final Focus Test Beam (FFTB) is to consistently and repeatably focus a 50 GeV electron beam onto an area which is 1 µm wide (horizontal) and 80 nm tall (vertical). The FFTB alignment system contributes in three ways.

(1) Tight initial alignment tolerances reduce the time required to initially focus the beam.
(2) Sensors which monitor the motions of magnets during a run, independent of the beam, are new tools which improve the ability to focus and control the beam.
(3) Sensors which monitor motions of the magnets between runs reduce the time required to return to a successful configuration.

2. INITIAL ALIGNMENT

2.1 Tolerances

The FFTB is composed of four straight sections as shown in fig. 1.

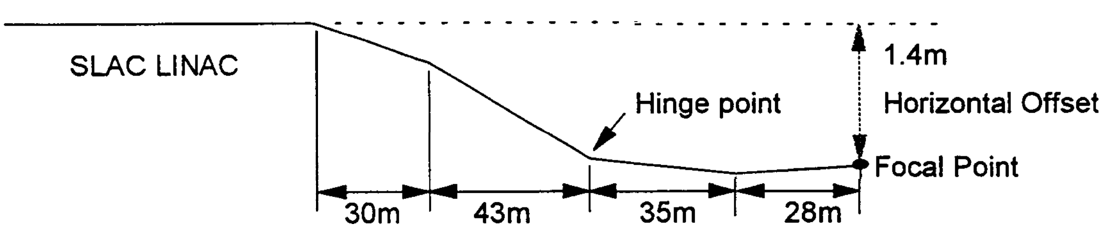

Fig. 1 FFTB composed of 4 Straight Sections

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The initial alignment tolerances for the FFTB quadrupoles and sextupoles are quite small: 100 µm horizontally and 30 µm vertically (see fig. 2). Additionally, the intersections between adjacent straight sections must have a closest vertical approach of no more than 30 µm.

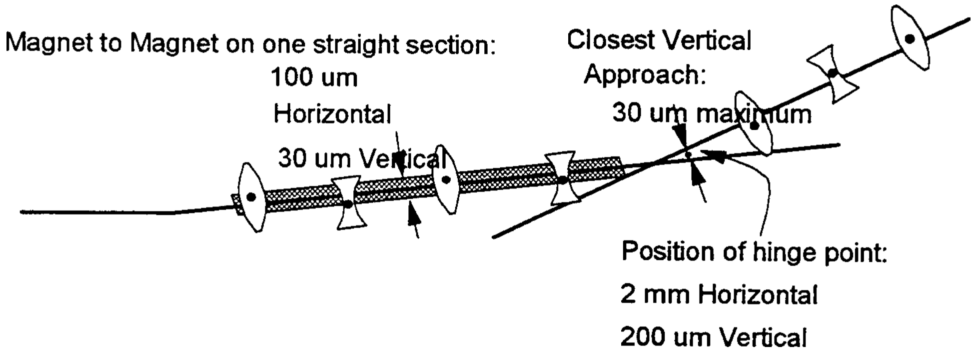

Fig. 2 Initial Alignment Tolerances

2.2 Tooling plates

The 30 µm vertical alignment tolerance applies to 23 quadrupole magnets and 4 sextupole magnets [1, 2]. We have fiducialized these magnets to within 12 µm using a technique developed here at SLAC [3]. The fiducials for these magnets are press fit into invar tooling plates. Two of these tooling plates are kinematically mounted on the horizontal and vertical split planes of each of the 23 quadrupole and 4 sextupole magnets. The mounting scheme of the tooling plates on a quadrupole is illustrated in fig. 3. One spherical contact point touches the vertical split plane, two spherical contact points touch the horizontal split plane and 3 spherical contact points press against the magnet in the longitudinal direction. We have found that these tooling plates may be removed and replaced on the magnet to within 3 µm of their original location.

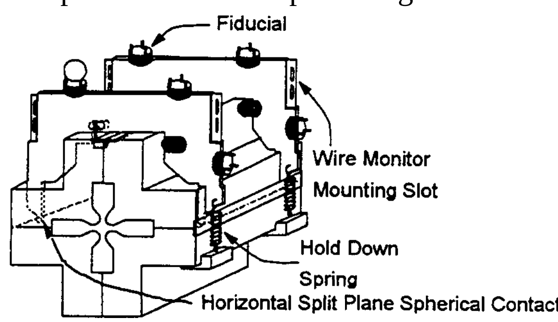

Fig. 3 Tooling Plates on a QuadrupoIe

Mounting slots for 2 wire position monitors (WPMs) are located on each tooling plate. WPMs will be described in section 3.2.

