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Experiment of Laser Pointing Stability on Different Surfaces to validate Micrometric Positioning Sensor

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Abstract
CLIC requires 10 µm precision and accuracy over 200m for the pre-alignment of beam related components. A solution based on laser beam as straight line reference is being studied at CERN. It involves camera/shutter assemblies as micrometric positioning sensors. To validate the sensors, it is necessary to determine an appropriate material for the shutter in terms of laser pointing stability. Experiments are carried out with paper, metal and ceramic surfaces. This paper presents the standard deviations of the laser spot coordinates obtained on the different surfaces, as well as the measurement error. Our experiments validate the choice of paper and ceramic for the shutter of the micrometric positioning sensor. It also provides an estimate of the achievable precision and accuracy of the determination of the laser spot centre with respect to the shutter coordinate system defined by reference targets.

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EXPERIMENTS OF LASER POINTING STABILITY ON DIFFERENT SURFACES TO VALIDATE MICROMETRIC POSITIONING SENSOR

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Abstract

The CLIC study requires 10 µm precision and accuracy over 200 m for the pre-alignment of beam related components. A solution based on laser beam as straight line reference is being studied at CERN. It involves camera/shutter assemblies as micrometric positioning sensors. It includes reference targets on the shutter in order to compute the coordinates of the laser spot centre from camera plane to shutter plane. To validate the micrometric positioning sensors, several parameters have to be examined. First, the most appropriate reference targets on the shutter have to be selected in terms of implementation and measurement of targets. Second, laser pointing stability has to be analysed with different types of shutter surfaces. Experiments are carried out with paper, metal and ceramic surfaces. This paper presents the standard deviations of the laser spot coordinates obtained on the different surfaces, as well as the measurement error. Our experiments validate the choice of paper and ceramic for the shutter of the micrometric positioning sensor. It also provides an estimate of the achievable precision and accuracy of the determination of the laser spot centre with respect to the reference targets.

INTRODUCTION

The Compact Linear Collider study has set challenging requirements for the pre-alignment of beam related components [1, 2]. In some parts of the future particles accelerator, the required alignment accuracy should be 10 µm (at 1 σ) over 200 m. In order to validate, complete and possibly replace existing systems based on stretched wires and Hydrostatic Levelling Sensors (HLS) [3, 4], a new alignment system based on laser beam as straight line reference is currently under study at CERN [5]. The name of the project is *LAMBDA* which is an acronym standing for Laser Alignment Multipoint Based Design Approach.

Laser based alignment systems have already been developed in other research centres, e.g. SLAC (Stanford Linear Accelerator Center), KEK (the High Energy Accelerator Research Organization of Japan) and DESY (Deutsches Elektronen-Synchrotron) but their estimated alignment accuracies did not meet CLIC requirements [6, 7, 8]. Compared to these systems, the LAMBDA project proposes a new type of sensor to measure the positions of the components with respect to the laser beam. The LAMBDA sensor is made of a camera and an open/close shutter. A measurement works as follows: (1) install the LAMBDA sensor on the component to be measured via an interface enabling micrometric reproducibility, (2) close the shutter, (3) take a picture of the laser spot on the closed shutter with the camera, (4) determine the coordinates of the laser spot by image processing, (5) deduce the position of the component attached to the LAMBDA sensor and (6) open the shutter and let the laser beam propagate until the next closed shutter.

In a first iteration, we tested the performance of the LAMBDA sensor at short distance [9, 10]. We found standard deviations of the laser spot coordinates of 10 µm at 3 m. In a second iteration, we tested the sensor over long distance [11]. We found that the standard deviations increase with the distance of propagation (up to 2 mm at 200 m). Since these values are much above CLIC requirements, we performed an additional test with laser beam under vacuum which gave standard deviations of 8 µm at 35 m [11].

All the experiments described above were done with a paper sheet glued on the shutter. Since such a paper surface has drawbacks like its fragility over time or its non flatness, we wanted to compare it with other surface like metal and ceramic. We therefore produced three different shutters (with paper, metal and ceramic surface) and performed experiments of laser pointing stability on them. Targets had to be added on the shutters in order to transform the coordinates of the laser spot from CCD plane to shutter plane.

