# EXPERIMENTS ON LASER-BASED ALIGNMENT 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. The new alignment system is strongly required in order to stably accelerate high intensity electron and positron beams with high bunch charges and also to keep the beam stability with higher quality toward the next generation of B-factories. A new laser optics with Airy beam has been developed and the laser propagation characteristics in vacuum has been systematically investigated at a 82-m-long straight section of a beam line at the KEKB injector linac. The laser-based alignment measurement based on the new laser optics was carried out with a measurement resolution of ±0.1 mm level by using a previously-used laser detection system. We report the outline of the new laser-based alignment system and the experimental results in detail.

## INTRODUCTION

The 600-m-long KEKB injector linac continuously provides the 8 GeV electron and 3.5 GeV positron beams for the KEKB rings. For the higher injection efficiency and stable beam operation, the precise alignment of accelerating structures and magnets are strongly required since the large misalignment causes the serious beam quality deterioration like a large beam orbit displacement and an emittance growth.

Although the original laser-based alignment system has been constructed at the KEK linac more than thirty-years ago, this system was partially developed in the energy upgrade toward the KEKB project in 1995 [1]. The alignment measurements of KEKB linac were actively carried out up to 1998, and however, since then, any measurements have not been performed because of a lack of easiness for adjusting the laser beam propagation.

In this decade, the alignment of KEKB linac could be worse due to ground subsidence and/or other reasons. Toward the next generation B-Factory project [2], the higher injection efficiency and lower emittance beam transport is strongly required because of the much shorter beam life time and small injection aperture in comparison with the present KEKB rings. For these reasons, the precise alignment of linac components is inevitable, and a new laser-base alignment system is now under development. In the new system, we adopted a new laser source with axially symmetric Airy beams generated by two consecutively aligned circular apertures [3].

## SYSTEM DESCRIPTION

### *Outline of Alignment at the KEKB Injector Linac*

A schematic layout of the KEKB injector linac is shown elsewhere [4]. It consists of 8 sectors (A-C and 1-5) in total. A 100-m-long and 500-m-long straight sections are connected by a 180-degree arc section. In a typical sector with a length of 76.8 m, there are eight accelerator units with a length of 9.6 m. One accelerator unit consists of four 2-m-long accelerating structures (S-band) which are mounted on an accelerator girder with a length of 8.4 m. The quadrupole magnets are basically installed on a magnet girder between two successive accelerator units.

The accelerator girder is composed of a cylindrical tube with an outer diameter of 508 mm made of stainless steel as shown in Fig. 1. The four accelerating structures are mounted on five separated stainless-steel plates fixed on the accelerator girder, and reference guide rails fixed on the plates align the four successive accelerating structures. A cylindrical laser pipe made of stainless steel with an inner diameter of 115 mm has been welded to the upper inner surface of the girder. Such coaxial structure has been originally designed in order to reduce convective air flow. The inner surface of laser pipe has been coated with a black paint basically comprised of acrylic resin for suppressing any unnecessary reflections and scatterings of the laser beams.

At both ends of the laser pipe, the quadrant-segmented photodiodes (PDs) are installed. The PD with a diameter of 10 mm (OSI Optoelectronics, Model SPOT-9D [5]) is attached to the PD chamber, which is connected to the flange of the laser pipe. When the laser beam hit the PD, the photocurrent signals are sent to a detector, and the detection electronics measures two-dimensional intensity centroids of the laser beam. Its measurement result means the displacement of the accelerator unit with respect to the reference straight line by the laser propagation. Before installation of the accelerator unit, the relative position among the centre of PD, accelerating structure and the

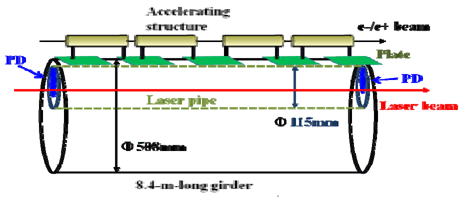

Figure 1: Schematic drawing of the typical accelerator unit in KEKB injector linac.

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reference guide rail surface has been aligned well. For this reason, when we align the centers of all PDs, all the accelerating structures and magnets can be consequently aligned.

### *Laser-based Alignment System*

Two laser-based alignment systems have been installed at the injector linac. One is for the alignment in sectors A and B, and the other is for the alignment in sector C up to the end of sector 5. A new laser source with a laser diode (LD) was developed for the later in this experiment.

