RECENT PROGRESS OF A LASER-BASED ALIGNMENT SYSTEM AT THE KEKB INJECTOR LINAC

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Abstract

A laser-based alignment system with the use of a He-Ne laser has been newly developed in order to precisely align accelerator units at the KEKB injector linac. The laser beam has been first implemented as a 500-m-long fiducial straight line for the alignment measurements. We experimentally investigated the propagation and stability characteristics of the laser beam passing through laser pipes in vacuum. The pointing stability of the laser beam at the fiducial end point has been successfully obtained with the transverse displacements of ±40 μm level in one standard deviation by applying a feedback control. The pointing stability corresponds to the angle stability of ± 0.08 μrad. In this report, the experimental investigation on the laser-based alignment system is in detail summarized.

INTRODUCTION

The Super KEK B-Factory (SuperKEKB) project [1] is a next generation B-factory under construction at KEK after the KEK B-Factory (KEKB) project [2], 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 in the accelerator complex are indispensable to maintaining the injection rate, stability of the beam collision, and peak luminosity to keep 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 cannot be easily performed for long distance (> 100 m) linacs. A laser-based alignment technique (see, for example, [3]) is advantageous as it can not only be applied to alignment measurements for long-distance linacs but can also be used for regular monitoring of straightness of the linac without any interruption during the operation.

A conventional laser-based alignment technique involving quadrature photodiodes (QPDs) with silicon semiconductor has been developed for the 600-m-long injector linac at KEK, while the original system was constructed in the KEK electron injector linac more than 30 years ago. The alignment technique has an advantage over other techniques because a long-distance fiducial straight line could be more definitely implemented. For this purpose, the implementation of highly pointing-stabilized laser beam is a challenge for high-precision alignment measurements for long-distance linacs.

LASER-BASED ALIGNMENT SYSTEM

KEKB injector linac

The KEKB injector linac [4] is a 600-m-long linear accelerator in total that directly injects electron and positron beams into the KEKB rings. It comprises eight sectors with a typical length of 76.8 m. There are two long straight sections for which one is 125-m-long comprised by two sectors (AB), and the other is 476-m-long comprised by six sectors (C5). They are connected to an 180° arc section with a circumferential length of 31 m. A typical sector comprises eight accelerator units, each having a length of 9.6 m. In the accelerator unit, an 8.44-m-long girder is installed on the floor level in the tunnel; four 2-m-long S-band accelerating structures are mounted on this girder. Quadrupole magnets for beam focusing are installed on special girders between two adjacent accelerator units.

Alignment system overview

Two independent laser-based alignment systems have been installed in which one is for the alignment of the AB straight section, and the other is for that of the C5 [5]. Two laser sources with commercially available 1-mW and 10-mW He–Ne lasers in the AB and C5 straight sections, respectively. Here, although only the alignment system of the C5 straight section is described, that of the AB is very similar except for the different distance. The laser source has been installed 16 m upstream from unit C-1. The propagation length of the laser beam is 500 m in total along the straight section. The optical system is mounted on an optical table in an atmospheric environment, while the laser pipes made out of stainless steel (outer diameter: 115 mm) are evacuated with the use of two scroll pumps with a pumping speed of 1000 *l*/min. The vacuum level can be attained to ~3 Pa. A QPD holder is precisely connected to both ends of the accelerator unit through a vacuum flange; a QPD is mounted at the center of the holder. The inner surface of the laser pipe is coated with a black paint composed of acrylic resin in order to prevent any unnecessary reflections and scatterings of the laser beams. The forty-eight accelerator units, with both regular and irregular lengths, are distributed along the straight section; these units need to be aligned along the fiducial straight line based on the laser beam. The propagation orbit should be adjusted in order to make straight as

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precisely as possible without any diffractions and instabilities.

The alignment measurements of the units can be carried out at the locations of QPDs. Each QPD can be manually inserted into the center of the laser pipe by means of a hinge structure in the holder. The transverse displacements of both the ends of the unit can be determined with respect to the laser axis by analyzing signal readouts from the QPD (diameter: 10 mm). On the other hand, the accelerator components mounted on each unit are precisely aligned with the use of a conventional laser tracker. Such a series of measurement procedures may support an accurate view in the high-precision alignment for long-distance linacs.

EXPERIMENTAL SETUP

The laser source and optical system is shown in fig. 1.