First, this article details how shutters look like. Second, it describes the setup and the protocol of the experiments. Third, it presents results regarding laser pointing stability.

SHUTTER DESCRIPTION

Manufacturing shutters mainly consists of adding targets on them. The present section explains why and presents how the three types of shutters (paper, metal, ceramic) are made.

Need for targets on shutters

The LAMBDA sensor comprises a shutter to interrupt the laser beam and a camera to take pictures of the laser spot on the shutter (see figure 1).

The LAMBDA sensor is installed on the accelerator component to be aligned so that any displacement of the

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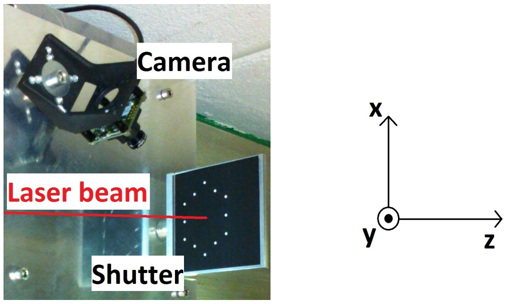

Figure 1: LAMBDA sensor

accelerator component results in a displacement of the LAMBDA sensor. However, in order to make the link between the laser spot on the shutter and the component to be aligned, targets have to be added on the shutter. The positions of the targets centres are measured with an uncertainty below 7 µm before the experiments by the metrology lab providing reference values. The targets are then captured during the experiments by the camera and their centres are computed by image processing. Based on the positions of the targets on CCD plane and shutter plane, the 8 parameters of projective geometry can be computed [12]. Projective geometry matches points from CCD plane to points from shutter plane. Thus, displacements of the laser spot on the shutter can be determined and subsequently displacements of the component to be aligned can be estimated.

Requirements for targets

For our application, targets are disks and their centres are detected by ellipse fitting. Disks have the advantage of looking like ellipses regardless of the position of the camera. In addition, important parameters for targets detection are the contrast between targets and their background as well as the roundness of the targets.

For the computing of the 8 parameters of projective geometry, a minimum number of targets is required. Since each target provides 2 coordinates for its centre, at least 4 targets have to be present on the shutters ($4 \times 2 = 8$ observations to determine 8 unknown parameters). In practice, we have at least 12 targets (and thus 24 observations) on the shutters to increase redundancy. A simulation will be conducted in the future in order to determine if this number of 12 targets is optimal. Indeed more targets increase redundancy but also increase the computing time of image processing, thus a compromise has to be found.

Finally, shutter flatness and roughness are important parameters. The flatness is the height difference between the lowest and the highest points of the surface. If the targets and the laser spot are not in the same plane, there will be a systematic error in the calculation of the coordinates of the laser spot. This error depends on the distance between the plane containing targets and the plane containing the laser spot as well as on the angle between camera axis and laser beam axis. For example, if the angle is 30°, the order of magnitude of the systematic error will be half of the distance between the plane containing targets and the plane containing the laser spot.

The roughness can be quantified by the R_a, which is the arithmetic mean of absolute deviations of the surface plane with respect to the average plane. The roughness is important because it reflects light homogeneously in all directions. If the surface roughness is too small (e.g. like a mirror), the laser beam will be reflected in one main direction. In this case, the camera can either receive a lot of light and be saturated, or no light at all and not be able to detect the laser spot.

Manufacturing of shutters

For the experiments described in this paper, the shutter of the LAMBDA sensor does not have an open/close mechanism but is fixed in order to eliminate uncertainty related to repositioning of the shutter. Three types of shutters are prepared (paper, metal and ceramic). These three materials are selected because they are low cost and relatively easy to transform in order to add targets on them. They also present the advantage of having different flatness and roughness values. A fourth type of shutter in steel was tested but not kept because laser spot detection was not satisfying with it (too rough surface).

The *paper* shutter is an aluminium plate with a sheet of paper glued on it. The sheet of paper is originally white. The black background is printed so that 12 white disks appear (see figure 2).

