High Resolution Fresnel Zone Plate Laser Alignment System*

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Abstract

The existing Fresnel zone plate laser alignment system is currently being extended and upgraded for the Final Focus Test Beam (FFTB). Previously, the resolution of this system has been several tens of micrometers. After the upgrade, the resolution will be a few micrometers. Details of the upgrade as well as simulation and experimental results will be presented.

1. INTRODUCTION

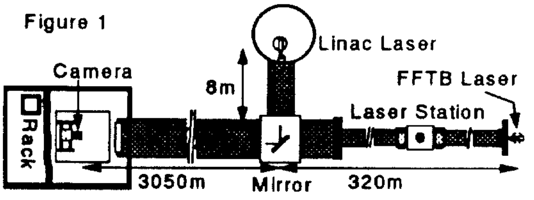
Currently we are constructing the Final Focus Test Beam (FFTB), a 300m final focus beam line extending from the end of the SLAC central beam. Quadrupole placement tolerances between FFTB quadrupoles is set at less than 30 micrometers. The alignment problem is three fold; we need (1) a straight line reference which is accurate to within 10 µm over 35 m (2) a distance/angle measurement technique which is accurate to within 15 µm over 15 m, and (3) a method for fiducializing components with an accuracy of about 10 µm. In this paper we will briefly describe the existing laser alignment system, and describe recent work on the image detection system.

2. EXISTING SYSTEM

The 3050 m long linac at SLAC is composed of approximately 270 girders, each of which is about 12 meters in length. Each girder consists of a length of 60 cm diameter vacuum pipe (light pipe) with components mounted on top. Inside of each section of light pipe resides a single fresnel zone plate and its acutator mechanism, which rotates the zone plate into and out of the incident laser light[1].

The laser is a 10mW HeNe located at one end of the linac as shown in figure 1. The laser beam is taken through a diverging lens in order to create a virtual point source. The laser is mounted in such a way that its center pivots about the virtual point source.

Figure 1



A diffraction image at the detector is produced by rotating <u>one</u> zone plate into the incident laser light. The center of this image is related to the position of the zone plate with a magnification factor of *(r+s)/r* where *r* is the distance from the laser source to the zone plate and *s* is the distance from the zone plate to the detector. For zone plates near the detector, this scale factor is approximately 1. For zone plates near the laser, this scale factor increases rapidly as does the sensitivity of the alignment system. By lowering a series of zone plates, one can determine the relative offsets of the various zone plates with respect to a single straight line which goes through the laser point source and the zero coordinate of the detection system. Subsequently, this line may be redefined as the line which goes through the exact center of 2 zone plates or as a best fit line for 3 or more zone plate centers. The positions of the physical centers of the original 270 zone plates were determined to within about 100 µm with respect to tooling outside of the light pipe. Also, previous methods used to detect the position of the center of the diffraction image were accurate to about +/- 25 µm.

3. THE FFTB LASER SYSTEM

The FFTB will extend beyond the linac as shown in figure 1, therefore, the FFTB laser alignment system will have its own laser and its own 320 m extension of 25 cm diameter light pipe which connects with the linac light pipe. Since the FFTB beam line bends horizontally by about 4.5 meters from start to finish, we have not designed a system where the beam components are physically tied to the laser alignment system. Instead, we will fiducialize each of 10 FFTB zone plates with respect to fiducials on the outside of their adjustable housings (laser stations) to within about 10 µm. These laser stations were previously used for the BSY (Beam Switch Yard) laser alignment system here. We will fiducialize the laser stations with a coordinate measuring machine which has an accuracy of about 2 µm over the required range. In the field, these laser stations will serve as alignment monuments. Using the image detection system and temperature sensors mounted on the laser stations, our goal is to be able to determine the positions of the fiducials on each FFTB laser station with respect to an arbitrary (but stable) straight line to within 10 µm.

4. THE DETECTION SYSTEM

The existing image detection system consists of a CCD camera mounted on a computer controlled X,Y translation system with position readback from magnetic scales with 2.5 µm resolution. The computer is a PC386 with a frame grabber to collect images from the camera. The size of the CCD array is about 8 mm by 8 mm. Images from most of

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the linac fresnel zone plates are small enough to fit entirely on the CCD array. The positions of all linac images which fit entirely on the CCD array are determined by computing the weighted average of their incident intensity pattern.

5. DETECTING LINAC IMAGES

Repeatability of the weighted average measurement, without moving the fresnel zone plate, is less than 10 µm. However, the detected center of these images is not guaranteed to correspond to the actual center of the fresnel zone plate itself, nor do we believe that there is a predictable relationship, at the 10 µm level, between the center of mass of the detected image from a linac fresnel zone plate and the actual position of that zone plate with respect to a set of other zone plates. A contour plot of a linac zone plate image is shown in figure 2. Distinct ripples in the intensity pattern of the image are apparent. We believe that these are caused by an effect known as vignetting[2]. Light emerges from a laser with a gaussian intensity profile. If the light encounters no obstructions or significant changes in refractive index, the beam will spread in a well behaved manner, maintaining its gaussian intensity profile and preserving its phase coherency. However, if an aperture is encountered such that 1 percent of the power of the beam is blocked, the intensity profile will change from a smooth gaussian to a gaussian which is modulated with ripples whose amplitude is equal to 17 percent of the height of the gaussian; distortions in the phase profile of the beam also result.

