FEASIBILITY STUDY OF MULTIPOINT BASED LASER ALIGNMENT SYSTEM FOR CLIC

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Abstract

CLIC (Compact LInear Collider) is a study for a future electron-positron collider that would allow physicists to explore a new energy region beyond the capabilities of today's particle accelerators. Alignment is one of the major challenges within the CLIC study in order to achieve the high requirement of a multi-TeV center of mass colliding beam energy range (nominal $3\,\mathrm{TeV}$). To reach this energy in a realistic and cost efficient scenario all accelerator components have to be aligned with an accuracy of $10\,\mu\mathrm{m}$ over a sliding window of $200\,\mathrm{m}$. The demand for a straight line reference is so far based on stretched wires coupled with Wire Positioning Sensors (WPS). These solutions are currently further developed in order to reduce the drawbacks which are mainly given by their costs and difficult implementation. However, it should be validated through inter-comparison with a solution ideally based on a different physical principle. Therefore, a new metrological approach is proposed using a laser beam as straight line reference. Optical shutters paired with CCD (Charge-Coupled Device) based cameras are proposed to visualise the laser beam. This new technology is currently studied and developed in an optical laboratory. The paper presents the alignment principle, the theoretical background, and introduces related key-parameters. First experiments were performed based on a $2\,\mathrm{m}$ long setup in order to validate the principle. Low cost components were implemented for these tests which are however showing encouraging results. The conclusion allows a first approximation of achievable measurement precision and repeatability. In addition these experiments are building up a basis for a first extrapolation of the accuracy over a longer distance.

INTRODUCTION

The Compact LInear Collider (CLIC) study is a feasibility study aiming at the development of a realistic technology at an affordable cost for an electron-positron linear collider [1]. One of the important technical challenges is the critical pre-alignment requirements for the two main linear accelerators (linacs), especially the Beam Delivery System (BDS). The beam related components have to be actively pre-aligned within an accuracy of $10\,\mu\mathrm{m}$ rms over a sliding window of at least $200\,\mathrm{m}$ along the $20\,\mathrm{km}$ of linac[2].

A solution based on overlapping wires and Wire Positioning Sensors (WPS) has been proposed for the Conceptual Design Report (CDR)[3, 4]. But this solution has some drawbacks and should be validated through inter-comparison with an alternative solution based on another technology. As currently no "off the shelf" solution exists, a new metrological approach is proposed using a laser beam as alignment reference.

This proposal is based on observing the laser diffraction pattern on targets oriented perpendicular to a laser beam and mechanically switched to intersect with the laser beam during the measurement. The technical concept is based on a high power laser source and an assembly of a lens with an optical sensor and image processing. This method would allow the implementation of N points in a sector length of about $200\,\mathrm{m}$. Moreover, the straightness of the reference beam is not damaged by the use of shutters.

In this paper, the alignment principle and its theoretical background are presented first. Then, laser beam and sensors relevant parameters are studied. Finally, some results obtained during experiments at short distance ($2\,\mathrm{m}$) are discussed.

ALIGNMENT PRINCIPLE

The straight line reference of the alignment system is the laser beam. The elements that have to be aligned with respect to the laser beam are linac components (see Figure 1).

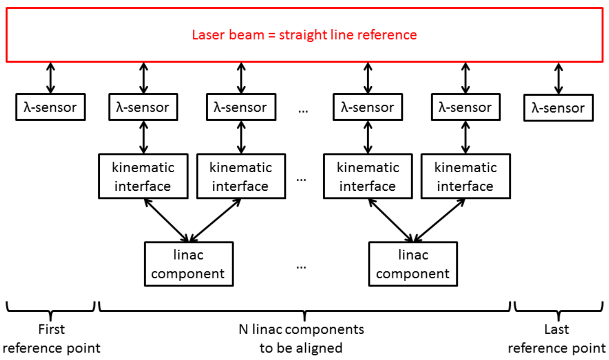

Figure 1: Alignment principle

The alignment is done by using λ-sensors[1]. A λ-sensor is made of a shutter/lens/CCD assembly (see also Figures 2, 3 and 4). When the shutter is closed, the sensor can provide

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

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the radial and vertical offset with respect to the laser beam in the sensor coordinate system. Each linac component is connected to two λ-sensors by means of kinematic interfaces. Linac components are fiducialised with respect to their kinematic interfaces, e.g. their reference axis have been determined with respect to external alignment references or fiducials.