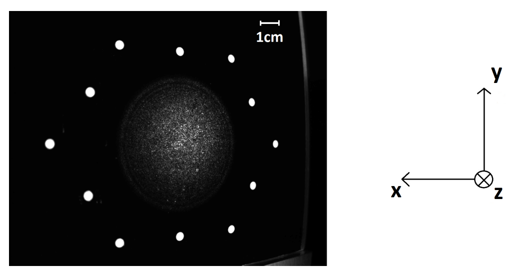

Figure 2: Shutter with laser spot in the middle and targets around (paper surface)

The *metal* shutter is an anodised aluminium plate with machined conical grooves as targets. The anodised surface is black, the drilled holes are silver.

The *ceramic* shutter is an alumina plate with targets obtained through laser siltering. The surface is white, the targets are black.

Typical values regarding shutter flatness are 30-110 µm (paper surface), 15-16 µm (metal surface) and 36-37 µm (ceramic surface). Typical values regarding shutter roughness are 2.8-4.8 µm (paper surface), 0.1-0.9 µm (metal surface) and 1.4-2.2 µm (ceramic surface).

EXPERIMENT DESCRIPTION

Objective

The experiment consists of studying laser pointing stability with respect to three shutter surfaces (paper, metal and ceramic).

Setup

The experiment takes place in an optical lab, which is located in the basement. It has a stable environment with no ventilation. The experimental setup is presented in Figure 3.

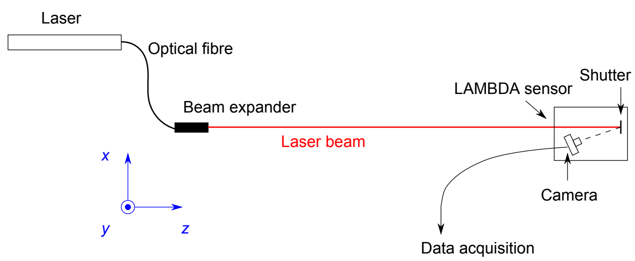

Figure 3: Schematic overview of the setup. The distance beam expander - shutter is 3 m and the distance shutter - camera is 10 cm.

The LAMBDA sensor is a camera/shutter assembly mounted on an aluminium plate. When the laser beam is projected onto the shutter, a laser spot appears on the shutter surface and the camera can capture pictures of the laser spot. The LAMBDA sensor is fixed on a motorised micrometric table allowing radial (along x) and vertical (along y) displacements with $0.1\,\mu m$ accuracy. The camera and the motorised micrometric table are controlled remotely, thus nobody enters the room during series of measurements.

Laser, beam expander and motorised micrometric table are installed on a marble bench to minimise ground vibrations. The optical lab is not ventilated to minimise air turbulences. Four temperature sensors are installed: (1) close to the beam expander, (2) close to the shutter, (3) in the middle between beam expander and shutter and (4) on the LAMBDA sensor plate. They show that temperature is stable within $0.1°$ during the experiments.

Image processing

For each picture captured by the camera, several steps are processed: (1) the position of the laser spot centre on the CCD is determined by two-dimensional Gaussian fitting, (2) the positions of the targets centres on the CCD are determined by ellipse fitting, (3) distortion is corrected, (4) the eight parameters of projective geometry characterising the transform between CCD plane and shutter plane are computed and (5) the position of the laser spot centre on the shutter is computed by application of projective geometry.

Protocol

For each shutter surface, two series of measurements are done.

The first series of measurements consists of capturing 1000 pictures without moving the LAMBDA sensor. It lasts approximately 10 min. The standard deviation of the laser spot coordinates gives information about measurement precision. Image processing lasts approximately 2 h for the 1000 pictures.

The second series of measurements consists of capturing pictures when the LAMBDA sensor moves along x (radial displacement) from 0 mm to 2 mm in steps of $10\,\mu m$, repeated 10 times. It lasts approximately 40 min. The residuals of the laser spot coordinates with respect to the best fitting line gives information about measurement accuracy. Image processing lasts approximately 4 h for the 2010 pictures. Due to long processing time, only a radial displacement is performed and not a vertical one. In addition, the present experiment can be compared with previous papers [9, 10, 11], where radial displacements were done.

