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Report

Experiments of Laser Pointing Stability in Air and in Vacuum to Validate Micrometric Positioning Sensor

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Abstract

Aligning accelerator components over 200m with 10 µm accuracy is a challenging task within the Compact Linear Collider (CLIC) study. A solution based on laser beam in vacuum as straight line reference is proposed. The positions of the accelerator's components are measured with respect to the laser beam by sensors made of camera/shutter assemblies. To validate these sensors, laser pointing stability has to be studied over 200m. We perform experiments in air and in vacuum in order to know how laser pointing stability varies with the distance of propagation and with the environment. The experiments show that the standard deviations of the laser spot coordinates increase with the distance of propagation. They also show that the standard deviations are much smaller in vacuum (8 µm at 35m) than in air (2000 µm at 200m). Our experiment validates the concept of laser beam in vacuum with camera/shutter assembly for micrometric positioning over 35m. It also gives an estimation of the achievable precision.

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EXPERIMENTS OF LASER POINTING STABILITY IN AIR AND IN VACUUM TO VALIDATE MICROMETRIC POSITIONING SENSOR

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Abstract

Aligning accelerator components over 200 m with 10 µm accuracy is a challenging task within the Compact Linear Collider (CLIC) study. A solution based on laser beam in vacuum as straight line reference is proposed. The positions of the accelerator's components are measured with respect to the laser beam by sensors made of camera/shutter assemblies. To validate these sensors, laser pointing stability has to be studied over 200 m. We perform experiments in air and in vacuum in order to know how laser pointing stability varies with the distance of propagation and with the environment. The experiments show that the standard deviations of the laser spot coordinates increase with the distance of propagation. They also show that the standard deviations are much smaller in vacuum (8 µm at 35 m) than in air (2000 µm at 200 m). Our experiment validates the concept of laser beam in vacuum with camera/shutter assembly for micrometric positioning over 35 m. It also gives an estimation of the achievable precision.

INTRODUCTION

The Compact Linear Collider study has tight requirements for the pre-alignment of beam-related components: down to 10 µm accuracy (at 1 σ) over 200 m [1,2]. Methods based on stretched wires (using Wire Positioning Sensors) and water level (using Hydrostatic Levelling Sensors) have already been developed but present some drawbacks like their cost or difficult implementation [3, 4]. They also need to be compared to a system based on another principle in order to be validated.

Laser beam in vacuum as straight line reference has already been used for several linear accelerators. At SLAC (Stanford Linear Accelerator Center), the linac is aligned by analysing diffraction pattern of Fresnel zone plates that are mechanically switched across the laser beam [5]. An estimation of the achieved accuracy is 500 µm over 3 km. At KEK (the High Energy Accelerator Research Organization of Japan), the linac is aligned by observing the laser spot position on quadrant-photodetectors that are also mechanically switched across the laser beam [6]. An estimation of the achieved accuracy is 100 µm over 500 m. At DESY (Deutsches Elektronen-Synchrotron), a laser based alignment system using diffraction pattern of spheres is under study [7]. The achievable accuracy is estimated between 100 µm and 200 µm over 150 m.

At CERN (European Organization for Nuclear Research), an alignment system based on laser beam was proposed in 2010, launching the LAMBDA project (Laser Alignment Multipoint Based Design Approach) [8]. The idea consists of using a camera/shutter assembly (called LAMBDA sensor) to measure the distance to the laser beam. Two main steps were planned for this project: first, to develop and validate the LAMBDA sensor over short distance (around 3 m), second, to use it over long distance (up to 200 m).

We already tested laser pointing stability at short distance [9, 10]. The standard deviations of the laser spot coordinates were computed to be smaller than 10 µm. Then, we wanted to know how laser pointing stability behaves over longer distance. We therefore performed an experiment over 200 m in air and another one over 35 m in vacuum. In this paper, we describe setup and protocol of both experiments. We also present results regarding laser pointing stability.

EXPERIMENT IN AIR

Objective

The objective of the experiment is to check laser pointing stability in air in order to have reference values and compare them later with the ones obtained in vacuum.

Setup

Due to space restrictions, the experiment is carried out in the CERN geodetic base where a rail of 50 m is available. The experimental setup is described in Figure 1.

