EXPERIMENTAL STUDY ON NEW LASER-BASED ALIGNMENT SYSTEM UTILIZING A SEQUENTIAL THREE-POINT METHOD AT THE KEKB INJECTOR LINAC

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Abstract

A new laser-based alignment system is under development in order to precisely align accelerator components along an ideal straight line at the KEKB injector linac. This system is based on a sequential three-point method using Fresnel zone plates (FZPs). We experimentally investigate the focusing characteristics of a He-Ne laser passing through the FZP at atmospheric pressure at the focal region. In this report, the focusing characteristics (alignment precision, resolving power, depth of focus) and performance of the circular FZP at the focal region are described in detail.

INTRODUCTION

There has been renewed interest in the study of high-precision alignment techniques, particularly with the aim of applying them to high-energy particle accelerators. The development of alignment techniques is essential for long-distance injector linacs for stabilizing the acceleration and transportation of particle beams with higher charge intensities and for preserving the beam quality and enhancing the injection efficiency of the beams into the storage rings.

The SuperKEK B-Factory (SuperKEKB) project [1] is the next-generation B-factory under construction at KEK after the KEK B-Factory (KEKB) project [2], which was stopped in 2010. The SuperKEKB is an asymmetric electron-positron collider comprising 4-GeV positron and 7-GeV electron rings. Because SuperKEKB is a factory machine, well-controlled operation and high-precision alignment of the KEKB injector linac [3] are indispensable to maintaining the injection rate, stability of the beam collision, and peak luminosity as high as possible.

Three (or more) points can be aligned along a reference straight line by measuring the transverse displacements from the reference line. This is a standard alignment technique known as the three-point method. This method employs light rays and is widely used in large accelerator complexes [4]. One such alignment technique is a laser-based alignment technique using FZPs, and its advantage is that it can be applied not only for high-precision alignment measurements of long-distance linacs but also for regular monitoring of the straightness of the linac in real time without interrupting the linac operation.

Systematic experimental studies will be beneficial with regards to optical physics and can improve the available laser-based alignment techniques in terms of higher precision. This study could also help in the practical design and optimization for the KEKB injector linac.

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EXPERIMENTAL SETUP

Optical Configuration

Systematic experiments were performed for studying the focusing characteristics using the circular FZP in the optical tunnel at AIST. The optical configuration and experimental setup are shown in fig. 1.

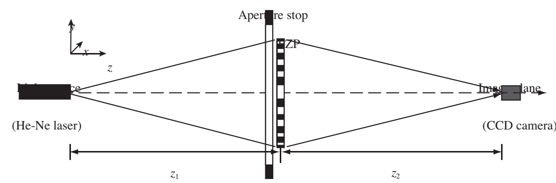

Figure 1: Optical configuration and experimental setup.

The light source is a commercially available 10 mW He-Ne laser having a wavelength of 632.8 nm at atmospheric pressure. The divergence angle of the laser beam is approximately 0.7 mrad. The waist position of the laser beam is just out of the laser source and the waist size is approximately 1.5 mm considering the full width at half maximum (FWHM). The FZP with a focal length of 66.7 m has been installed at a distance of z_1 = 125.07 m downstream from the laser source. Thus, the laser source can be treated as a point-like source of light at the location of the FZP. The image plane at the focal point is located at a distance of z_2 = 142.78 m downstream from the FZP. The total distance ($L = z_1 + z_2$) of the laser propagation from the laser source to the image plane is L = 267.85 m. A commercially available CCD camera has been used for measuring the two-dimensional intensity distribution of the focused spot at the image plane.

Developed Fresnel Zone Plate

A Soret-type FZP has been developed for use as an alignment target in this experiment (fig. 2). This FZP is composed of radiation-hard circular synthetic quartz having a diameter of 60 mm and a thickness of 4 mm; its refractive index is 1.456, and its surface flatness is less than $\lambda/4$. Twenty concentric open and opaque annuli (N = 20) were formed in an alternating order on one side of the circular plate by the photoresist technique, which is widely used in industrial processes. The circular plate was coated with 0.2-μm-thick chromium through the vacuum evaporation technique; on completion of the coating process, the transparent annuli (or open annuli) were formed by removing the chromium-coated zones by the photoresist technique.

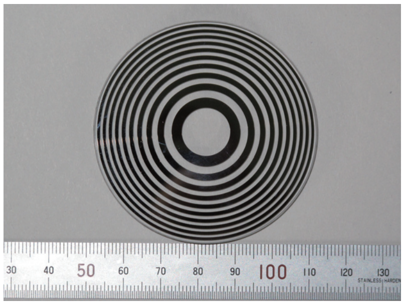

Figure 2. Developed circular Fresnel zone plate.