2.2 Alignment Instruments

In addition to theodolites, we will use two new alignment instruments for FFTB initial alignment: (1) Laser Tracker, and (2) Portable Water Hydrostatic Level.

2.2.1 Laser Tracker

The laser tracker [4] is an interferometer whose pointing direction "tracks" a retroreflector mounted inside of a 1.5 inch diameter sphere. By moving the sphere between fiducials, one may quickly measure the relative azimuth and elevation angles between the fiducials, as seen by the tracker, to within a few arc seconds. The radial distance difference between fiducials may be measured to a few µm. From these observables one can easily calculate the relative difference vector or the Cartesian coordinate differences.

2.2.3 Portable water level

In order to achieve 30 mm vertical alignment of the magnets we must support the vertical measurement component of the tracker. This will be done by a portable hydrostatic level [5]. The measurement range of this instrument is approximately 25 mm, and we typically achieve 10 µm repeatability after a series of measurements spanning several meters and taken over the course of an hour. For increased accuracy over large distances, the hydrostatic level, and the laser tracker will use the Fresnel laser system as a global straight line reference.

2.3 Fresnel Laser Reference System

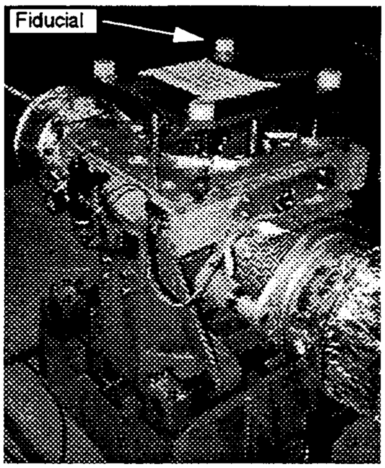

Fig. 4 A typical Laser Station

The SLAC linac Fresnel laser alignment system has been extended to the FFTB [6]. Thirteen new zone plates have been installed and calibrated to within 10 µm with respect to fiducials on the outside of their respective laser stations (see fig. *4).* By detecting the images produced from these zone plates we may compute to within 5 mm the relative offset of each zone plate from a straight line which goes through the center of two zone plates. Thus the relative positions of the laser station fiducials throughout the FFTB may be computed to within about 10 mm. These fiducials will serve as a straight line reference extending the length of the FFTB. Appendix A gives a detailed description of the system.

3. ON LINE MONITORING

3.1 Description

On line monitoring is the process by which the stretched wire alignment system monitors the relative motions of the magnets in a straight section while the beam is turned on. Each of the magnets with tooling plates is installed on a mover which can roll the magnet in increments of several mrad and which can move the magnet horizontally and vertically in increments of approximately 1 mm. On line monitoring using the stretched wire system will allow us to directly observe subtle changes in the relative alignment of the magnets in one straight section. Previously such changes could only be observed indirectly via beam position monitors and other devices which monitor the beam.

3.2 Stretched wire alignment

Our collaborators from DESY have provided a stretched wire alignment system which will be used for on line (and off line) monitoring of magnet positions. The system consists of a pair of wires for each of the 4 straight sections. Three WPMs are installed on the tooling plates of each of the 23 quadrupoles and 4 sextupoles. Each WPM is similar to a beam

