NEW LASER-BASED ALIGNMENT SYSTEM FOR THE 500-M-LONG KEK ELECTRON/POSITRON INJECTOR LINAC

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Abstract

A new laser-based alignment system is under development. This system is strongly required in the next generation of B-factories for the stable acceleration of high-brightness electron and positron beams with high bunch charges and also for maintaining the stability of injection beams with higher quality. A new laser optics technique for the generation of so-called Airy beams has been developed for this laser-based alignment system. The laser propagation experiment has been performed at atmospheric pressure in a 120-m-long straight line in the accelerator tunnel. In this report, the basic design of the new optical system along with the experimental results is described in detail.

INTRODUCTION

The KEK B-Factory (KEKB) project [1] is in progress for testing CP violation in the decay of B mesons at KEK. The KEKB is an asymmetric electron-positron collider comprising 3.5-GeV positron and 8-GeV electron rings. Since KEKB is a factory machine, a well-controlled operation and also a precise alignment for the injector linac is required to maintain the injection rate, stability of the beam collision, and peak luminosity as high as possible.

An optical alignment system with a high-precision telescope is generally used for relatively short-distance (<100 m) linacs; however, alignment measurements with a resolution of ±0.1 mm level cannot be easily performed for long-distance (>100 m) linacs. A laser-based alignment technique is advantageous as it cannot only be applied to alignment measurements for long-distance linacs but it can also be used for regular monitoring of the straightness without any interruption during linac operation. After considering the previous alignment system, we have been proceeding with experimental studies to develop a new laser-based alignment system. In particular, we aim to develop a new laser source along with an optical system for stable propagation of lasers with axially symmetric Airy beams that are generated using two successively aligned circular apertures. An Airy beam is a useful and practical optical source in the laser-based alignment for long distance [2]. Experimental studies have been systematically performed for testing the laser propagation with Airy beams in atmosphere on the basis of the new laser-based alignment system.

LASER-BASED ALIGNMENT OVERVIEW

In this section, we briefly describe the injector linac for a clearer understanding of the laser-based alignment system. A schematic layout of the KEKB injector linac has been provided elsewhere [3]. The linac comprises eight sectors (A–C and 1–5) which together constitute two long straight sections. One straight section is 125 m long and is composed of sectors A and B; the other is 476 m long and is composed of sectors C and 1–5. These two straight sections are connected to a 180° arc section with a circumferential length of 31 m.

A typical sector with a length of 76.8 m comprises eight accelerator units, each with a length of 9.6 m. The accelerator unit structure has been described in detail elsewhere [4]. In a typical accelerator unit, an 8.44-m-long accelerator girder is installed on the floor level in the accelerator tunnel; four 2-m-long S-band accelerating structures are mounted on the accelerator girder. Quadrupole magnets for beam focusing are basically installed on a special magnet girder between two adjacent accelerator units. The accelerator girder is composed of an earthquake-resistant, stainless-steel cylindrical tube (outer diameter: 508 mm) and L-shaped plates connected to both ends of this cylindrical tube; this girder supports the entire weight of the accelerator unit. The four accelerating structures are mounted on five separate stainless-steel plates fixed on the accelerator girder and are aligned within a standard mechanical precision (±50 μm) by reference guide rails fixed on the plates. The electron and positron beams pass through the center holes of the accelerating structures mounted 1.2 m over the floor level. A cylindrical laser pipe made of stainless steel (inner diameter: 115 mm) is welded to the upper inner surface of the girder tube. Such a coaxial structure was originally designed in order to reduce convective air flow caused by any temperature variation and fluctuation in the accelerator tunnel. A laser beam passes through the center of the laser pipe installed 780 mm over the floor level.

OPTICAL SYSTEM

A laser source with a laser diode coupled with an optical fiber has been developed in this experiment. The laser beam is focused on the cross-sectional area of a single-mode optical fiber (diameter: 3.5 μm) through an aspheric lens with a diameter of 4.7 mm. The effective focal length of the aspheric lens is 2.95 mm. The maximum output power (CW) of the laser diode with a wavelength of 660 nm is 120 mW. In such a coupling scheme, the transmission efficiency of the laser beam has been approximately 20%. The laser beam is transmitted to an optical system, which delivers the laser beams with the suitable beam sizes required for the alignment measurement.

The complete mechanical drawing of the optical system is shown in Fig. 1 (a). The optical system comprises a spherical reflective mirror and a plane mirror that can be coupled with an optical fiber cable. The spherical reflective mirror is aluminum-coated and has a diameter of 152.4 mm, a wavefront aberration of $\lambda/4$, and an effective focal length of 152.4 mm. The plane mirror is composed of quartz and has a thickness of 6 mm and diameter of 90 mm. Dielectric multilayers with a thickness of 2 µm are evaporated in vacuum on the reflection surface of this plane mirror. Its reflectance is greater than 99.5% at 660 nm, and its wavefront aberration is $\lambda/2$. The plane mirror has a circular aperture (diameter: 1 mm) for the laser beam injection and is inclined by 45° with respect to the laser axis.

