LASER-BEAM PROPAGATION CHARACTERISTICS IN NEW LASER-BASED ALIGNMENT SYSTEM AT THE KEKB INJECTOR LINAC

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Abstract

A new laser-based alignment system for the precise alignment of accelerator components along an ideal straight line at the KEKB injector linac 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 high quality. New laser optics for the generation of Airy beam has been developed for the laser-based alignment system. The laser propagation characteristics both in vacuum and at atmospheric pressure have been systematically investigated in an 82-m-long straight section of the injector linac. The results are analyzed by numerical calculations based on Gaussian spherical wave optics with a fundamental mode in free space. The experimental results are in good agreement with the numerical ones. In this report, we describe the laser-beam propagation characteristics in the new laser-based alignment technique.

INTRODUCTION

A precise alignment of accelerator components along an ideal straight line is essential for constructing long-distance injector linacs because it enhances the beam quality, and increases the stability of injection beams during acceleration and transportation, and also maintains high injection efficiency in storage rings.

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 cannot be easily performed for long-distance (> 100 m) linacs. A laser-based alignment technique is advantageous as it can not only be applied to alignment measurements for long-distance linacs but it can also be used for regular monitoring of straightness of the linac without any interruption during a linac operation.

Research and development (R&D) studies for the reconstruction of the alignment system in the next generation of B-factories commenced in 2009. One of the aims of these studies is the development of a new alignment system for the Super B-factory project [1]. In these studies, the laser-based alignment system was reconsidered and we have been proceeding with experimental studies of the new laser-based alignment system. In particular, we are developing a new laser source with an optical system for stable propagation of a laser with axially symmetric Airy beams that can be generated using two adjacently aligned circular apertures. It is a useful and practical optical beam in the laser-based alignment measurement for long distance [2]. The experimental studies along with numerical calculations have been systematically performed for testing the laser propagation with Airy beams in vacuum.

LASER SOURCE AND THE OPTICAL SYSTEM

We developed a laser source with a laser diode (Mitsubishi Electric, ML101J27) coupled to an optical fiber. Because owing to the increase in the beam charges and energies of the injector linac, it is difficult to avoid radiation damage to a laser source if it is installed on the floor level of the accelerator tunnel. The laser beam is focused on the cross-sectional area of a single-mode optical fiber (core diameter: 3.5 μm) through an aspheric lens (diameter: 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 (λ) of 660 nm is 120 mW. In such a coupling scheme, the maximum transmission efficiency of the laser beam has been approximately 20%.

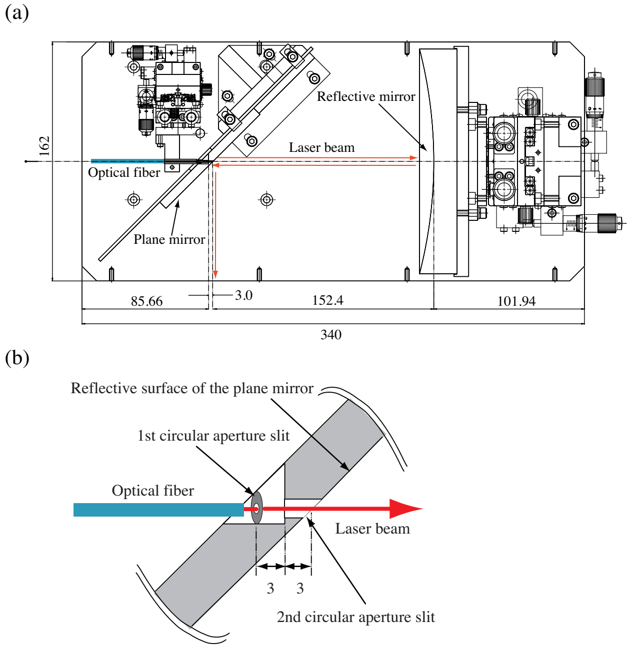

Figure 1: Optical system with two reflective mirrors. (a) Mechanical drawing of the optical system and (b) the enlarged schematic drawing (not scaled) of the central portion of the plane mirror. The length is indicated in millimeters.

The laser beam is transmitted to an optical system, which delivers it after expanding the beam sizes required for the alignment measurement. The laser diode delivers a laser beam with a nominal power of ~108 mW; laser beam is transmitted to an optical system connected to a

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single-mode optical fiber. 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 two mirrors are rigidly fixed on an aluminum plate with lateral dimensions 162 mm × 340 mm and thickness 10 mm. 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 λ = 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 (b) shows the enlarged schematic drawing of the central portion of the plane mirror.

