DEVELOPMENT OF A LASER-BASED ALIGNMENT SYSTEM UTILIZING FRESNEL ZONE PLATES AT THE KEKB INJECTOR LINAC

T. Suwada*, M. Satoh, KEK, Tsukuba, Japan
S. Telada, K. Minoshima, AIST, Tsukuba, Japan

Abstract

A new laser-based alignment system utilizing Fresnel zone plates (FZPs) is under development in order to precisely align accelerator components along an ideal straight line at the KEKB injector linac. We experimentally investigate focusing and propagation characteristics of a He-Ne laser passing through a laser pipe under an effect of the laser reflection and scattering from the inner surface of the pipe at atmospheric pressure. In a case of the large effect, it may cause the reduction of the alignment precision. In this report, the experimental focusing and propagation characteristics of the laser utilizing circular FZPs 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 [1]. The development of alignment techniques is essential for long-distance injector linacs not only for stabilizing the acceleration and transportation of particle beams with higher charge intensities, but also for preserving the beam quality and enhancing the injection efficiency of the beams into the storage rings.

The SuperKEK B-Factory (SuperKEKB) project [2] is the next generation of B-factories under construction at KEK after the KEK B-Factory (KEKB) project [3], which was stopped in 2010. 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 [4] are indispensable to maintaining the injection rate, stability of the beam collision, and peak luminosity as high as possible.

A conventional laser-based alignment technique involving fourfold segmented silicon photodiodes (PDs) has been developed for the 600-m-long injector linac at KEK [5]. This alignment technique has an advantage over other techniques due to its relative simplicity. The suitably focused laser beam is directly detected by a fourfold-segmented photodiode, which measures the gravity center of the intensity distribution in the transverse directions in the alignment measurement. However, this system requires more photodiodes with increasing the length of the linac. In general, since these photodiodes are installed just below the beam line, they may easily suffer heavy damage due to hard radiation during long-term accelerator operation [6]. This is the reason that we develop the new laser-based alignment system with FZPs. This new technique may be practically free and robust from radiation damage even under long-term accelerator operation because it uses FZPs as the optical reference targets in the alignment measurement [7].

However, there are several difficulties to replace our present laser-based alignment system with PDs to the new one. One of main difficulties is that the diameter of a laser pipe is so small that it is not easy to propagate a laser beam with a divergence angle, which needs to propagate in vacuum in order to irradiate the whole transverse area of the FZP. The propagation of such the laser beam may cause unnecessary reflection and scattering from the inner surface of the laser pipe. Moreover, this effect may deteriorate the focusing characteristics of the laser beam, and it may reduce the alignment precision. This is a main reason to investigate the experimental focusing and propagation characteristics of the laser beam with a large divergence angle utilizing circular FZPs at the focal region.

EXPERIMENTAL SETUP

Optical configuration for the laser propagation

Systematic experiments were performed for studying the focusing characteristics and laser propagation in the beam line (sector C) at the KEKB linac [4]. The optical configuration and experimental setup are shown in fig. 1.

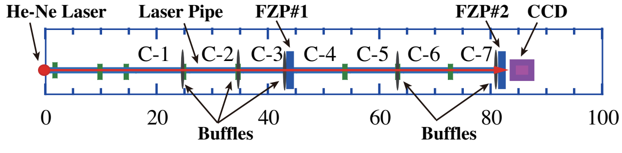

Figure 1: Optical configuration and experimental setup.

A light source is a commercially available 1-mW He–Ne laser having a wavelength of 632.8 nm at atmospheric pressure. The waist position of the laser beam is just out of the laser source and the waist size is ~1.5 mm considering the full width at half maximum (FWHM). The transverse beam size of the laser is expanded with two concave lenses (focal length: *f*=50 mm and *f*=1000 mm) successively mounted on an optical table along with the laser source. The laser beam with a divergence angle

* Corresponding author. *e*-mail address: tsuyoshi.suwada@kek.jp.

of ~1.7 mrad just behind the second concave lens (f=1000 mm) propagates along the beam line through the center of the laser pipe installed 780 mm above the floor level. The laser pipe is made out of stainless steel and the inner surface of the pipe has been coated with a black paint composed of acrylic resin in order to prevent any unnecessary reflection and scattering of the laser beam. In order to keep a similar condition for the laser propagation in vacuum, vacuum windows made out of synthetic quartz have been attached to the inlet and outlet of the beam line, and short pipes with a similar black paint composed of acrylic resin were installed instead of the present PDs after removing them, while the experiment was carried out at atmospheric pressure. In such the optical configuration, the laser beam is fully truncated with a laser pipe (outer diameter: 115 mm) at the location of an intermediate point in unit C-2. Two circular FZPs newly developed with focal lengths of f = 21.46 m and f = 3.63 m have been installed at a distance of L = 43.7 m and L = 82.2 m, respectively, downstream from the laser source. Thus, the laser source can be treated as a point-like source of light at the location of each FZP. The image plane at the focal region is located at a distance of L = 86 m. Five buffles with an inner diameter of 100 mm have been also installed in order to prevent any unnecessary reflection and scattering of the laser beams along the beam line (see Fig. 1). A commercially available silicon charge-coupled-device (CCD) camera [Ophir, USB L11058 [8]] has been used for measuring a two-dimensional intensity distribution of the focused spot at the image plane. The camera can scan a two-dimensional area of 36 × 24 mm^2 with the effective number of pixels of 4008 × 2672, and it can record the image profiles at a speed of ~2 Hz with a 12-bit resolution. The spatial resolution of the acquired images is estimated to be 111 pixels/mm in both the directions. The intensity distribution of the focused image is measured in real time on a Windows-based personal computer (PC). A series of parameters of the focused spot image, the peak intensity, peak positions, and widths are also calculated on the PC. These parameters are obtained on the basis of a least-square fitting procedure with a two-dimensional Gaussian function for the intensity distribution.