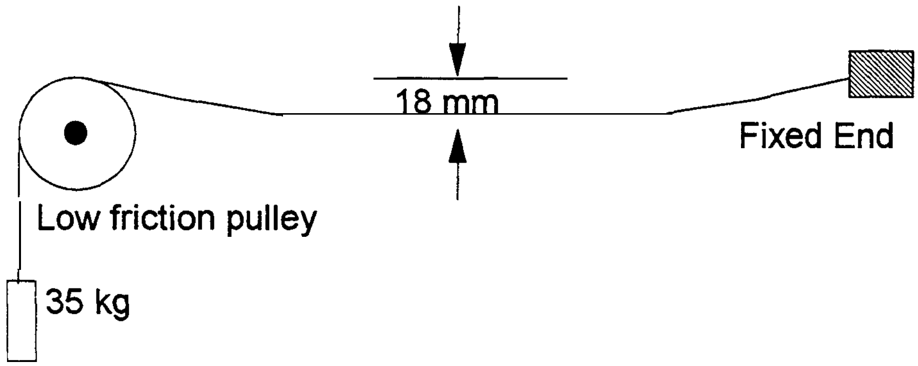

Fig. 5 The Stretched Wire

position monitor (BPM) in that it contains 4 antenna and the differential signal strength received from opposite pairs of antenna is the quantity of interest. However, unlike a BPM which receives its signal from a packet of charged particles, the WPMs receive their signal from a stretched wire which is excited at the fixed end with a 3 Watt, 140 MHz signal and which is grounded through a 250W resistor at the pulley end. The wire is centered to within +/- 150 µm inside an 8 mm (inner diameter) brass tube. The tube serves as the outer conductor in a coaxial structure which presents a constant impedance to the 3 Watt signal and which shields the signal from the outside world where it would interfere with FM radio broadcasts. A precision made aluminum extrusion provides a straight and rigid support for the brass tube.

The 3 WPMs on each magnet allows us to measure horizontal, vertical, roll, pitch and yaw motions of the magnet. The standard deviation of a set of readings from one WPM is typically less than 1 µm. The stretched wire oscillates at approximately 5 Hz with an amplitude of several micro meters. Therefore it is necessary to average readings from each WPM for about a second in order to achieve sub micro meter standard deviation.

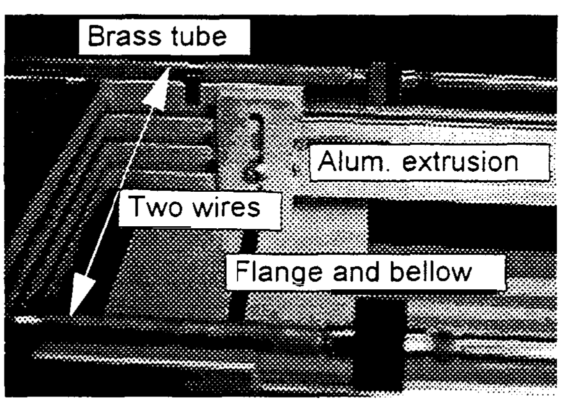

Fig. 6 Support Structure for Wire system

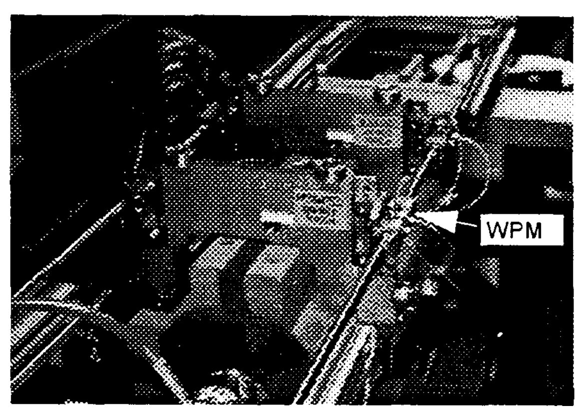

Fig. 7 Quadrupole with Wire Monitors

4. RECONFIGURATION

4.1 Description

We anticipate that the FFTB will have runs lasting for one week or less separated by down times of one or more weeks. Therefore, it is important to be able to return the magnets to their previous positions quickly. Our goal is to reconfigure the FFTB to within +/-10 μm using the alignment system. Reconfiguration applies not only to the alignment of magnets on one straight section but also to the intersection of adjacent straight sections, see figure 2. In order to do this we need a way of monitoring the motions of the ends of the wires.