The laser beam is injected into the optical system after being delivered from one end of another 50-cm-long single-mode optical fiber, another end of which is connected to the optical fiber by means of a fiber connector. 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) made from a washer with a thickness of 0.1 mm. Such optical configurations transform the laser beam into a beam with well-known Airy patterns. The laser beam is completely diffracted, and thus, it has the center spot (Airy disc) with causing diffraction fringes (so-called Airy beam). The Airy beam with Airy patterns is truncated at the first dark fringe by the second circular aperture slit of the plane mirror. Such an optical truncation technique can be used to generate an Airy beam without any diffraction fringes (*i.e*., Airy disk) even in a far field region because a truncated Airy beam has a non-diffraction property [2].

The truncated Airy beam is then transmitted to the spherical reflective mirror. The spherical reflective mirror suitably expands the beam sizes in accordance with the alignment measurements; the expanded beam is reflected by 90° with respect to the laser axis at the plane mirror. The beam sizes are determined by the transmission distance between the centers of the spherical and plane mirrors under the condition of the fixed focal length of the spherical mirror. The collimated laser beam is delivered to the center positions of the laser pipe. The laser power at the plane mirror is $\sim$1 mW while the laser power injected into the optical system is $\sim$14 mW. The total transmission efficiency of the laser power is obtained to be $\sim$1%.

EXPERIMENTAL SETUP

The laser-beam propagation characteristics have been investigated in sector C of the injector linac, where the laser-based alignment experiments have been also carried out (see [3] in detail). The total length of the laser propagation is 82 m, while the total length of seven accelerator units in this beam line is approximately 66 m. Figure 2 shows a schematic drawing of the experimental setup along with the new vacuum system that is under development.

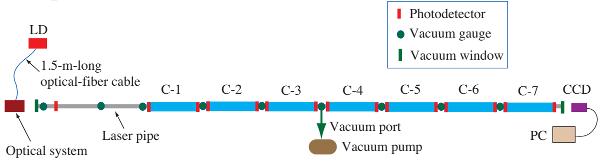

Figure 2: Setup of the laser-based alignment experiment.

The laser pipes penetrating till the end of unit C-7 have been evacuated for stable laser propagation. The total volume of the laser pipes is 847.2 *l*. A vacuum port is attached to the center of the laser pipe between units C-3 and C-4 in the vertical direction. This vacuum port is connected to an oil-free scroll pump that has a pumping speed of 1000 *l*/min. Nine Pirani gauges are distributed at almost regular intervals up to the end of unit C-7.

An inlet (outlet) vacuum window with a relatively high radiation hardness is used for laser injection (ejection) from atmosphere (vacuum) to vacuum (atmosphere) with a transmittance of $\sim$95% at λ = 660 nm. These windows are composed of synthetic quartz. The inlet and outlet windows are 20 mm and 15 mm thick, respectively. A silicon CCD camera has been installed just behind the outlet vacuum window in order to measure laser profiles and to monitor the propagation stabilities.

EXPERIMENTAL RESULS

Beam-size measurements

Since it is difficult to measure the beam sizes at each PD location in vacuum, they have been measured along the beam line at intervals of 20 m from the laser source at atmospheric pressure. On the other hand, they have been measured at the end of unit C-7 in vacuum. Figure 3 shows the variations in the horizontal and vertical beam sizes as a function of the distance from the laser source.

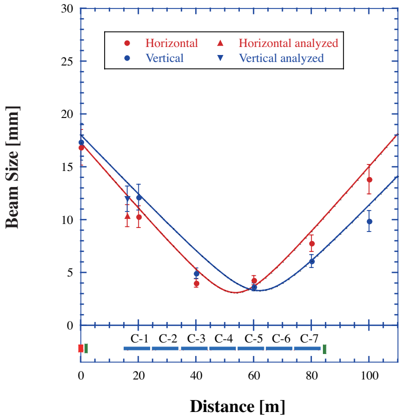

Figure 3: Variations in the horizontal and vertical beam sizes as a function of the distance from the laser source. The plotting of the analyzed beam sizes obtained in the calibration procedure is shown with the up and down triangles. The solid lines indicate the numerical results.

In Fig. 3, the analyzed beam sizes are simultaneously plotted; these beam sizes have been obtained in the calibration procedure in vacuum with a movable PD installed at the location in front of unit C-1 (see [4] in detail). The beam sizes measured at atmospheric pressure have been calibrated to those in vacuum by normalizing them using the beam sizes measured at the end of unit C-7 and those obtained in the calibration procedure in vacuum. Thus, it should be noted that the corrected beam sizes in vacuum are plotted in Fig. 3.

The laser propagation optics has been tuned in such a way that the laser beam is focused from the optical system down to a waist point and then symmetrically expanded over a distance of 120 m. The solid lines indicate the numerical results described in the following section. Although the stable laser propagation could be performed, it can be found that the variations in the beam sizes along the laser axis are slightly asymmetric in the horizontal and vertical directions. This may be owing to insufficient angular tunings of the spherical mirror.