A schematic layout of the new optical system is shown elsewhere [6]. The LD (Mitsubishi Electric, ML101J27 [7]) output is coupled into a single-mode optical fiber with a diameter of 3.5 µm. In this way, we could isolate the alignment optical system from the laser source so that it is not affected by the pointing stability of the laser itself. The output power (CW) of laser with a wavelength of 660 nm is 120 mW at maximum, whereas the final laser power injected into the laser tube is about 1 mW because of the fiber coupling loss and the insertion loss of optical system.

The exit end of fiber is fixed on an optical system plate with a size of 162 mm x 340 mm. The emitted laser light is transmitted through two successive circular apertures with a diameter of 10 µm and 0.1 mm for generating the Airy beam without diffraction fringes. Only the central Airy disk beam can be transmitted since the second aperture of a 0.1 mm diameter can truncate the fringe generated by the first aperture.

A flat and spherical mirror are also mounted on the same plate. The spherical mirror is aluminum-coated with a diameter and focal length of 152.4 mm. This optical system is mounted on a four-axis motorized stage. The position and angle of laser beam output are adjustable with the horizontal, vertical positions and the elevation and azimuthal angles. The schematic drawing of the optical system is shown in Ref. 6.

## EXPERIMENT

### *Setup*

The laser-based alignment experiment was carried out at sector C. The total length of the laser propagation is 82 m. Figure 2 shows a schematic drawing of the experimental setup along with a new vacuum system under development. The room temperature in the accelerator tunnel was kept within 23±0.1 °C. Furthermore, the laser source along with the optical system was entirely surrounded with heat reserving material for avoiding the local temperature drift and unnecessary air flow around the optical system.

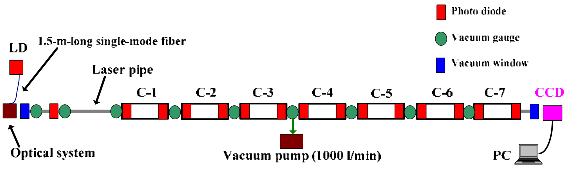

Figure 2: Schematic drawing of the experimental setup.

In this experiment, the total volume of the laser pipes was 847.2 l. A vacuum port was attached to a middle point of the laser pipe installed between units C-3 and C-4. It was connected with an oil-free scroll pump with a pumping speed of 1000 l/min. Nine Pirani gages were distributed at almost regular intervals up to the end of unit C-7. A inlet (outlet) vacuum window was used for laser injection (ejection) from atmosphere (vacuum) to vacuum (atmosphere) with transmittance of ~95% at λ = 660 nm. They are comprised of synthetic quartz (Shin-Etsu Quartz, SUPRASIL-P20 [8]) with a thickness of 20 mm and that of 15 mm for the inlet and outlet windows, respectively.

### *Laser Beam Size Measurement*

First of all, we measured the laser beam size along the sector C in the atmospheric environment since the signal output of PD depends on the incident laser beam size. After then, the beam profile was measured with a CCD camerat (OPHIR, USB L11058 [9]) at the location just behind the end of unit C-7 in atmospheric pressure and vacuum condition since the beam size in vacuum is slightly shrink in comparison with that in atmospheric pressure. Its shrink factor was taken into account to correct the measured beam size in atmospheric pressure for the expected beam size in vacuum condition.

Figure 3 shows the measured beam size of horizontal and vertical direction in vacuum condition along sector C. In this figure, the filled triangles denote the beam size analyzed on the basis of a least-squares fitting procedure with the analytic formula [6]. The measured beam size shows a good agreement with that of theoretical calculation in both beam sizes of horizontal and vertical.

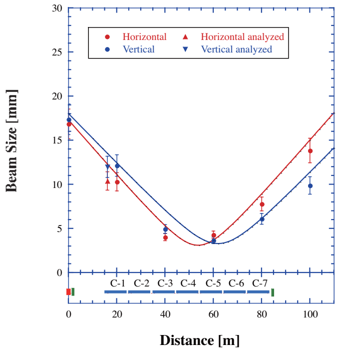

Figure 3: Variations of the horizontal and vertical beam sizes in vacuum condition as a function of the distance from the laser source.