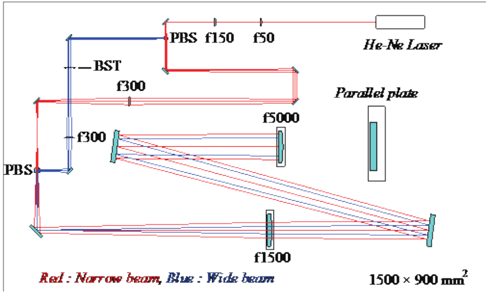

Figure 1: Laser source and optical system. PBS: polarizing beam splitter, BST: beam stopper.

The optical system is based on a dioptric system with the use of dioptric lenses and reflecting mirrors. It can deliver two kinds of laser beams with different beam widths. One is a laser beam (red: narrow beam) with a narrow width used in this experiment, and the other is that (blue: wide beam) with a large width for another purpose. Thus, the wide beam was stopped with a beam stopper (BST) in this experiment. The transverse width of the narrow beam is W_x (or W_y) ~ 0.83 mm at the point 10 cm away from the outlet of the laser tube and its divergence is ~0.7 mrad. Here, it should be mentioned that the beam width is defined by a four-sigma width of the intensity distribution projected onto the horizontal (x) or vertical (y) axes in the two-dimensional intensity profile. The beam width is slowly expanded up to W_x (or W_y) ~ 29 mm at the outlet of the optical system with five spherical plano-convex lenses (BK7, focal length: f=50, 150, 300, 1500, and 5000 mm) mounted on the optical table with a dimension of 1500 × 900 mm^2. The path length of the laser beam is ~5.5 m in total in the optical table. Such a long path length was carefully designed to increase the pointing stability as much as higher.

There are two fiducial points, which specify the transverse coordinates in terms of the fiducial straight line. They are the center positions of the first and end QPDs installed at 6.3 m and 500 m downstream from the optical system, respectively. The propagation directions and positions of the laser beam can be adjusted by controlling the emitting angle and transverse positions at the outlet of the optical system. The emitting angle is automatically adjusted by moving the final spherical plano-convex lens (f5000) in the perpendicular plane with respect to the beam axis with a feedback control. The transverse positions are manually adjusted by inclining the parallel plate (BK7) with respect to the beam axis. This plate is coated with antireflective coating on dielectric multilayer. Its thickness and diameter are 20 mm and 150 mm, respectively.

The laser beam passes through the laser pipes installed 780 mm above the floor level. Two vacuum windows (thickness: 20 mm and 15 mm) made out of transparent synthetic quartz have been attached to the inlet and outlet of the straight section, respectively, to keep vacuum higher in the laser pipes.

A commercially available silicon charge-coupled-device (CCD) camera (Ophir, USB L11058 [6]) has been used for measuring a two-dimensional intensity distribution of the laser beam just after the end QPD.

EXPERIMENTAL RESULTS

Propagation and stability characteristics of the laser beam

The laser beam propagates from the optical system up to the end QPD in total length of z = 500 m through the laser pipes (see fig. 4). Figure 2 shows a picture of the laser beam obtained through the vacuum window at z = 500 m with the CCD camera.

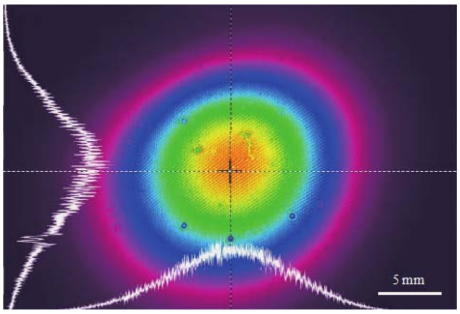

Figure 2: Intensity profile of the laser beam at z = 500 m.

The beam widths are W_x ~ 21.2 mm and W_y ~ 17.8 mm in the x and y directions, respectively. The beam widths were adjusted with the final convergent lens (f5000) by moving it with respect to the beam axis so as to become as symmetrical as possible in terms of variations in the beam widths along the linac.

The variations in the beam widths were analyzed by taking mapping data at the locations where movable QPDs are mounted, while the laser beam was fixed. On the other hand, the beam widths were directly measured at the two fiducial points. The mapping data were taken by measuring the variations in the signal level outputted from the QPD depending on the displacement from the fiducial line. The beam widths were analyzed on the basis of a least-square fitting procedure with a two-dimensional Gaussian function for the intensity distribution [5]. The result is shown in fig. 3. The solid and open circles indicate the analysed and directly measured widths, respectively. The Rayleigh lengths were estimated in this analysis to be z_{rx} ~ 308 m and z_{ry} ~ 321 m in the x and y directions, respectively. The waist widths at the locations, z_x ~ 358 m and z_y ~ 399 m, are W_x ~ 18.8 mm and W_y ~ 18.0 mm in the x and y directions, respectively.

