EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH
CERN – ACCELERATORS AND TECHNOLOGY SECTOR

CERN-ACC-2013-0038

DEVELOPMENT AND VALIDATION OF A MULTIPOINT BASED LASER ALIGNMENT SYSTEM FOR CLIC

G. Stern_, CERN, Geneva, Switzerland, ETHZ, Zurich, Switzerland

J. Kemppinen, F. Lackner, H. Mainaud-Durand, D. Piedigrossi,

J. Sandomierski, M. Sosin, CERN, Geneva, Switzerland

A. Geiger, S. Guillaume, ETHZ, Zurich, Switzerland

Abstract

Alignment is one of the major challenges within CLIC study, since all accelerator components have to be aligned with accuracy up to 10 μm over sliding windows of 200 m. So far, the straight line reference concept has been based on stretched wires coupled with Wire Positioning Sensors. This concept should be validated through inter-comparison with an alternative solution. This paper proposes an alternative concept where laser beam acts as straight line reference and optical shutters coupled with cameras visualise the beam. The principle was first validated by a series of tests using low-cost components. Yet, in order to further decrease measurement uncertainty in this validation step, a high-precision automatised micrometric table and reference targets have been added to the setup. The paper presents the results obtained with this new equipment, in terms of measurement precision. In addition, the paper gives an overview of first tests done at long distance (up to 53 m), having emphasis on beam divergence

CERN-ACC-2013-0038
12/05/2013

Presented at the International Particle Accelerator Conference (IPAC'13) –

May 12-17, 2012, Shanghai, China

Geneva, Switzerland, May 2013

DEVELOPMENT AND VALIDATION OF A MULTIPOINT BASED LASER ALIGNMENT SYSTEM FOR CLIC

G. Stern*, CERN, Geneva, Switzerland, ETHZ, Zurich, Switzerland
J. Kemppinen, F. Lackner, H. Mainaud-Durand, D. Piedigrossi,
J. Sandomierski, M. Sosin, CERN, Geneva, Switzerland
A. Geiger, S. Guillaume, ETHZ, Zurich, Switzerland

Abstract

Alignment is one of the major challenges within CLIC study, since all accelerator components have to be aligned with accuracy up to $10\ \mu\mathrm{m}$ over sliding windows of $200\ \mathrm{m}$. So far, the straight line reference concept has been based on stretched wires coupled with Wire Positioning Sensors. This concept should be validated through inter-comparison with an alternative solution. This paper proposes an alternative concept where laser beam acts as straight line reference and optical shutters coupled with cameras visualise the beam. The principle was first validated by a series of tests using low-cost components. Yet, in order to further decrease measurement uncertainty in this validation step, a high-precision automatised micrometric table and reference targets have been added to the setup. The paper presents the results obtained with this new equipment, in terms of measurement precision. In addition, the paper gives an overview of first tests done at long distance (up to 53 m), having emphasis on beam divergence.

INTRODUCTION

One of the important technical challenges within CLIC (Compact LInear Collider) study consists of achieving the pre-alignment of the two main linear accelerators (linacs), especially the Beam Delivery System (BDS) [1]. Indeed, in order to meet the demanding luminosity requirements, the beam related components have to be actively pre-aligned with accuracy of $10\ \mu\mathrm{m}$ rms over sliding windows of at least $200\ \mathrm{m}$ along the $20\ \mathrm{km}$ of linac [2].

This challenge can be solved by using a wire as straight line reference coupled with Wire Positioning Systems (WPS) [3, 4, 5]. However, this method has drawbacks like its cost or difficult implementation. A second solution based on a laser beam as straight line reference coupled with beam positioning sensors is presented in this paper. The beam positioning sensor is called LAMBDA-sensor[1] and is made of a shutter and a camera [6]. Linac components that have to be aligned are equipped with LAMBDA-sensors.

To check the alignment, all LAMBDA-sensors are used one after the other with the following process: the shutter is mechanically switched across the beam, the camera takes a picture of the laser spot formed at the shutter surface, the picture is processed to compute the spot centre coordinates. Finally, the spot centre coordinates given by all LAMBDA sensors are compared to see whether the linac components are well aligned or not.