Developed Fresnel zone plate

A Soret-type FZP has been developed for use as an alignment target in this experiment. This FZP is composed of a radiation-hard circular glass plate made out of synthetic quartz with a 0.1-μm-thick antireflective (AR) coating to reduce any reflection. The glass plate has a diameter of 60 mm and a thickness of 4 mm; its refractive index is 1.456; a parallelism between both end faces of the glass plate is less than 1 μrad, and its surface flatness is less than λ/4 within the central 80% area. One side surface of the glass plate is vapor-deposited with 0.2-μm-thick chromium based on magnetron sputter deposition. Twenty concentric open and opaque annuli patterns (N = 20) have been formed in an alternating order on the side of the glass plate by a standard photolithographic technique. This fabrication technique is described elsewhere in detail [6].

EXPERIMENTAL RESULTS

Propagation and focusing characteristics of the laser beam

The laser beam propagates in total length of L = 86 m through the laser pipes along the beam line at atmospheric pressure, while the intensity center of the beam was not definitely adjusted to the pipe center in order to study the laser reflection and scattering from the inner surface of the laser pipe. Figure 2 shows a photo-picture of the inner surface of the laser pipe viewed upstream from the location at the distance of L = 13.385 m after removing another downstream pipe.

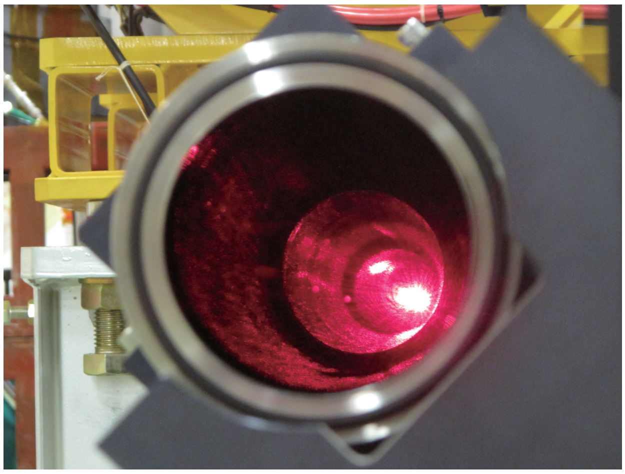

Figure 2: Photo-picture of the inner surface of the laser pipe viewed upstream from the location at the distance of L = 13.385 m.

Although the inner surface of the laser pipe has been coated with a black paint composed of acrylic resin, we can clearly see sprinkled speckles due to the laser scattering. This may show roughness of the inner surface with the black paint. After restoring the laser pipe to the beam line, the laser images were taken with the CCD camera without any FZPs at the end of unit C-7. The dynamic range of the camera was adjusted with neutral density filters mounted in front of the camera. The obtained images are shown in fig. 3. Figure 3(a) shows the image without any buffles along the beam line, and however, fig. 3(b) shows the image after installing the five buffles.

We can clearly see two lines (blue) produced by the laser scattering (see fig. 3(a)) and also see interference fringes along with sprinkled speckle patterns. However, after installing the buffles, it is easily understood that these two lines clearly are disappeared by aperture stops based on the buffles, and the brightness of the interference fringes is also effectively reduced. In this measurement, the five buffles were installed along the beam line one-by-one. We confirmed the gradual intensity reduction for these two lines. This means that relatively hard scattering of the laser beam with a shallow angle to the inner surface of the laser pipe was produced. On the other hand, the sprinkled speckle patterns did not change even after installing the buffles. This means that the laser hallo might be truncated by the pipe diameter due to the relatively weak scattering.