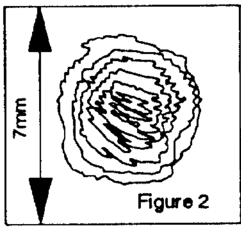

Figure 2

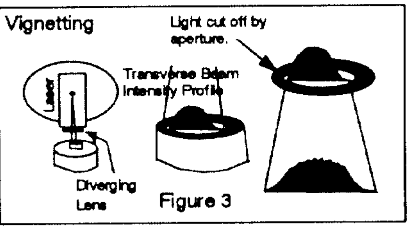

Figure 3

More than simply modulating the intensity profile of the detected image, we believe that any asymmetric vignetting which has a significant effect on the intensity of the detected image will change the apparent center of the image at the detector. Using the Fresnel approximation[3], we have simulated the effects of apertures placed both before and after a zone plate. In these simulations, if the aperture is small enough to significantly reduce the intensity of the detected image, and if, the aperture is placed not at the center of the line which goes through the laser point and the center of the zone plate, then the detected position of the image will change many micrometers per millimeter of aperture offset. Although we have not run simulations of vignetting near the laser source, we assume that such vignetting will significantly impact the detected position of the image.

6. ABOUT VIGNETTING OF LINAC LASER

As shown in figure 1, the linac laser is mounted perpendicular to the linac and its light must bounce off a mirror in order to achieve the proper trajectory. The angle of the mirror must be adjusted so that light from the laser passes through all 270 linac targets and falls on the detector whose range is approximately +/- 6 cm vertical. The position of the laser itself is severely constrained by the small (about 2 cm diameter) window through which laser light must pass before entering the light pipe, see figure 3. This yields an alignment tolerance for the housing containing the mirror of about +/- 30 µm. This alignment may be achieved, with difficulty, by observing light incident at the detector.

Following the earthquake of October 1989, we found that the mirror was misaligned. Realignment of the mirror could not be achieved by moving its housing; we found it necessary to move the laser away from the center of its small window, thereby causing asymmetric vignetting. Presently one can see reflected laser light around the aperture of the small window. In order to avoid significant vignetting, the center of the beam must be at least 2.5 beamwidths away from the nearest obstruction. Beamwidth is defined as width at half maximum intensity.

7. NEW DETECTION ALGORITHM

All of the FFTB diffraction images will be much larger than the CCD array. Figure 4 is a simulated image corresponding to a fresnel target located near the middle of the FFTB. Previously, large linac images have been detected by placing a transparent grid on the glass at the detector room and observing by eye where a given image falls on the grid. This technique is not suitable for FFTB for two reasons: (1) Even with the large magnification factors for FFTB (typically 20 to 1) the grid technique yields alignment tolerances no better than +/-25 µm. (2) The FFTB laser alignment system must be fully automated.

Two general philosophies concerning how we might accurately detect these large images were considered (1) Reduce the size of the images with a lens or (2) move the camera and detect the images one piece at a time. Reducing the size of the images with a lens would distort the images. Techniques for reducing the effects of these distortions have been developed, even so, the lens required would be rather large, cumbersome and expensive, and would demagnify the image by a factor of at least 7, thereby reducing the sensitivity of the system. Thus we decided to investigate a detection system based on moving the camera about on a single image.

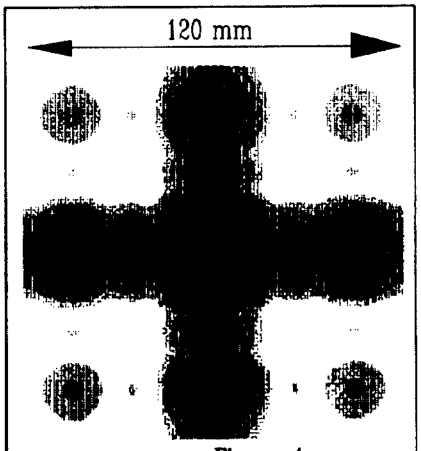

Figure 4

We created the test setup shown in figure 5 in order to test our intended image detection algorithm. The use of actual fresnel images would have been preferable if these images had not been distorted by vignetting. Also our access to the linac laser system is intermittent and dependent on the operational schedule for the linac, furthermore, the FFTB laser system will not be available until at least November 1992.