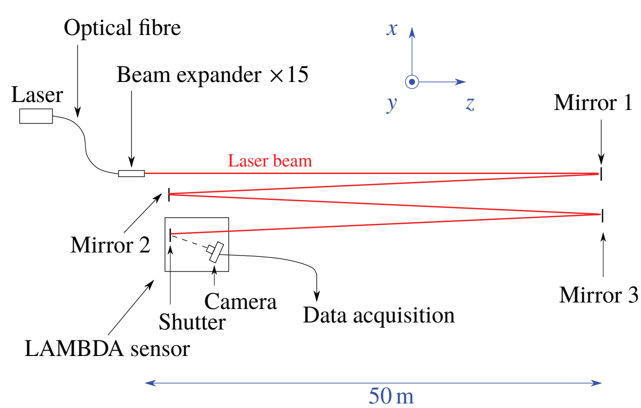

Figure 1: Schematic top view of the setup in air.

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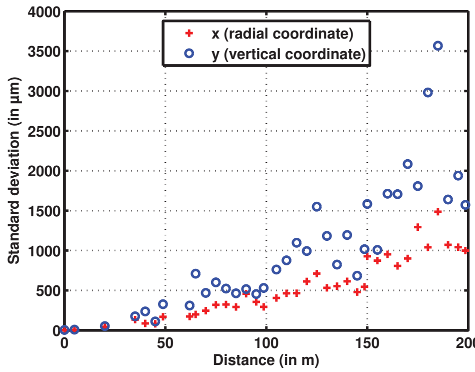

Figure 2: Laser pointing stability when laser beam propagates over 200 m in air.

The laser beam is produced by a HeNe laser and passes through optical fibre and beam expander. Using three mirrors makes it possible for the laser beam to propagate over 200 m. Mirrors have $\frac{1}{20}\lambda$ roughness and $R_{\text{avg}} > 98\%$ coating.

The LAMBDA sensor is made of a camera and a shutter mounted on the same plate. When the laser beam hits the shutter, a laser spot appears on its surface and pictures can be captured by the camera. The LAMBDA sensor can move in two directions, along the axis of laser propagation (z) and perpendicular to this axis (x). It can also rotate by 180° around y. Thus, pictures of the laser spot can be captured for distances of propagation between 0 m and 200 m. The camera is positioned at a distance of about 10 cm from the shutter. Its resolution is 1280 × 1024 and its pixel size is 3.6 µm. The shutter surface is equipped with reference targets in order to compute laser spot centre coordinates from camera plane to shutter plane.

Protocol

The LAMBDA sensor is set at several positions from 0 m to 200 m with steps of 5 m. For each position, 40 pictures are captured. The time interval between two captures is 1 s. For each picture, two-dimensional Gaussian fitting and projective geometry are applied in order to compute laser spot centre coordinates on the shutter. Finally, the standard deviations of the spot centre coordinates are computed over the 40 pictures.

Some positions are skipped (50 m, 55 m, 60 m, 100 m) because the LAMBDA sensor is too close to the mirrors and hides the laser beam before reflection.

Results and Discussion

Figure 2 presents the standard deviations of the laser spot coordinates with respect to the distance of propagation.

We observe that the standard deviations increase with the distance of propagation (around 100 µm every 10 m). Values for the vertical coordinate are larger than the ones for the radial coordinate. This may be explained by atmospheric effect: temperature variations are larger in vertical than in horizontal direction, which implies that the vertical deflection of the laser beam is noisier than the horizontal one. In any case, these standard deviations are much larger than CLIC requirements, which confirms that a vacuum pipe is needed for further experiments.

EXPERIMENT IN VACUUM

Objective

The objective of the experiment is to check laser pointing stability in vacuum and compare the results with the ones obtained in air.

Setup

The experiment is done in the CERN geodetic base. This place is chosen because it has a vacuum pipe of 12 m length. The experimental setup is described in Figure 3.

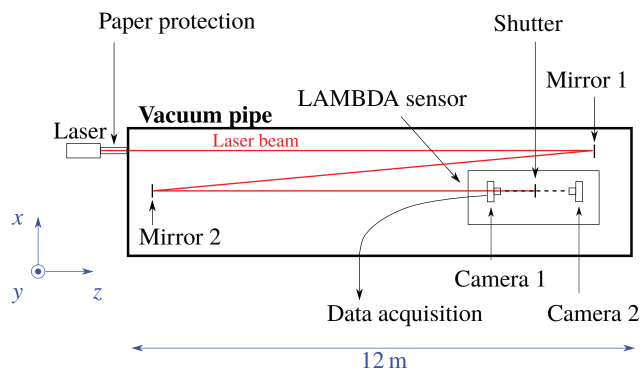

Figure 3: Schematic top view of the setup in vacuum (both cameras are placed 5 cm below the laser beam so that they can capture pictures of the laser spot on the shutter without obstructing the laser beam).