### *Measurement of PD Calibration*

A calibration of the PD should be carried out to investigate a relation between the laser positions and the readouts of the detector. The calibration was performed with a mechanically-movable PD installed in the front location of unit C-1. The calibration can be performed by moving it in both horizontal and vertical directions with a step length of 0.5 mm over the ranges of ±3 mm while the laser beam is fixed. The horizontal (Vx) and vertical (Vy) voltages are measured via averaging the data 100 times with an oscilloscope at each PD position.

Figure 4 shows typical calibration results. The results show that both horizontal and vertical outputs in the detector readouts show good linear relations with the corresponding horizontal and vertical position of the movable PD within the measurement range while the output is slightly depending on the laser position in another axis. The sensitivities of the PD are obtained to be 2.1 V/mm and 2.0 V/mm in the horizontal and vertical directions, respectively. The beam sizes can be analyzed by assuming that the laser propagation follows a Gaussian optics. They were calculated on the basis of a least-squares fitting procedure with two-dimensional Gaussian distribution of the intensity profiles.

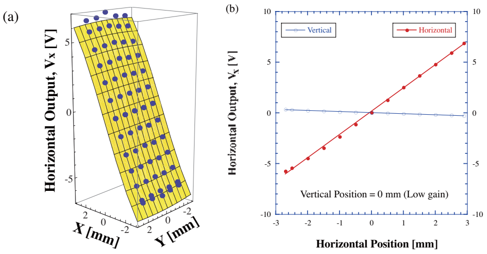

Figure 4: Typical calibration results obtained with a movable PD (a) in three and (b) two dimensional spaces.

### *Alignment Measurement*

The alignment measurements were finally carried out at each location of the PD under vacuum condition. Before the alignment measurements, the laser line was corrected by tuning the positions and angles ejected from the optical system with the precision four-axis stage to make a straight line connecting two points which are at the front end of unit C-1 and the other is that at the end of unit C-7. The horizontal and vertical voltages were similarly measured via averaging the data 100 times with an oscilloscope at all the PD locations in series and the similar measurements were repeated four times in total. The horizontal and vertical readouts measured at each PD location are transformed to the corresponding position displacements with each mapping curve.

Figure 5 shows the obtained results in the horizontal and vertical directions, respectively. As a comparison, those measured with a standard optical telescope (Taylor-Hobson, Micro-Alignment Telescope [10]) are also shown in the figure. The maximum displacements are obtained to be larger than 2 mm at the end location of accelerator unit C-3 in the horizontal direction, and also at the front location of accelerator unit C-4 in the vertical direction. The deviations from the average displacements in both the directions are within ±0.1 mm at maximum in the four-successive measurements.

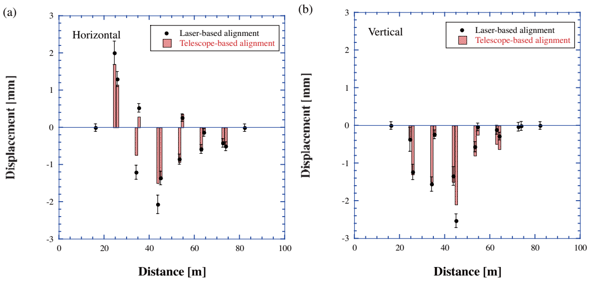

Figure 5: Alignment measurement results (a) in the horizontal and (b) vertical directions along sector C.

This result shows that the measurements was stably performed with good repeatability, and however, the correspondence to the telescope-based alignment results is not very good at the PD locations with the displacements of larger than ±1 mm, while the correspondence is relatively good at the PD locations with short displacements (< ±1 mm). This may be caused due to the calibration procedures with not very small systematic errors. This systematic error may reduce the reliability of the mapping curves obtained in the calibration procedure. The improvement of the measurement precision in the calibration procedure is one of the important issues for the next step toward the 500-m-long alignment of the injector linac in full length.

## SUMMARY AND FUTURE PLAN

The new optical system to the laser-based alignment system at the KEKB injector linac, and the alignment experiments were successfully carried out along a 82-m-long beam line of the injector linac. The experimental results show that the displacements of the accelerator units were measured with the measurement resolution of ±0.1 mm in both horizontal and vertical directions with respect to the laser axis.

An Airy beam was stably generated by using the new optical system and its propagation characteristics in vacuum and at atmospheric pressure was also investigated. The good applicability of the Airy beam was confirmed in this experiment. In the next step, we will carry out the full-length alignment of the KEKB injector linac and its result will be presented elsewhere in the near future.

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