4.2 Bridges

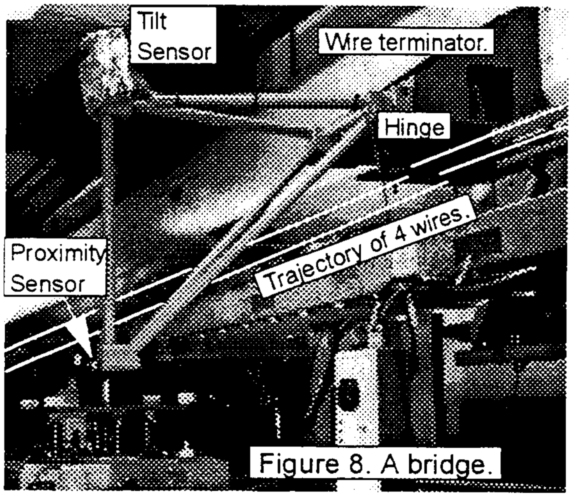

Figure 8. A bridge.

The bridge is a rigid invar structure which transfers the motion of a wire terminator to the top of a laser station whose location may be monitored with respect to other laser stations throughout the FFTB. The bridge rests on a ball which touches the top of the laser station, and the bridge is attached to the wire terminator via a precision hinge. The ends of 4 wires, spanning 2 straight sections, are also mounted on the wire terminator. The roll of the bridge is monitored with sub micro radian precision by a tilt sensor whose temperature is maintained constant to within 1/100 degree C. The horizontal displacement of the bridge with respect to the laser station is monitored to within 2 μm by a proximity sensor. Using these sensors and a number of temperature sensors located on the wire terminator and the laser station, we will monitor the horizontal and vertical motion of the wire ends with respect to the laser station to within a few μm.

5. SUMMARY

- Initial alignment of the FFTB will be achieved by supplementing theodolites with two new survey instruments, a laser tracker and a portable hydrostatic leveling system, used in conjunction with the laser reference system.
- On line monitoring of each FFTB straight section will be accomplished using the stretched wire alignment system.
- Reconfiguration of the FFTB after a down time will be accomplished using information from the stretched wire system, the laser reference system and the bridges which connect them.

APPENDIX A

0. Abstract

The original design for the SLAC linac included an alignment reference system with 270 diffraction gratings situated along the 3000 m linac. These gratings have provided SLAC with a global reference line repeatable to within 200 µm. For the Final Focus Test Beam, this laser system has been extended and 13 new diffraction gratings have been installed. Improvements in the image detection system, in the calibration of the targets and the availability of new instruments allows us to evaluate the performance of the laser reference system at the 5-10 µm level. An explanation of the system and the results of our evaluation are presented.

1. Introduction

Components of the FFTB laser alignment system are illustrated in figure 1. A 1 mW HeNe laser provides images with peak intensity of approximately 1 lux at the detector. (Note that all FFTB zone plates are less than 150 m from the laser). The divergent lens is chosen such that the intensity of light at the edges of the zone plate is about 75% of the intensity of light at the center of the zone plate.

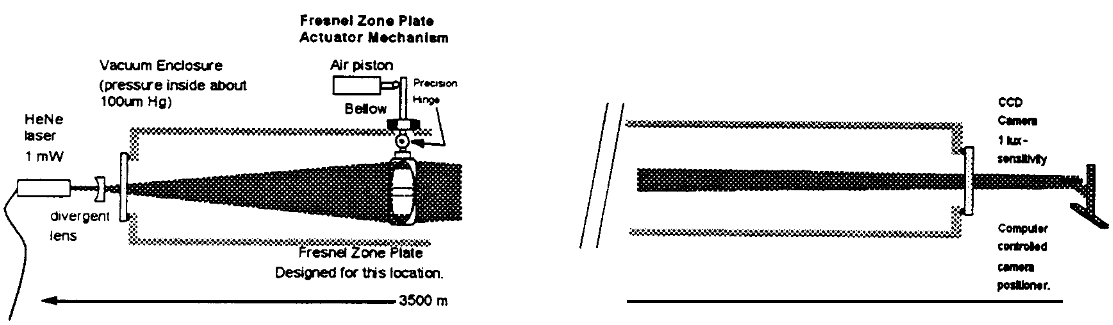

Fig. 1 Components of the Laser Reference System

A precision hinge which enables the zone plate to return to the same position with each actuation is required; only one zone plate may be lowered into the light at one time.