The HeNe laser source is positioned outside of the vacuum pipe. The laser beam enters the pipe through a window. Using two mirrors at both ends of the 12 m vacuum pipe makes it possible for the laser beam to propagate over 36 m.

The LAMBDA sensor is made of two cameras and a shutter. It can move in two directions, along the axis of laser propagation (z) and perpendicular to this axis (x). Depending on the position of the LAMBDA sensor within the vacuum pipe, the laser beam is interrupted on the front side or on the back side of the shutter. A laser spot appears on its surface and pictures can be captured by the appropriate camera. Both cameras are positioned 5 cm below the laser beam at a distance of about 10 cm from the shutter. Their resolution is 1600 × 1200 and their pixel size is 4.5 µm.

A temperature sensor is attached to the LAMBDA sensor in order to check temperature variations during the measurements. The pressure within the vacuum pipe is smaller than 0.1 mbar.

Protocol

First, the LAMBDA sensor is set at 35 m from the laser source and pictures are captured every minute during 48 h

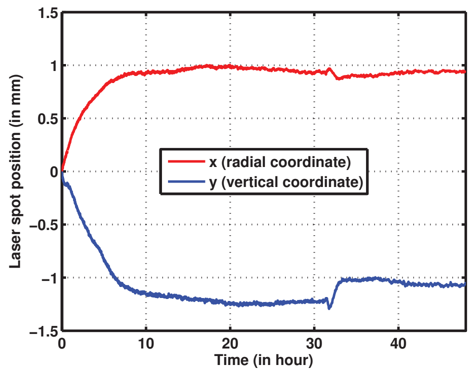

Figure 4: Laser spot position with respect to time when laser beam propagates over 35 m in vacuum.

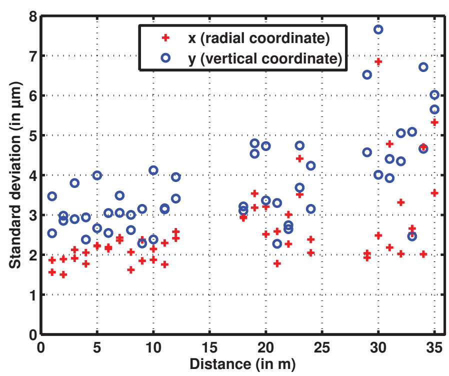

Figure 5: Laser pointing stability when laser beam propagates over 35 m in vacuum.

in order to have an idea of long-term stability. Second, the LAMBDA sensor is set at several positions from 0 m to 35 m with steps of 1 m. Some positions are skipped (13 m to 17 m; 26 m to 29 m) because the shutter is to close to the mirror and hides the reflection. For each position, 40 pictures are captured. The time interval between two picture captures is 1 s. Image processing is the same as in the experiment in air.

Remark: when we move the LAMBDA sensor inside the vacuum pipe, the temperature varies. After each movement, we wait a few minutes to have the temperature stable within 0.1° and then we capture pictures.

Results and Discussion

Figure 4 presents the variations of the laser spot coordinates over 48 h.

We can see 1 mm drifts for both coordinates during the first 8 hours. This corresponds to warm-up and stabilisation time of the whole system (laser, cameras). Then, both coordinates remain stable within 0.1 mm. The peaks and gaps around 32 h could not be explained so far.

Figure 5 presents the standard deviations of the laser spot coordinates with respect to the distance of propagation.

The graph shows that the maximum values of the standard deviations increase with the distance of propagation (around 1 µm every 10 m). Uncertainty brought by the mirrors can be seen in particular after mirror 2 (distance of propagation larger than 29 m). Again, the radial coordinate is more stable than the vertical one. Compared to the experiment in air, the laser spot is about 100 times more stable.

CONCLUSION

An experiment of laser pointing stability was performed in a vacuum pipe with a total distance of propagation of 35 m and compared with a previous experiment performed in air over 200 m.

Results show that the standard deviations of the laser spot coordinates are much smaller in vacuum (about 8 µm at 35 m) than in air (about 200 µm at 35 m). They also show that the standard deviations increase with the distance of propagation. The experiments confirm that a vacuum pipe is needed for the future alignment system and give an estimation of the achievable accuracy.

For next studies, the LAMBDA sensor is going to be modified in order to further decrease measurement uncertainty. For instance, a comparison between different types of surfaces (paper, metal and ceramic) will be carried out. The open/close mechanism will also be tested and compared with the fixed shutter.

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