The study and development of LAMBDA-sensors is divided into two steps: validation of the principle at short distance (up to $3\ \mathrm{m}$) and application to CLIC project at long distance (up to $200\ \mathrm{m}$). Concerning the step 'validation of the principle', first tests were done with a simple setup and gave encouraging results [7]. The idea was then to further decrease measurement uncertainty with an improved setup. Results regarding measurement precision at short distance are presented in the first part of this paper. Concerning the step 'application to CLIC project', it was necessary in a first iteration to check the beam diameter over a long distance because this is a key parameter for the size of the LAMBDA-sensor. Results regarding beam divergence at long distance are presented in the second part of this paper.

TEST AT SHORT DISTANCE

Objective

First tests for the validation of concept had already been done at short distance (up to $3\,\mathrm{m}$) with a simple setup [7]. Even though low cost components were used, results were encouraging: the position of the spot centre was measured in a range of [-4 $\mu\mathrm{m}$,4 $\mu\mathrm{m}$] around the expected value and its standard deviation was computed below $5\ \mu\mathrm{m}$. After these tests, the idea was to further decrease measurement uncertainty during the validation step. Thus, several changes were made to the experimental setup, e.g. a motorised micrometric table was added. In order to compare results obtained with the old and the new setup, the same experiment protocol was used for both tests.

Configuration

Figure 1 gives an overview of the experimental setup. The shutter is placed at a distance of $3000\,\mathrm{mm}$ from the beam expander. The camera lens is placed at a distance of $100\,\mathrm{mm}$ from the shutter. The angle between camera axis and laser beam axis is $30°$. The laser is HeNe with a wavelength $\lambda = 633\,\mathrm{nm}$. The CCD has a resolution of 1280×1024 and a pixel size of $3.6\ \mu\mathrm{m}$.

The differences with the experimental setup used in [7] are summarised in the following list:

---

* guillaume.stern@cern.ch

[1] The name LAMBDA-sensor comes from the LAMBDA-project; LAMBDA stands for Laser Alignment Multipoint Based Design Approach

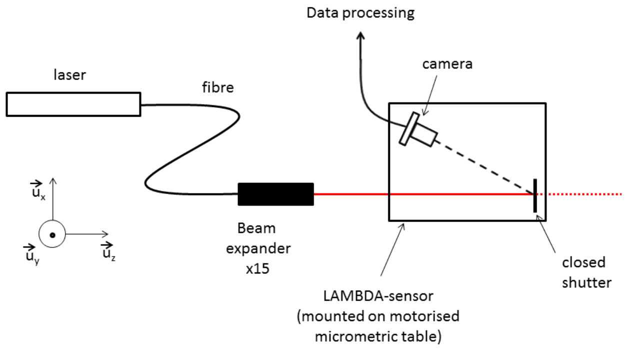

Figure 1: Top view of the experimental setup

- The camera and the shutter are put together on the same plate in order to have a first prototype of the future LAMBDA-sensor.
- The manual micrometric table is replaced with a motorised one enabling two translations (along $\overrightarrow{u}_\mathrm{x}$ and $\overrightarrow{u}_\mathrm{y}$) and one rotation (around $\overrightarrow{u}_\mathrm{y}$). The uncertainty of positioning of the motorised micrometric table is $0.1\ \mu\mathrm{m}$ (value given by the manufacturer Aerotech).
- The collimator is replaced with a beam expander of magnifying power 15. This enlarges the laser beam at the beginning but reduces its divergence, which is necessary for the future alignment system over $200\ \mathrm{m}$ [8].
- Targets are added on the shutter in order to have reference points for the computing of the laser spot coordinates. These targets are white disks with a diameter of $2\,\mathrm{mm}$, printed on black paper. The positions of their centres are determined in the metrology lab with a measurement uncertainty of $3\ \mu\mathrm{m}$.
- Four temperature sensors are added to the setup. Three of them are in the air (one close to the beam expander, one between beam expander and shutter, one close to the shutter) and the last one is put on the LAMBDA-sensor plate. These sensors are needed to check temperature stability. Indeed, the metal parts of the setup expand when temperature increases, which modifies the vertical position of the LAMBDA-sensor and the beam expander.