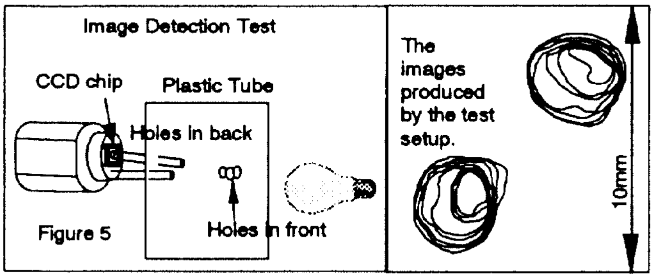

Figure 5

Our image detection algorithm is illustrated in figures 6 through 9:

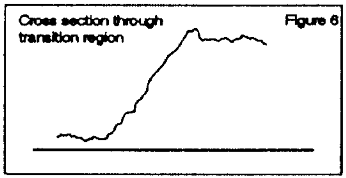

Figure 6

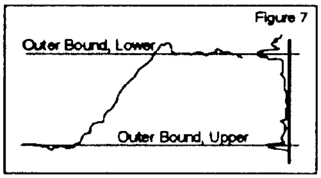

Figure 7

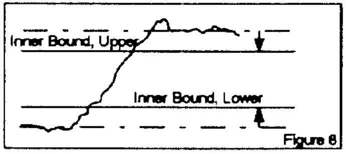

Figure 8

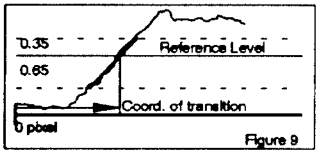

Figure 9

7.1 Establish inner transition bounds:

A region of interest in the image must be found. This region will include a transition from light to dark or dark to light. The algorithm is one dimensional, thus a cross section through the region of interest is selected; this is shown in figure 6. The outer boundaries of the transition must be established. This is accomplished by finding the two peaks in a histogram representation of the data as shown in figure 7. The inner transition bounds will be defined in terms of the outer transition bounds; see figure 8. Once the inner bounds are established, they are recomputed infrequently and only if the mean intensity changes significantly. Different images will have different inner transition bounds.

7.2 Compute the coordinate of a transition:

The pixel coordinate of a transition is computed by taking the pixels between the inner transition bounds and fitting a straight line to them and finding the intersection of this line with the reference level which is defined in terms of the inner transition bounds; see figure 9. The coordinate of the transition thus computed is a floating point number. We have found for our artificial images that the standard deviation of the transition coordinate computed with pixel data averaged over 5 frames without moving the camera is approximately 1/20 of a pixel or 0.7 μm.

7.3 Iterative algorithm for finding image center:

Our iterative algorithm for finding the image center is illustrated in figure 10. The position of an image is computed by (a) moving the camera between the upper, lower, left and right edges of the image, (b) averaging upper and lower, left and right to get the horizontal and vertical coordinates for the image, (c) comparing the horizontal and vertical coordinates with the previous, (d) stopping if the present horizontal and vertical coordinates agree with the previous to within 1.5 μm, (d) redefining the positions of the upper, lower, left and right edges according to the most recent data, (e) repeat. Note that the transition of interest is centered on the CCD array. This minimizes the effects of any nonlinearities in the relative positions of the pixels.

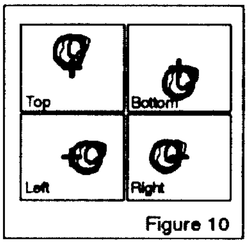

Figure 10

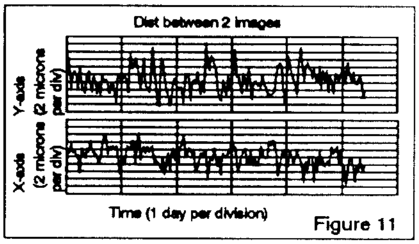

Figure 11

In order to test the performance of this system we created a program which would automatically measure the position of the two images once every 30 minutes. The measurement of the two images required about 50 seconds on average; most of this time was spent moving and stopping the camera. Results from this test are shown in figure 11. The apparent drift of the relative measurement over 5 days is not significant. The standard deviation of our measurement is ultimately limited by the 2.5 μm resolution of the magnetic scales. We believe that with a little more robust pixel data averaging this system will find the center of an image with a standard deviation of less than 3 μm. For the large images of the FFTB our detection algorithm will be complicated by the fact that an entire transition will not fit on the CCD array. None the less, we are confident that we will be able to detect the centers of these images with far greater accuracy than the required 100 μm. Recall that 100 μm at the detector is equal to 5 μm at the FFTB zone plate.

ACKNOWLEDGEMENTS

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[1] W.B.Herrmannsfeldt et al.. "Precision Alignment Using a System of Large Rectangular Fresnel Lenses", Applied Optics, Vol. 7, pg 995, June 1968

[2] A.E.Siegman. LASERS, University Science Books, Mill Valley, CA, 1986, pg 667.

[3] J.W.Goodman. INTRODUCTION TO FOURIER OPTICS, McGraw-Hill, New York, 1976.