The concentricity of the annuli to the plate center is within ±10 µm, and the accuracy of the radius of each annulus is within a few µm. The outer radii of the first transparent annulus and the outermost opaque annulus are r_1 = 6.50 mm and r_{20} = 29.06 mm, respectively. The theoretical investigations on the focusing characteristics of the circular FZP have been reported elsewhere [5].

EXPERIMENTAL RESULTS

Depth-of-focus Measurement

The depth of focus of the circular FZP was determined by measuring the intensity distribution of the focused spot on the CCD camera installed at the focal region; the depth of focus was measured as a function of the differential distance dz_2 from the focal point while the distance z_1 was fixed. Here, $dz_2 > 0$ ($dz_2 < 0$) represents a downstream (upstream) direction from the focal point. A neutral density filter is placed in front of the CCD camera to adjust the peak intensity of the focused spot so that it remains within the dynamic range. The peak intensity, peak positions, and widths of the focused spot were obtained by averaging successive data about 100 times on the PC in order to remove the data fluctuations that arise because of any atmospheric fluctuation after the background subtraction procedure. The typical focused spot images obtained at the focal point are shown in fig. 3.

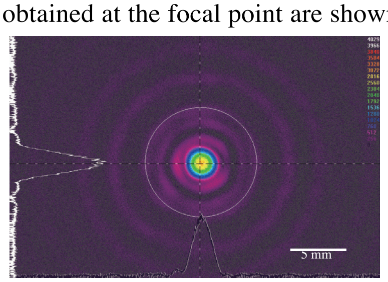

Figure 3: Typical focused spot image measured at the focal point ($dz_2 = 0$).

The widths of the focused spot obtained at the focal point are 3.7 mm and 3.8 mm in the x and y directions, respectively. Here, the spot width is expressed as four times the root mean square (rms) radius obtained in each direction. The results of the depth-of-focus measurement are shown in fig. 4; this figure shows the variations in the width of the focused spot as a function of the distance dz_2.

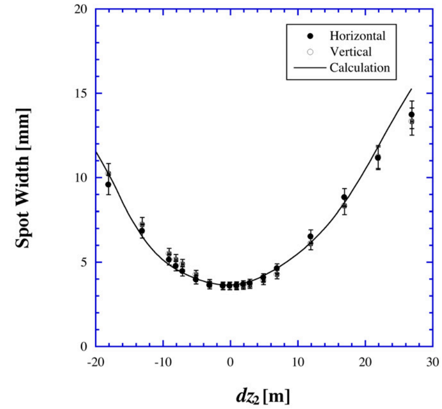

Figure 4: Variations in width (x and y directions) of the focused spot as a function of the distance dz_2. The solid lines indicate the theoretical curve. The vertical and horizontal error bars represent the statistical uncertainties and errors in measurement, respectively.

The experimental results are in good agreement with the theoretical calculations [5]. The depth of focus should be as long as possible so that it can be practically applied in the laser-based alignment technique for long-distance linacs. The results show that the depth of focus obtained is ~27 m (FWHM). These results make the design of the laser-based alignment system viable for our injector linac because the error of the FZP location along the laser axis can be considerably mitigated.

Focusing Characteristics of the FZP

The resolving power of the circular FZP greatly depends on the number of Fresnel zones. It is defined by the spatial resolution of two-point light sources. Rayleigh's criterion can be applied for analyzing the resolving power [6]. Based on Rayleigh's criterion, two images are regarded as just resolved when the central maximum of one image in the diffraction profile is situated at a point corresponding to the first minimum of the other image in the diffraction profile on the image plane. In the optical configuration shown in fig. 1, the diffraction-limited resolving power (δ) obtained using a simple aperture lens with a diameter D is given by [7]

$$\delta = B\frac{\lambda}{2N_A} = B\frac{\lambda z_2}{D}, \tag{1}$$

where N_A is the numerical aperture defined as $N_A = D/(2z_2)$ and B is a constant value given by B = 1.22. On the other hand, eq. (1) may be modified for the case when the diffraction-limited resolving power is calculated using a FZP with the same diameter of D as follows:

$$\delta = B\frac{\lambda z_2}{2r_1\sqrt{N}}, \tag{2}$$

where the relation $D = 2r_N = 2r_1\sqrt{N}$ is used. In this case, it should be noted that the parameter B is not constant but a function of the total number of zones and that it is also related to the resolving power of the FZP.

The experimental investigation on the relation between the resolving power and B could prove the reliability of

Rayleigh's criterion and also validate the measured data. For this purpose, the variations in the focused spot width have been measured as a function of the aperture stop width. The circular aperture stop with a diameter of 70 mm is installed 11 cm upstream from the FZP (fig. 1). The resolving power is defined by the half width of the focused spot based on Rayleigh's criterion, and hence, the measured width data, as a function of the number of zones, could be applied to eq. (2). The obtained result is shown in fig. 5.