An inexpensive CCD camera with an array of size 8x6 mm is used. FFTB images are much larger than this CCD array. Therefore the camera must be moved many times in order to detect one FFTB image [6]. The accuracy of the camera positioning system is approximately 10 µm. However, FFTB images have high sensitivity, fig. 2, and need only be detected to within tens or hundreds of micro meters in order to achieve alignment information at the zone plate with precision of a few µm.

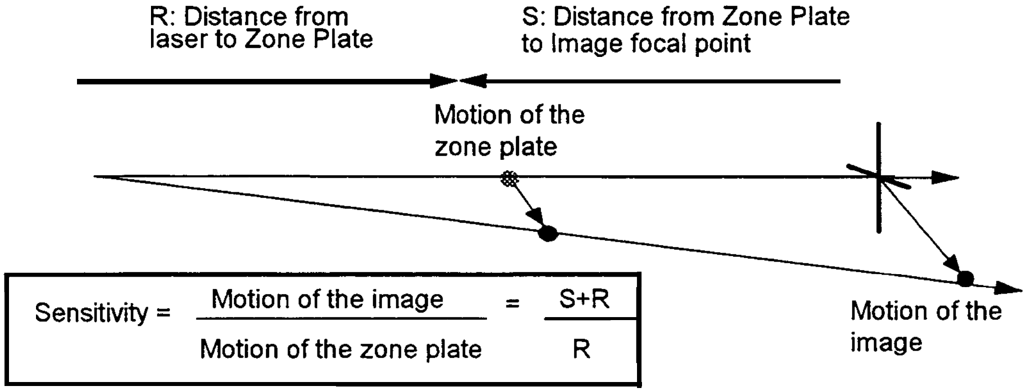

Fig. 2 Definition of Sensitivity

2. Image Measurements

Three days of data from the FFTB laser alignment system are show in fig. 3. This data was produced by lowering a *single* zone plate and repeatedly measuring the image from this zone plate. Motions indicated by the data are a combination of motions of the zone plate, the camera and the laser. Motions of the camera and the laser may be eliminated when a set of three or more different images are monitored. However that was not done in this case. The data from fig. 3 is useful in order to evaluate the standard deviation or quality of the measurements made by the image detection system. The standard deviation of these measurements, computed in terms of the position of the zone plate, is less than 5 μm.

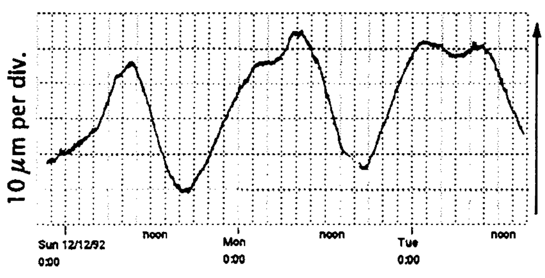

Fig. 3a Measurement of LSX1 Image (Vertical)

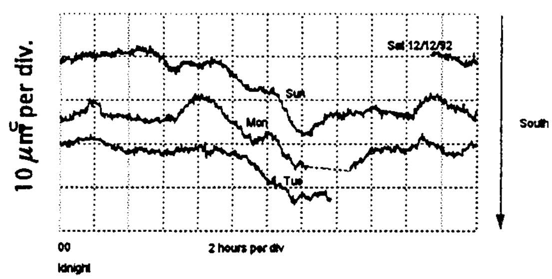

Fig. 3b Measurement of LSX1 Image (Horizontal)

3. Accuracy Of Images

Figure 3 illustrates the *repeatabiliy* of the measurement of zone plate images. However, this data says nothing about the accuracy of these measurements. Notice that the standard deviation of the vertical measurements is less than the standard deviation of the horizontal measurements. The algorithm which is used to detect the center of the image uses (1) the vertical cross section of the image to compute the vertical coordinate of the center of the image and (2) the horizontal cross section of the image to compute the horizontal coordinate of the center of the image.