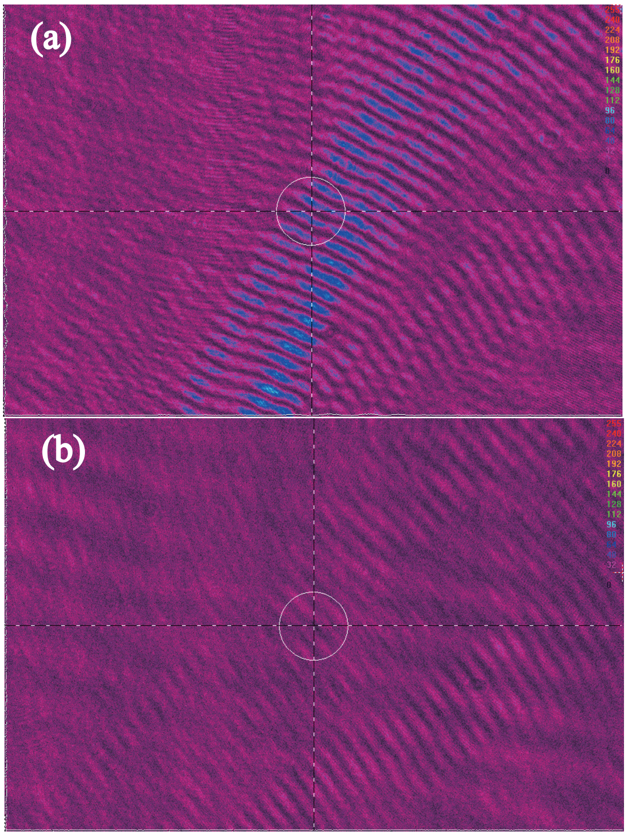

Figure 3: Typical background images of the laser beam (a) without any buffles and (b) with five buffles obtained at the focal region without any FZPs. In this measurement, the gain of the CCD camera was set to be 16 dB.

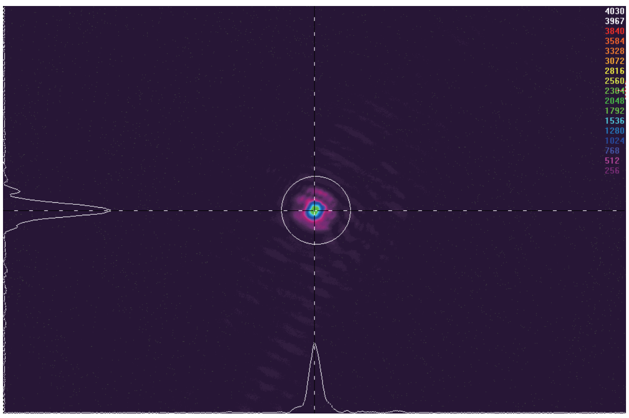

Figure 4: Typical focused spot image of the laser beam with the FZP2 obtained at the focal region. The solid circle (white) with a diameter of 5 mm indicates the analyzed area, and the solid lines (white) indicate the projected intensity distributions in the horizontal (x) and vertical (y) directions. The gain of the CCD camera was set to be 1 dB.

The focused spot images for the FZP1 and FZP2 were clearly obtained at the focal region. The spot widths (4-σ size) for the FZP1 (FZP2) were measured to be $W_x \sim$ 1.64 (0.38) mm and $W_y \sim$ 1.43 (0.38) mm, which are consistent with calculations. Figure 4 shows the focused spot image obtained for the FZP2. After the gain correction calculation of the camera, the signal-to-noise (S/N) ratio of the peak intensity in the intensity distribution is ~ 39 (~ 63) for the FZP1 (FZP2). In this measurement, after the insertion of the vacuum glass windows, the background levels without any FZPs were much the same, while the focused spot width became slightly wider and the peak intensity was also slightly reduced.

Based on these measurements, the background levels of the laser beam could be sufficiently suppressed without disturbing the intensity distribution of the focused spot image with adequate S/N ratio required for the alignment measurement. In actual optical setup, since the vacuum condition in the laser pipes is adequately kept, it is expected for further brightness increase in the peak intensity of the laser beam.

SUMMARY

Systematic experimental investigation on the focusing and propagation characteristics of a He–Ne laser using circular Fresnel zone plates has been successfully performed at atmospheric pressure.

When the laser beam with a divergence angle of 1.7 mrad propagates through the laser pipe along the beam line, the scattering and reflection of the laser beam from the inner surface of the pipe occur, and however, it is understood that they can be sufficiently reduced with the use of several buffles. However, it is difficult to fully remove sprinkled speckles produced by the laser scattering, which may indicate the surface roughness of the laser pipe coated with a black paint composed of acrylic resin.

REFERENCES

[1] See http://www-group.slac.stanford.edu/met/IWAA/IWAAProceedings.html for the past proceedings of the International Workshop on Accelerator Alignment (IWAA).

[2] M. Masuzawa, *Proceedings of the First International Particle Accelerator Conference (IPAC'10)*, KICC, Kyoto, Japan, 2010, p. 4764.

[3] K. Akai *et al.*, Nucl. Instrum. Methods Phys. Res. A499 (2003) 191.

[4] I. Abe *et al.*, Nucl. Instrum. Methods Phys. Res. A499 (2003) 167.

[5] T. Suwada *et al.*, Rev. Sci. Instrum. 81, 123301 (2010).

[6] T. Suwada *et al.*, Rev. Sci. Instrum. 83, 053301 (2012).

[7] R. B. Neal (*ed.*), The Stanford Two-Mile Accelerator (W. A. Benjamin, New York, 1968), p. 821.

[8] See http://www.ophiropt.com for Ophir Optronics.