Protocol

The LAMBDA-sensor does two round-trips in $\overrightarrow{u}_\mathrm{x}$ direction (radial) between $x = 0\ \mu\mathrm{m}$ and $x = 50\ \mu\mathrm{m}$ in steps of $10\ \mu\mathrm{m}$[2]. Thus, the sensor occupies six different positions ($0\ \mu\mathrm{m}$, $10\ \mu\mathrm{m}$, $20\ \mu\mathrm{m}$, $30\ \mu\mathrm{m}$, $40\ \mu\mathrm{m}$, $50\ \mu\mathrm{m}$), four times each. This results in $6 \times 4 = 24$ data points (crosses in Figure 2). Each data point is obtained by an average over 40 measurements. A measurement comprises three steps: first, a picture with laser spot is captured; then, the spot centre coordinates are computed in the CCD plane by application of two-dimensional Gaussian matching [9]; finally, the spot centre coordinates are computed in the shutter plane by means of projective geometry [10, 11, 12]. In total, the whole experiment lasts $30\ \mathrm{min}$.

Results

First of all, when the laser and the motorised micrometric table are switched on, the room temperature increases by $0.5°$ during the first three hours. After this time, the four temperature sensors give values that are stable enough to neglect the temperature effect on the position of the laser spot centre. The capture of pictures is performed when the temperatures are stable.

Figure 2 presents the x-position of the laser spot centre with respect to the x-position of the LAMBDA-sensor. All values remain in an interval of [-3 μm,2 μm] around the expected value. This is significant improvement compared to results achieved using the manual micrometric table, where the interval was [-4 μm,4 μm]. Moreover, the standard deviation over of the x-position 40 measurements is always below $1.2\ \mu\mathrm{m}$, which is also better than previously ($5\ \mu\mathrm{m}$).

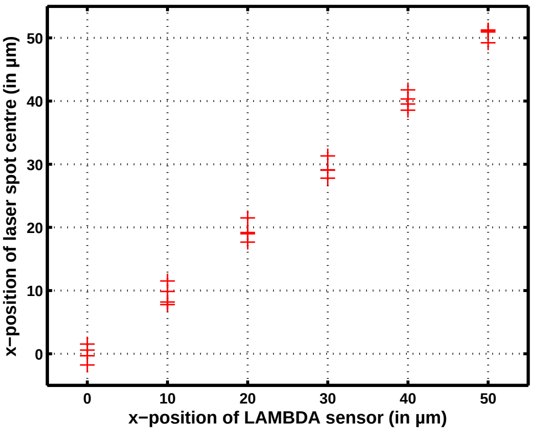

Figure 2: x-position of the laser spot centre computed from pictures with respect to x-position of LAMBDA-sensor determined by the motorised micrometric machine

Results are similar regarding the vertical coordinate of the spot centre on the shutter. The y-position of the spot centre on the shuter remains in an interval of [-2 μm,2 μm] around the expected value (instead of [-2 μm,3 μm] with the manual micrometric table). The standard deviation of y-position over 40 measurements is always below $2\ \mu\mathrm{m}$, which is also better than previously ($3\ \mu\mathrm{m}$).

These tests show how measurement uncertainty is reduced with a motorised micrometric table instead of a

---

[2] The motorised micrometric table can move in smaller steps than $10\ \mu\mathrm{m}$ but the manual one cannot go below this value. Since the goal of this paper is to compare the old and the new setup, the experimental protocol applied with the manual micrometric table is reused in this paper.

manual one. The results contribute to the step ’validation of the principle’ at short distance. The next step dealing with ’application to CLIC project’ at long distance is described in the following section.

TEST AT LONG DISTANCE

Objective

The objective of the experiment is to do a first test over a long distance (up to 53 m) regarding one crucial parameter for the alignment project: laser beam divergence, which plays a major role in the sizing of the future sensor. The beam diameter should be as small as possible over the $200\,\mathrm{m}$ in order to have a compact sensor. Without beam expander, the beam diameter remains approximately in a range from $1\,\mathrm{mm}$ to $140\,\mathrm{mm}$. With a beam expander of magnifying power 15, the range is from $15\,\mathrm{mm}$ to $30\,\mathrm{mm}$ [8], which is acceptable for the project.

In the experiment presented below, the idea is to check how the beam diameter varies over a long distance using a beam expander.