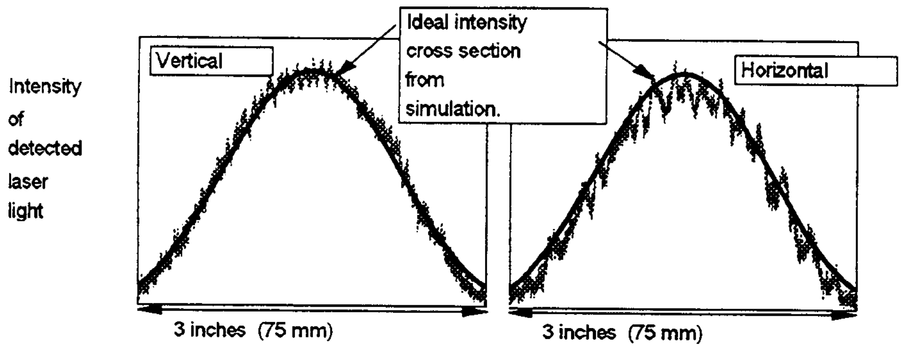

Fig. 4 Image Intensity Cross- Section of Target LX7

Therefore if the standard deviation of the computed vertical coordinate of the image is less than the standard deviation of the computed horizontal coordinate of the image, we would expect that the vertical cross section of the image would be of better quality than the horizontal cross section of the image. Figure 4 illustrates that this is indeed true.

The imperfection in the images shown in figure 4 are caused primarily by stray light, reflected off the interior of the vacuum enclosure. These imperfections are stable; cross sections taken on different days contain the same imperfections.

Looking at figure 4, one might wonder if the computed center of such an image is a good measurement of the center of the "ideal" image. Figure 5 illustrates the image detection algorithm. By varying the reference level and remeasuring the center of the image, one may gain a sense of how well we are computing the center of the ideal image.

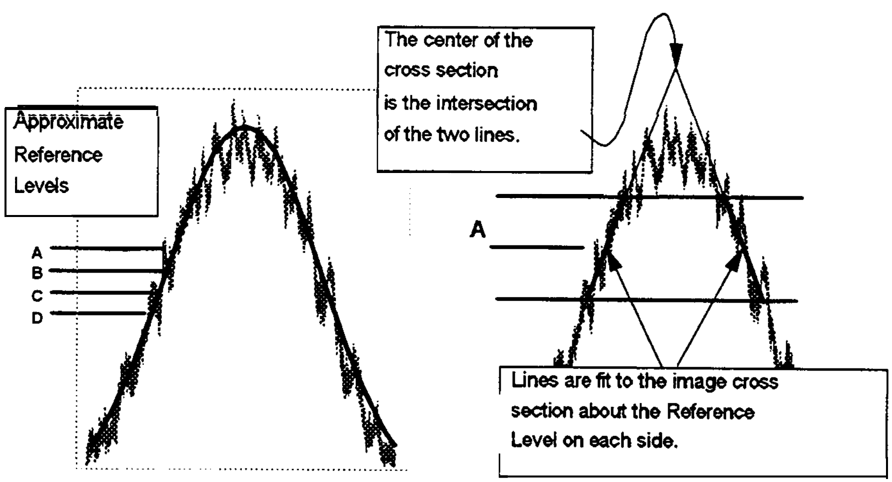

Fig. 5 Image Detection Algorithm Background

The data from figure 6 is taken directly from the database which is attached to the image detection program. This data consists of 12 different measurements of the center of the LSX7 image at 4 different reference levels. X and Y are the horizontal and vertical coordinate of the image in inches as measured in the coordinate system of the image detector. Etime is the time required for the algorithm to converge in seconds. Center Amp determines the effective reference level.

Name	Reference Level	X	Y	Time	MODE	Etime	Cen A
32-7		-0.6011	-0.2413	1992□2/09□4:14	TRANS	13 7	113.0
32-7	B	-0.6174	-0.2428	1992⌐12/09⌐14:21	TRANS	31 9	113.0
32-7		-0.6154	-0.2414	1992□2/09□4:24	TRANS	51 0	113.0
32-7		-0.6342	-0.2425	1992□2/09□4:30	TRANS	02 8	100.0
32-7	C	-0.6358	-0.2432	1992□2/09□4:36	TRANS	72 3	100.0
32-7		-0.6069	-0.2434	1992□2/09□4:43	TRANS	33 4	100.0
32-7		-0.6289	-0.2426	1992□2/09□4:48	TRANS	22 2	85.00
32-7	D	-0.6258	-0.2455	1992¦12/09¦14:56	TRANS	82 8	85.00
32-7		-0.6171	-0.2450	1992⌐12/09⌐15:00	TRANS	61 6	85.00
32-7		-0.6187	-0.2283	1992□2/09□5:05	TRANS	62 8	130.0
32-7	A	-0.6236	-0.2305	1992□2/09□5:09	TRANS	41 6	130.0
32-7		-0.6192	-0.2380	1992□2/09□5:12	TRANS	51 1	130.0