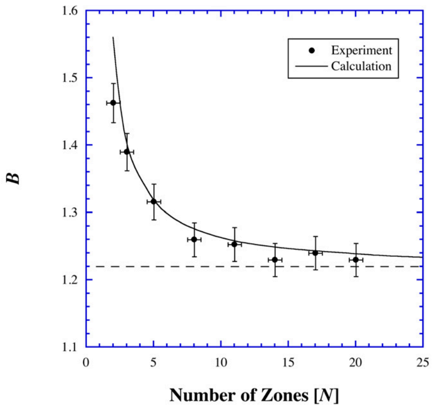

Figure 5: Variations in the parameter B as a function of total number of zones (N). The solid lines indicate the theoretical curve. The dashed line indicates the line where the parameter B = 1.22. The vertical and horizontal error bars represent statistical uncertainties and errors in measurement.

Here, the solid line indicates the theoretical result [5], with which the experimental results are in very good agreement. Moreover, B asymptotically approaches B = 1.22 with the increase in N. This result implies that the parameter B of the circular FZP asymptotically approaches B = 1.22 for a simple aperture lens with the same diameter. Thus, it can be observed that the measured widths of the focused spots are very close to the diffraction-limited widths within the allowable experimental errors.

Responses to Decentering of the FZP

The response to a decentered FZP was investigated by measuring the transverse displacement of the focused spot on the CCD camera as a function of the transverse displacement of the FZP. The result shows that the slope of the fitted line is 2.153±0.004 based on a straight-line fit to the data. On the other hand, the calculated magnification factor of the displacement of the focused spot using the decentered FZP is 2.149, based on the theoretical calculations [5]. Here, the magnification factor (M) can be defined as the ratio of the transverse displacement of the focused spot on the image plane to the transverse displacement of the FZP. The good agreement between the obtained results and the theoretical calculations is within the allowable experimental errors. The measurement precision (or alignment precision) can be obtained from data, which are calculated by subtracting the fitted line (ΔCX_{fit}) from the data (ΔCX_{meas}) in the displacement of peak position and dividing the subtracted data by the magnification factor (M). The obtained result is shown in fig. 6.

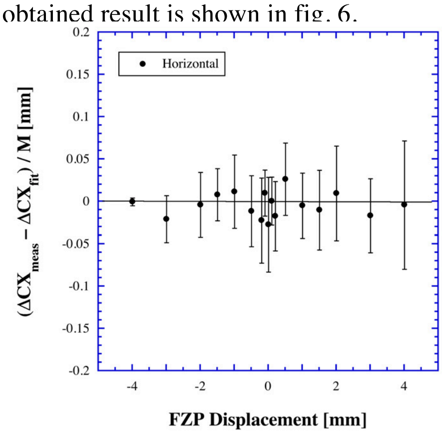

Figure 6: Variations in subtracted data (see text) as a function of the horizontal displacement of FZP. The error bars represent statistical uncertainties.

The precision is within ±30 μm over a horizontal displacement of ±4 mm. Vacuum pipes will be used for the laser propagation in the alignment system of our injector linac, and this vacuum system is expected to further enhance the alignment precision.

SUMMARY

The experimental investigation on the focusing characteristics of a He-Ne laser using the circular Fresnel zone plate with a diameter of 60 mm has been successfully performed at atmospheric pressure. The alignment precision of the FZP target is obtained by an averaging procedure to be within ±30 μm for the laser propagation distance of 268 m. The obtained depth of focus of the FZP is ~27 m in FWHM. From the analysis of the resolving power of the FZP, we inferred that the measured focused spots are nearly diffraction-limited within the allowable experimental errors. The obtained results are encouraging us and highly satisfactory in terms of achieving the expected precision of the laser-based alignment system for the KEKB injector linac.

REFERENCES

[1] M. Masuzawa, *Proceedings of the First International Particle Accelerator Conference (IPAC'10)*, KICC, Kyoto, Japan, 2010, p. 4764.
[2] K. Akai *et al.*, Nucl. Instrum. Methods Phys. Res. A499 (2003) 191.
[3] I. Abe *et al.*, Nucl. Instrum. Methods Phys. Res. A499 (2003) 167.
[4] R. B. Neal (ed.), The Stanford Two-Mile Accelerator (W. A. Benjamin, New York, 1968), p. 821.
[5] T. Suwada *et al.*, to be submitted to Applied Optics.
[6] R. W. Ditchburn, Light (Dover Publications, Inc., New York, 1991), p. 226.
[7] D. J. Stigliani, Jr., R. Mittra, and R. G. Semonin, J. Opt. Soc. Am. 57, 610 (1967).