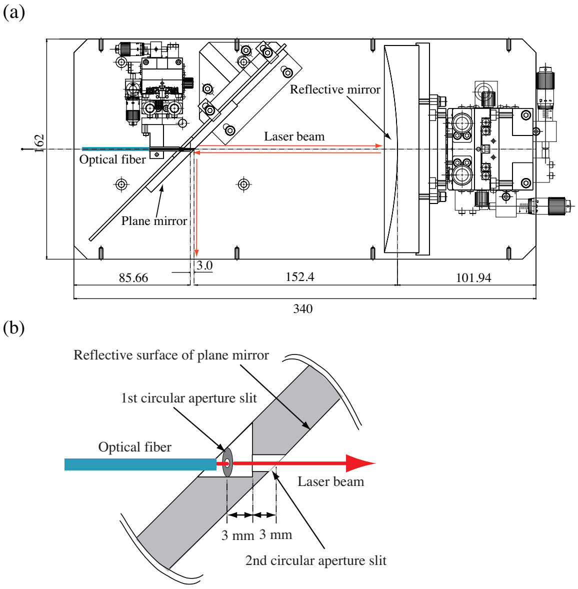

Figure 1: Optical system with two reflective mirrors. (a) Mechanical drawing of the optical system and (b) the enlarged drawing (not scaled) of the central portion of the plane mirror.

Figure 1 (b) shows the enlarged schematic drawing of the central portion of the plane mirror. The laser beam is ejected from the fiber end with a numerical aperture of 0.1 and is transmitted through the first circular aperture slit (diameter: 10 µm) fixed 0.1 mm behind the end of the fiber. Such optical configurations transform the Gaussian laser beam into a beam with the well-known Airy patterns. The laser beam is completely diffracted, and thus, it has the center spot (Airy disc) with causing diffraction fringes. The second circular aperture slit may generate a so-called Airy beam without any diffraction fringes because this slit truncates such fringes and retains the central Airy disc. This Airy beam is then transmitted to the spherical reflective mirror, which suitably expands the beam sizes as per requirements in the alignment measurements; these expanded beams are reflected to the plane mirror. The beam sizes are determined on the basis of the transmission length between the centers of the reflective and plane mirrors under the condition of a fixed focal length. The laser beam is reflected by the plane mirror, and this collimated laser beam is delivered to the central positions of the laser pipe. The laser power delivered by the plane mirror is ~1 mW, while the laser power injected into the optical system is ~14 mW. The total transmission efficiency of the laser power has be obtained to be ~1%.

LASER-PROPAGATION EXPERIMENT

A laser beam propagation experiment was performed at atmospheric pressure along a 120-m-long straight line in the accelerator tunnel. In order to adjust the laser optics, the laser beam was focused from the optical system down to a waist point, and symmetrically expanded again over the distance of 120 m.

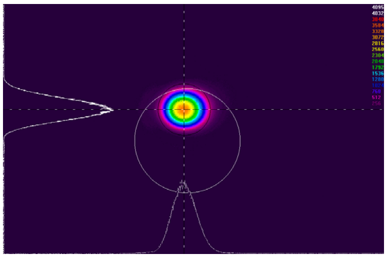

Figure 2: Laser profile obtained at a distance of 60 m away from the laser source.

The beam sizes were measured using a CCD camera along the line at intervals of 20 m from the laser source. Figure 2 shows a typical laser profile obtained at 60 m, which is close to the waist point. Figure 3 shows the variations in the horizontal and vertical beam sizes as a function of the distance from the laser source.

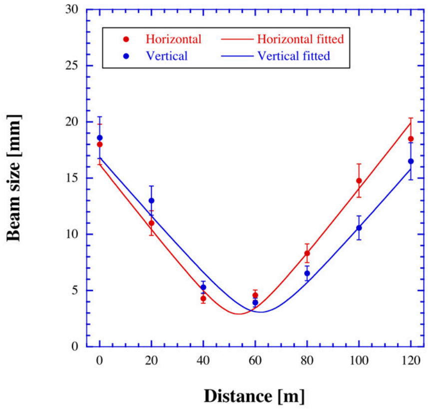

Figure 3: Variations in the horizontal and vertical beam sizes as a function of the distance from the laser source.

It can be observed that the horizontal and vertical variations in the beam sizes along the line are slightly asymmetric. This may be due to the insufficient angular adjustment of the spherical reflective mirror.

LASER-PROPAGATION ANALYSIS

The obtained results are analyzed on the basis of a least-squares fitting procedure with well-known Gaussian laser optics [5] as

$$\omega = \omega_0 \sqrt{1 + \left(\frac{z - z_0}{z_R} \right)^2}, \qquad (1)$$

where ω is the beam size at each location depending on the distance (z) from the laser source; ω_0, the beam size at the waist point ($z = z_0$); and z_R, the Rayleigh length. The results show that at the waist points that are 53.7 m and 62 m away from the laser source, the horizontal and vertical beam sizes are 2.9 mm and 3.1 mm, respectively. In addition, the Rayleigh lengths in the horizontal and vertical directions are 9.8 m and 11.5 m, respectively. The observed values are in good agreement with those obtained by numerical analyses.