Fig. 6 Image Measurements at Different Reference Levels

The total range of all the Y (vertical) measurements is 440 μm and 840 μm for the X (horizontal) measurements. Translating these measurements into distance at the zone plate we have: *Vertical Range: 5.6* μm *Horizontal Range:* 2.9 μm. As. far as the image detection algorithm is concerned, these images are quite symmetric. Therefore, when we compute the center of the "imperfect" image, we are computing the position of the center of the zone plate to within about 5 μm.

4. Image Simulations

Prior to the construction of the FFTB laser alignment system we investigated the feasibility of a Fresnel zone plate laser alignment system with 5 μm accuracy. Several of the questions on our mind were: (Q1) How precisely must the slots of a zone plate be fabricated? (Q2) How large must a zone plate be? (Q3) Does the angle of the zone plate with respect to the incident light wave matter? (Q4) What happens when light from the laser is not symmetrically distributed across the surface of the zone plate?

In order to answer these questions we conducted one and two dimensional simulations which assumed (1) Light incident on the zone plate has a gaussian intensity profile and has spherical phase, originating at the laser. (2) The zone plate is located at distance R from the laser. (3) The zone plate may move horizontally or vertically with respect to the laser line. (4) The zone plate may pitch or yaw with respect to the laser line. (5) The camera is located distance S from the zone plate.

Available space does not permit a description of the simulation algorithm, therefore we will simply present results.

(Q1) How large must a zone plate be? or in other words, what is the required number of slots in the zone plate? this is an important issue since as the slots become small, manufacture of the zone plate becomes increasingly difficult and expensive the number of slots in the zone plate is given by the order of the zone plate, N.

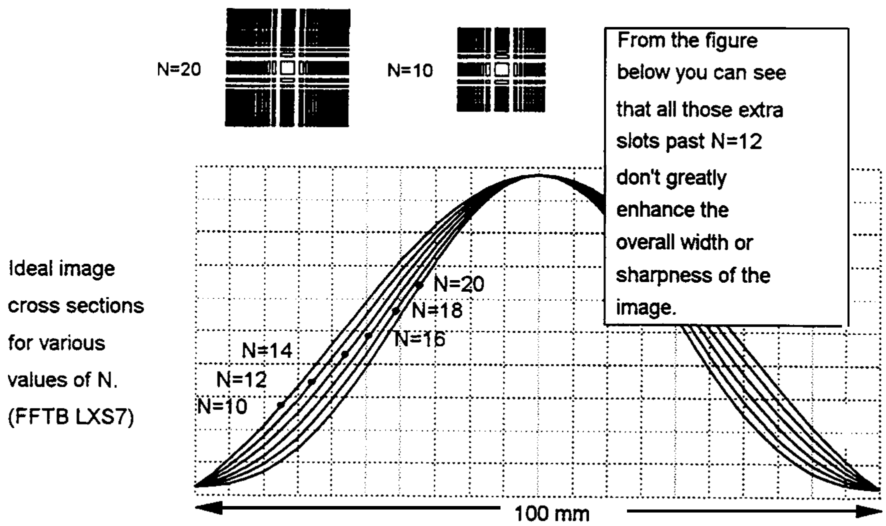

Fig. 7 Discussion of Question I

(Q2) How precisely must the slots of a zone plate be fabricated? Simulations were conducted for the LSX7 zone plate (r=22.9 m, s=3424.5 m, N=20). The simulated zone plate had been given random asymmetric imperfections with standard deviation A and the center resulting image was computed.