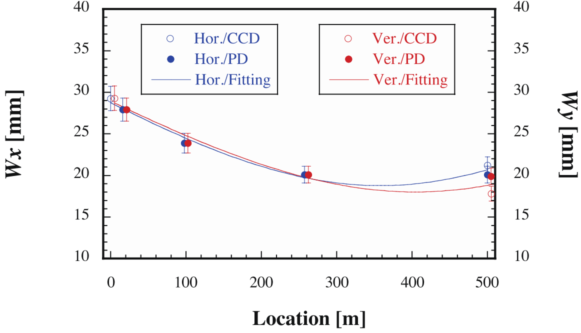

Figure 3: Variations in the horizontal and vertical beam widths along the linac.

Feedback control of the laser beam

The pointing of the laser beam has been stabilized at the end QPD by controlling the emitting angle at the optical system with the use of the feedback control (see fig. 4).

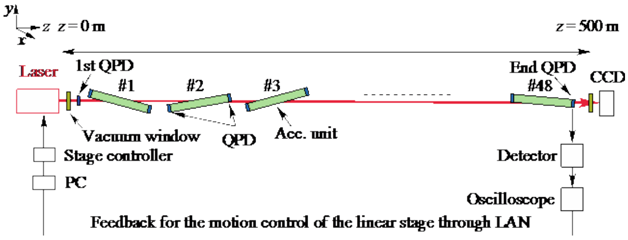

Figure 4: Feedback control system for stabilizing the laser pointing at the end QPD.

The emitting angle is controlled with the use of the final convergent lens (f5000). This lens is mounted on high-precision linear stages in the xy axes with pico-motors (M-562-XYZ, Newport [7]), which are controlled by the feedback control with a PC. A minimum step of the stages combined with the pico-motors is 30 nm/step. The transverse positions of the laser beam at the end QPD are continuously measured and stabilized by the feedback control. The photocurrents from the QPD are transformed to the voltages by detection electronics [5]. The detector outputs the four voltages proportional to the intensities of the photocurrents. The voltage signals are directly fed into a digital oscilloscope in which the transverse displacements of the center of the end QPD from the fiducial laser line are calculated by following a standard position-calculation algorithm [5].

A simple algorithm is applied to the feedback control working in the PC in real time by which the transverse positions at the end QPD are stabilized around its center. The parameters in the feedback control have been adjusted in the experiment. The successive acquisition number in one measurement is 100 for averaging. Calculations in the average positions and their standard deviations are successively performed in the oscilloscope every ~3 sec. Based on the position data, the step numbers required for the linear stages are calculated in the xy directions. The feedback control moves the stages in the x and y directions in series by following the calculated step numbers, while the maximum steps in one movement are limited to be 40 and 70 in the x and y directions, respectively. Such a feedback control procedure continues until the laser pointing is within the center region of the end QPD, which is defined in the transverse positions within ±50 μm. The feedback control resumes to work if the laser positions are out of ±70 μm from the center of the end QPD.

The typical result in the horizontal pointing stability of the laser beam is σ_x ~ 33 μm in one standard deviation during eight hours (see fig. 5). A similar vertical pointing stability was obtained to be σ_y ~ 41 μm. It should be mentioned that the pointing stability has been stably kept during more than 3 days without any adjustments.

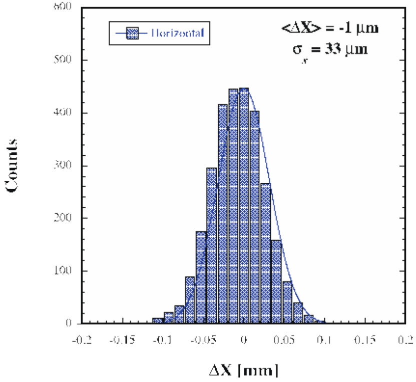

Figure 5: Horizontal position displacement distribution in the laser pointing stability at the end QPD during 8 hours.

SUMMARY

Systematic investigations on the propagation and stability characteristics of a fiducial straight line based on a He-Ne laser beam has been successfully performed at the KEKB injector linac. The 500-m-long fiducial straight line has been successively implemented for high-precision alignments of accelerator units. The pointing stability of the laser beam at the fiducial end point has been obtained to be with the displacements of ±40 μm level in one standard deviation in the transverse directions. This pointing stability corresponds to the angle of ±0.08 μrad. The results may serve as in the development of high-precision alignment techniques in future particle accelerators.

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