NUMERICAL CALCULATIONS

Numerical calculations to investigate the laser propagation characteristics can be carried out according to Gaussian spherical wave optics based on paraxial approximation of ray optics shown in Fig. 4.

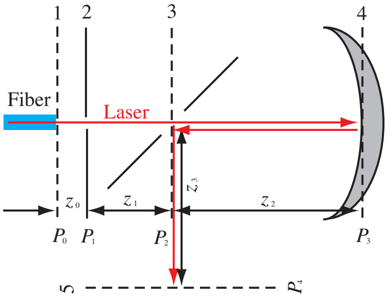

Figure 4: Laser propagation optics for numerical calculations. 1 (fiber exit), 2 (1st aperture slit, radius a_0), 3 (2nd aperture slit of the plane mirror, radius a_1), 4 (reflection mirror), 5 (observation point).

The transverse field distribution of a Gaussian beam can be analytically expressed in vacuum at the fiber exit (P_0) where the beam waist is approximately made up. The normalized field distribution ($\tilde{u}_0$) with one transverse dimension (x) propagating up to the axial distance ($z<z_0$=10 μm) away from the fiber exit is given by [5]

$$\tilde{u}_0(x_0,z)=\sqrt{\frac{2}{\pi}}\frac{\exp[-jkz+j\psi(z)]}{w(z)}\exp\left[-\frac{x_0^2}{w^2(z)}-jk\frac{x_0^2}{2R(z)}\right], \quad (1)$$

where R is the radius of the spherical wave, k the wave number, $w(z)$ the beam size, $\psi(z)$ the axial phase shift. These parameters are given in the following:

$$w(z)=w_0\sqrt{1+\left(\frac{z-z_0}{z_R}\right)^2},\ R(z)=z+\frac{z_R^2}{z},\ \psi(z)=\tan^{-1}\left(\frac{z}{z_R}\right). \quad (2)$$

Here w_0 and z_R are the beam size at the fiber exit and the Rayleigh length, respectively. The Rayleigh length is related to the waist size with a relation $z_R=\pi w_0^2/\lambda$.

The normalized field distribution at the point P_2 is given with a transfer matrix from P_1 to P_2 as follows [5]:

$$\tilde{u}_2(x_2,z_1)=\sqrt{\frac{j}{B\lambda}}\int_{-a_0}^{a_0}\tilde{u}_0(x_0,z_0)\exp\left[-j\frac{\pi}{B\lambda}(Ax_0^2-2x_0x_2+Dx_2^2)\right]dx_0, \quad (3)$$

where a_0 is the truncation radius of the first aperture slit, and the transfer matrix is expressed by

$$\begin{pmatrix} A & B \\ C & D \end{pmatrix}=\begin{pmatrix} 1 & z_1 \\ 0 & 1 \end{pmatrix}. \quad (4)$$

Here the drift lengths are $z_0 = 0.1$ mm and $z_1 = 6$ mm. Thus, at the observation point P_5, the field distribution is also expressed with similar transfer matrices,

$$\tilde{u}_5(x_5,z_3)=\sqrt{\frac{j}{B\lambda}}\int_{-a1}^{a_1}\tilde{u}_2(x_2,z_1)\exp\left[-j\frac{\pi}{B\lambda}(Ax_2^2-2x_2x_5+Dx_5^2)\right]dx_2, \quad (5)$$

where a_1 is the truncation radius of the second aperture slit, and the transfer matrix is expressed by

$$\begin{pmatrix} A & B \\ C & D \end{pmatrix}=\begin{pmatrix} 1 & z_3 \\ 0 & 1 \end{pmatrix}\begin{pmatrix} 1 & z_2 \\ 0 & 1 \end{pmatrix}\begin{pmatrix} 1 & 0 \\ -2/R_e & 1 \end{pmatrix}\begin{pmatrix} 1 & z_2 \\ 0 & 1 \end{pmatrix}. \quad (6)$$

We use an approximation with effective focal length $R_e/2$ (R_e=304.8 mm) for the reflection mirror. Any effects caused by the aperture of the plane mirror for the reflected laser beam and the two slit widths are neglected for the sake of simplicity.

The transverse beam size in 4σ can be analyzed by fitting the calculated field distribution with a Gaussian function, where the drift length z_2 is analyzed as a fitting parameter independently for each transverse direction. The results are shown in Fig. 3 (solid lines). At the waist points, which are 53.7 m and 62.0 m away from the laser source, the horizontal and vertical beam sizes are 2.9 mm and 3.1 mm, respectively. 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 the numerical results.

SUMMARY

We have applied a new optical system to the laser-based alignment system at the KEKB injector linac. An Airy beam has been stably generated from the new optical system, and the propagation characteristics in vacuum and at atmospheric pressure have been investigated. A good applicability of the Airy beam was confirmed in this experiment. With this experiment, we obtained useful technical information concerning the laser propagation and proper optical-lens configurations.

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