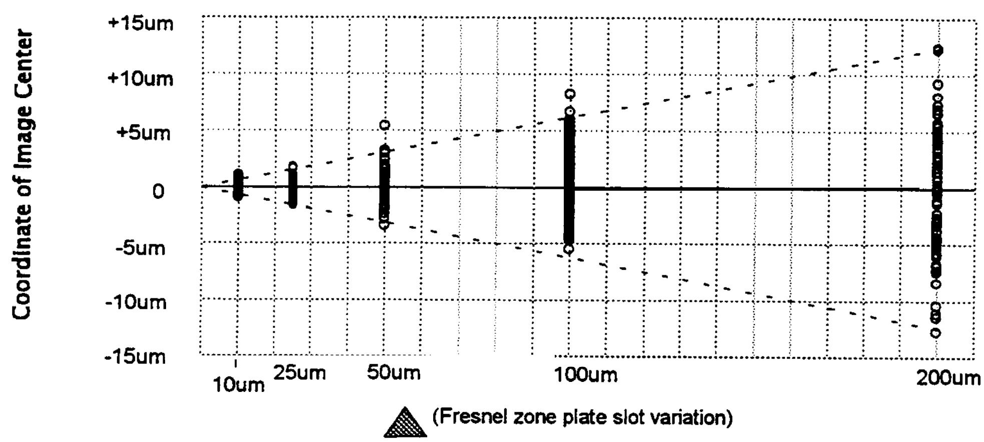

Fig. 8 Discussion of Question 2

(Q3) Does the angle of the zone plate with respect to the incident light wave matter? By working through the mathematics of our simulation algorithm we found that this angle Θ does not significantly effect the image produced by this zone plate for values of Θ less than several degrees.

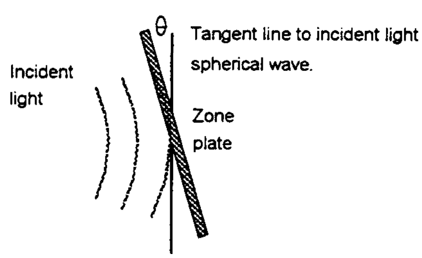

Fig. 9 Discussion of Question 3

(Q4) What happens when light from the laser is not symmetrically distributed across the surface of the zone plate or in other words, is not centered?

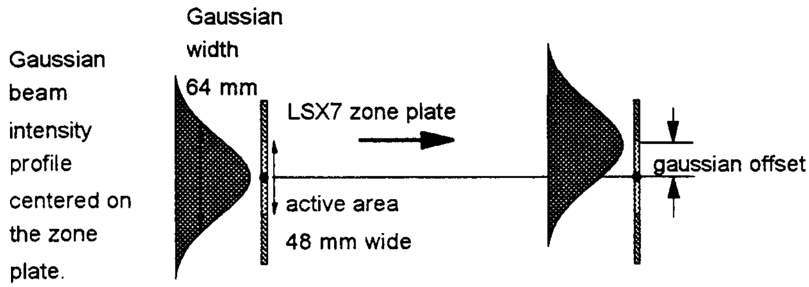

Fig. 10 Discussion of Question 4

If the Gaussian beam intensity profile is not centered on the zone plate, image offsets will result. Fig. 11 shows the offset values for the case of the LSX7 zone plate.

Gaussian Offset [mm]	Image Offset [μm]
5	3.9
10	7.0
20	13.5

Fig. 11 Resulting Offsets

5. Conclusion

Fresnel zone plate alignment systems can provide alignment information with relative accuracy from zone plate to zone plate of 5 μm without expensive image detection hardware and with zone plates fabricated to 5 μm tolerances. FFTB Fresnel zone plate alignment images have been shown to be, (1) Symmetric to within 5 μm (2) Re-measurable to within 5 μm.

REFERENCES

[l] These magnets were constructed for the collaboration by the Institute of Physics, Novosibirsk, Russia.

[2] The FFTB also includes three quadrupoles just upstream of the focal point which are aligned to within 5 μm with respect to one another and which are mounted on their own table which may be translated horizontally, vertically, rolled, pitched and yawed with sub-μm precision. This entire system is provided to the collaboration by the KEK laboratory, Japan.

[3] G.E.Fischer et al. (1992), "Precision Fiducialization of Transport Components", Proceedings EPAC, p. 138.

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[5] Pellissier Instrument Corp., Denver, CO, U.S.A

[6] V.E.Bressler, G.E.Fischer, R.E.Ruland, T. Wang, "High Resolution Fresnel Zone Plate Laser Alignment System", Proceedings of EPAC '92, Vol. 2 (March 1992) pp. 1613-1615