RESULTS

LAMBDA sensor at the same position

For the first series of measurements, the LAMBDA sensor does not move. 1000 pictures are captured by the camera. The standard deviation of the coordinates of the laser spot centre is computed over 1000 pictures. Results are summarised in table 1.

Surface type	Standard deviations (in µm)	
	Radial coordinate	Vertical coordinate
paper	1.6	2.8
metal	5.2	6.4
ceramic	3.5	4.9

Table 1: Laser pointing stability without moving the LAMBDA sensor

The surface showing the best laser pointing stability is paper, followed by ceramic and then metal. In addition, the vertical coordinate is more spread than the radial coordinate for the three types of surface.

This phenomenon is a bit surprising since we did not expect a difference between radial and vertical coordinates. Actually, the other way round would be more logical. Indeed, the camera is located on the side of the laser beam. Thus, the captured laser spot looks like an ellipse with a radial diameter larger than the vertical diameter. Subsequently, the standard deviations of the coordinates of the laser spot centre should be larger in radial direction than in vertical direction.

Otherwise, another reason explaining the difference between radial and vertical coordinates could be temperature gradient that is generally larger in vertical than in radial direction.

LAMBDA sensor moving along x

For the second series of measurements, the LAMBDA sensor moves along x (radial displacement) from 0 mm to 2 mm in steps of $10\,\mu m$ and 1 picture is captured for each stop. This displacement is repeated 10 times. Thus 10 pictures are captured per position. Results are presented in figure 4.

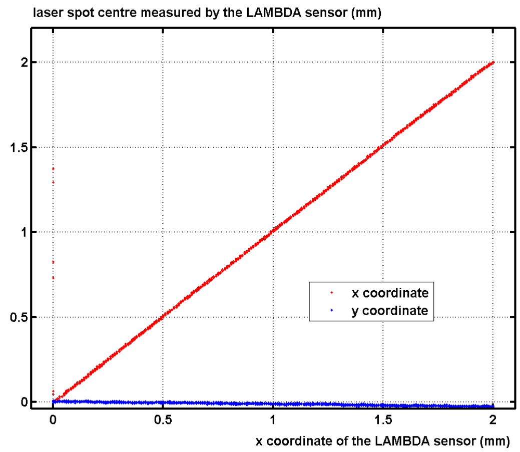

Figure 4: Displacement of the laser spot centre measured by the LAMBDA sensor with respect to displacement of the LAMBDA sensor (paper surface)

Both coordinates have the expected behaviour. The y coordinate presents a drift of 30 µm after 2 mm. This can happen if there is a small rotation between the coordinate system defined by the targets and the coordinate system defined by the motorised micrometric table.

Based on these results, we were interested in knowing how the measured coordinates vary around their best fitting lines. Since outliers are observed for the position $x = 0$ mm, they are eliminated before computing residuals. Results are shown in figures 5 and 6.

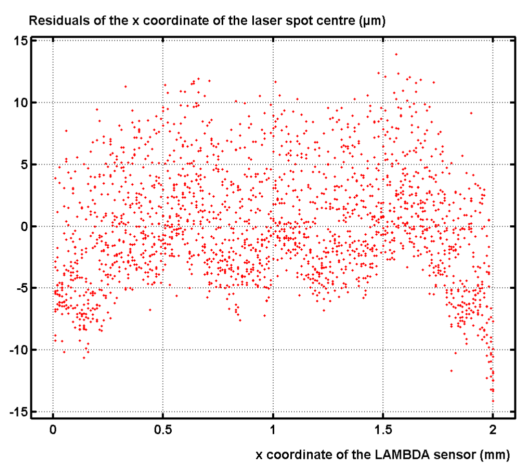

Figure 5: Residuals of the x coordinate of the laser spot centre with respect to displacement of the LAMBDA sensor (paper surface)