Configuration

Due to space restrictions, the long distance tests were carried out in the CERN geodetic base, where a rail of $53\,\mathrm{m}$ is available, instead of the optical lab. The geodetic base is ventilated, which causes additional noise in the laser beam propagation. The experimental setup is similar to the previous one shown in Figure 1, except that the LAMBDA-sensor is not mounted on the motorised micrometric table but on a rail. Thus, the sensor can move along $\overrightarrow{u}_\mathrm{z}$ from $z = 3\,\mathrm{m}$ to $z = 53\,\mathrm{m}$.

Protocol

The shutter/camera assembly is moved in $\overrightarrow{u}_\mathrm{z}$ -direction from $z = 3\,\mathrm{m}$ to $z = 53\,\mathrm{m}$ in steps of $z = 10\,\mathrm{m}$. This means that the sensor occupies six different positions (3 m, 13 m, 23 m, 33 m, 43 m, 53 m).

Results

The beam diameter remains between $6\,\mathrm{mm}$ and $7\,\mathrm{mm}$ with distances up to $23\,\mathrm{m}$ but then it starts to grow. At a distance of $53\,\mathrm{m}$, the beam diameter is comprised between $10\,\mathrm{mm}$ and $12\,\mathrm{mm}$.

CONCLUSION

The latest results of a new alignment concept using laser beam as straight line reference have been presented.

The study was started by experiments with low cost components, resulting in a position of the spot centre remaining in an interval of [-4 μm,4 μm] around the expected value and a standard deviation below $5\,\mu\mathrm{m}$. In order to further decrease measurement uncertainty during the validation step, a motorised micrometric table was added to the setup. With this improvement, the position of the spot centre remained in [-3 μm,2 μm] around the expected value and the standard deviation dropped to below $2\,\mu\mathrm{m}$.

Moreover, a first test dealing with beam divergence was done over a long distance (up to $53\,\mathrm{m}$). The laser beam diameter was computed smaller than $12\,\mathrm{mm}$ over a distance of $53\,\mathrm{m}$.

In order to decrease measurement uncertainty for future experiments, the sensor will be further studied and developed, e.g. material, colour and roughness of the shutter. The image processing software will be also improved, using ellipse fitting and taking into account distortion for a more accurate spot centre detection. In parallel, a test with mirrors over $200\,\mathrm{m}$ is going to be performed in order to check measurement precision as well as beam divergence.

REFERENCES

[1] `http://clic-study.org/`

[2] T. Touzé, “Proposition d’une méthode d’alignement de l’accélérateur linéaire CLIC”, PhD thesis, Université de Paris Est, France, 2011.

[3] A Multi-TeV linear collider based on CLIC technology: CLIC Conceptual Design Report, edited by M. Aicheler, P. Burrows, M. Draper, T. Garvey, P. Lebrun, K. Peach, N. Phinney, H. Schmickler, D. Schulte and N. Toge, CERN-2012-007

[4] H. Mainaud-Durand et al., “CLIC Active Pre-Alignment System: Proposal for CDR and Program for TDR”, IWAA’10, Hamburg, Germany, Sept. 2010.

[5] H. Mainaud-Durand et al., “Optical WPS versus capacitive WPS”, IWAA’12, Chicago, United States, 2012.

[6] F. Lackner et al., “Technical Proposal: Laser Alignment Multipoint Based - Design Approach”, EDMS n° 1066954, 2010.

[7] G. Stern et al., “Feasibility Study of Multipoint Based Laser Alignment System for CLIC”, IWAA’12, Chicago, United States, 2012.

[8] `http://www.edmundoptics.com/learning-and-support/technical/learning-center/application-notes/lasers/beam-expanders/`

[9] M. Ploner, “CCD-Astrometrie von Objekten des geostationären Ringes”, Technische Universität Wien, Austria, 1996.

[10] G. Stern, “Projective geometry”, EDMS n° 1282043, 2013.

[11] S. Guillaume et al., “QDaedalus: Augmentation of Total Stations by CCD Sensor for Automated Contactless High-Precision Metrology”, FIG Working Week, Rome, Italy, 2012.

[12] B. Buerki et al., “DAEDALUS: A versatile usabledigital clip-on measuring system for Total Stations”, International Conference on Indoor Positioning and Indoor Navigation (IPIN), Zurich, IEEE, 2010.