This optical system generates an Airy beam, which is a Gaussian beam that is truncated after it passes through the two successively aligned aperture slits. The optical configuration is shown in Fig. 4. In this section, we briefly discuss the dependence of the Fresnel number (F) on the propagation distance along the laser axis; this dependence is owing to the fact that after the Airy beam passes through the second slit, it becomes a truncated Gaussian beam and is then focused by a thin lens with a focal length of f at an observation point (m). It should be noted that the physical meaning of the Fresnel number gives the number of Fresnel zones contributing to the diffraction fringe pattern at the observation point.

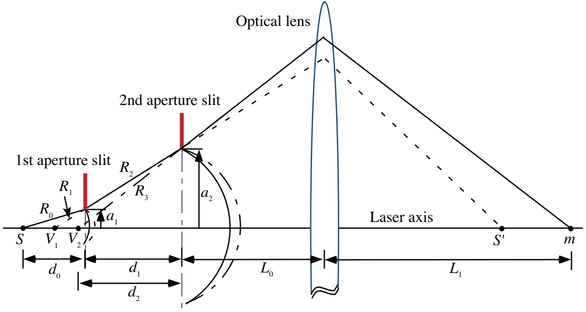

Figure 4: Schematic of the laser propagation with diffractions in an optical configuration with two aperture slits and a thin lens.

The laser beam generated at the source (S) is diffracted at the first aperture slit that has a radius of a_1. The solid line indicates the diffracted wave, while the dashed line indicates the wave passing through the first slit without diffractions; the virtual source point for the latter is at V_1. It is again diffracted at the second aperture slit that has a radius of a_2. The solid line indicates the diffracted wave for which the virtual source point is at V_2, while the dashed line indicates the wave without diffractions. Thus, the wave originates at V_1 and is focused at S' by the lens, while the diffracted wave originates at S and is focused at m. The Fresnel number subtended at m is derived by calculating the difference (Δ) of the pass lengths with and without diffractions as follows:

$$\Delta = F(\lambda / 2), \tag{2}$$

By extending the theoretical analysis described in ref. [6], the Fresnel number in this optical system is given by

$$F = \frac{a_1^2}{\lambda}\left(\frac{1}{d_0} - \frac{a_2}{a_1 d_1}\right) + \frac{a_2^2}{\lambda}\left(\frac{1}{d_1} - \frac{1}{d_2}\right). \tag{3}$$

Here,

$$d_2 = \frac{1 - L_0\left(1/L_1 + 1/f\right)}{\left(1/L_1 + 1/f\right)}. \tag{4}$$

The first (second) term in eq. (3) indicates the contribution of the first (second) aperture slit to the Fresnel number.

Figure 5 shows the variations in the Fresnel number calculated in the horizontal and vertical directions as a function of the propagation distance from the laser source. The parameters, $\lambda = 660$ nm, $a_1 = 5$ µm, $a_2 = 0.5$ mm, $d_0 = 0.1$ mm, $d_1 = 6$ mm, and $L_0 = 146.76$ mm ($L_0 = 146.71$ mm) have been applied to the calculations in the horizontal (vertical) direction. The parameters, L_0, have been estimated in the numerical simulations on the basis of the results shown in Fig. 3.

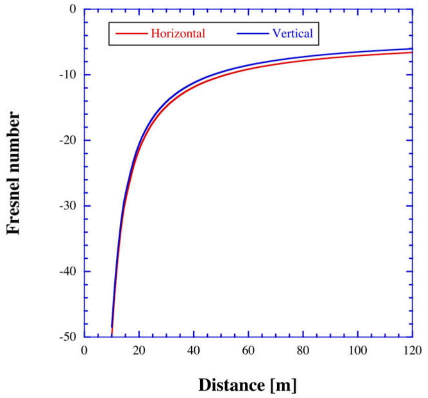

Figure 5: Variations in the Fresnel number calculated in the horizontal and vertical directions as a function of the propagation distance.

The results show that the Fresnel numbers obtained are not very small; that is, $|F| \gg 1$ over the propagation distance. However, the diffraction pattern fringes of the obtained profiles are not very large. The experimental results may indeed indicate stable propagation characteristics of Airy beams.

SUMMARY

We have successfully applied a new optical system to the laser-based alignment system at the KEKB injector linac. The experimental results show that an Airy beam has been stably generated from the new optical system. The propagation characteristics at atmospheric pressure have been investigated, and a good applicability of the Airy beam has been confirmed in this experiment. The present result encourages us to consider the application of the laser-based alignment system to the next generation of B-factories.

REFERENCES

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

[2] S. Wang, Q. Lin, D. Zhao, and Q. Chen, Optics and Laser Technology, 31 (1999) 437.

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

[4] T. Suwada *et al.*, to be submitted to Rev. Sci. Instr.

[5] A.E. Siegman, *Lasers* (University Science Books, California, 1986), p.777.

[6] R.G. Wenzel *et al.*, J. Opt. Soc. Am. A 3(6) (1986), 838.