As a result, we can see that residuals follow a certain path when the LAMBDA sensor is moving over 2 mm, especially for the x coordinate. This may be related to the fact that the surfaces are not flat. However, this phenomenon remains limited since standard deviations of the residuals are computed to be smaller than 5 µm for the paper surface (see

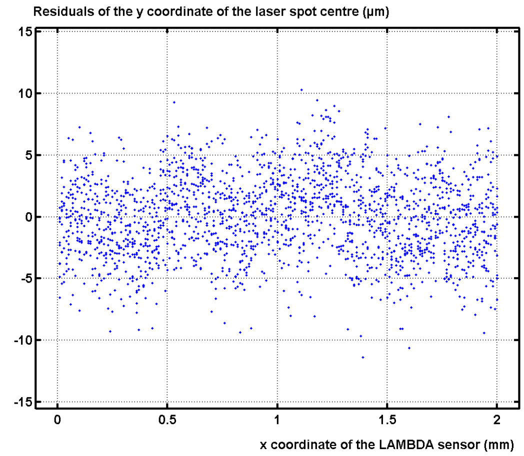

Figure 6: Residuals of the y coordinate of the laser spot centre with respect to displacement of the LAMBDA sensor (paper surface)

table 2).

Surface type	Standard deviations (in µm)	
	Radial coordinate	Vertical coordinate
paper	4.7	3.3
metal	11.9	6.9
ceramic	4.9	5.8

Table 2: Laser pointing stability when the LAMBDA sensor moves in radial direction

Again, in terms of laser pointing stability, the most interesting surfaces are paper and ceramic (below 6 µm). Results showed by metal are twice less stable. This could be explained by surface roughness. Indeed, paper and ceramic have larger roughness values than metal. Thus, paper and ceramic reflect light homogeneously in all directions whereas metal reflects it in one direction.

In addition, we can observe that the residuals of the x coordinate are more spread than the residuals of the y coordinate for the paper and the metal surface whereas it is the contrary for the ceramic surface. We expected the uncertainty in determining the coordinates of the laser spot centre to be larger in radial direction than in vertical direction because of the radial displacement of the sensor. The fact that results are different for the ceramic plate is surprising. Maybe the machining of the ceramic plate done in a particular direction implies a slightly different roughness in radial and vertical directions.

CONCLUSION

A comparison between paper, metal and ceramic was conducted in order to find the most appropriate surface for the shutter of the LAMBDA sensor.

First, shutter flatness and roughness were studied. The metal surface has the best flatness (around 16 µm) followed by ceramic (around 36 µm) and paper (between 30 µm and

110 µm). The metal surface also has the smallest roughness (R_a below 1 µm) compared to ceramic (R_a between 1.4 µm and 2.2 µm) and paper (R_a between 2.8 µm and 4.8 µm).

Second, experiments of laser pointing stability were performed. When the LAMBDA sensor did not move, the paper surface presented the smallest standard deviations (below 3 µm) compared to ceramic (below 5 µm) and metal (below 7 µm). When the LAMBDA sensor moved in radial direction over 2 mm, the order was the same: the standard deviations were smaller for paper (below 5 µm) than ceramic (below 6 µm) and metal (below 12 µm). This might be explained by roughness values.

However, even though the paper surface has the best results regarding laser pointing stability, its flatness does not allow to meet requirements coming from the CLIC project. The metal surface is the opposite of the paper surface: it has the best flatness but does not provide a good laser pointing stability. In this scope, the ceramic shutter presents a good compromise between paper and metal surfaces.

The ceramic shutter used for the present paper was made of an alumina plate. Targets were added on it by means of laser siltering. Other types of ceramics like macor could be tested in order to determine the surface with the best flatness and laser pointing stability.

In a future study, the LAMBDA sensor is going to be improved with an open/close mechanism. Laser pointing stability will be tested with respect to shutter repositioning. When this is done, and assuming that shutter repositioning is guaranteed at a tolerable level, we will be able to remove targets from the shutter and keep only targets on the frame around the shutter. Indeed, the frame around the shutter is directly related to the components to be aligned, and not the shutter itself.

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