During one measurement cycle, all λ-sensors are used one after the other: shutter is closed, data is acquired, shutter is reopened. Moreover, reference points at both ends are registered before and after a measurement cycle in order to detect possible laser beam fluctuations.

THEORETICAL BACKGROUND

The theoretical background of the laser alignment system has already been presented in [5]. The main ideas of the technical proposal are summarised in this section.

A first result of the theoretical analysis is based on geometrical optics and shows how to determine the spot centre coordinates on the shutter with respect to the spot centre coordinates on the CCD. Figure 2 and Figure 3 give the transversal and the vertical overview of a CCD/lens/shutter assembly.

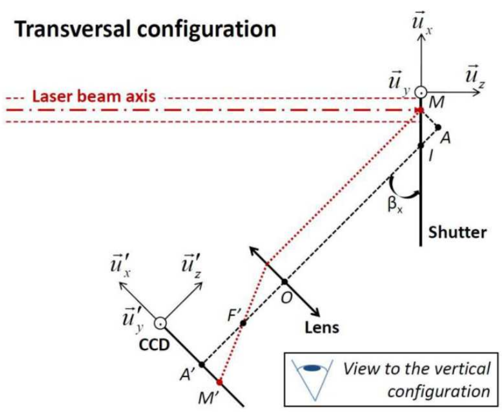

Figure 2: Top view of the sensor principle

Following variables are used in order to simplify the equations:

$$\begin{aligned} \overline{OI} &= d_1 \\ \overline{A'F'} &= d_2 \\ \overline{F'O} &= f \\ \overline{IA} &= \overline{IM} \cdot cos(\beta) \\ \overline{AM} &= \overline{IM} \cdot sin(\beta) \end{aligned}$$

In the transversal case, the angle β becomes β_x, the reading of the CCD is $x_\mathrm{ccd} = \overline{A'M'}$ and the transversal coordinate of the spot centre on the shutter is $x_\mathrm{sh} = \overline{IM}$.

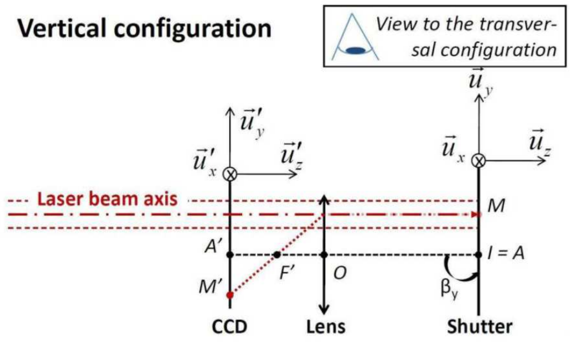

Figure 3: Side view of the sensor principle

In the vertical case, the angle β becomes β_y, the reading of the CCD is $y_\mathrm{ccd} = \overline{A'M'}$ and the vertical coordinate of the spot centre on the shutter is $y_\mathrm{sh} = \overline{IM}$. Thus, it is possible to write a relation between the spot centre coordinates on the shutter and the spot centre coordinates on the CCD:

$$x_\mathrm{sh} = -\frac{d_1 \cdot x_\mathrm{ccd}}{(f + d_2) \cdot sin(\beta_\mathrm{x}) + x_\mathrm{ccd} \cdot cos(\beta_\mathrm{x})}$$

$$y_\mathrm{sh} = -\frac{d_1 \cdot y_\mathrm{ccd}}{(f + d_2) \cdot sin(\beta_\mathrm{y}) + y_\mathrm{ccd} \cdot cos(\beta_\mathrm{y})}$$

Another result of the theoretical analysis deals with estimations for lens and CCD requirements and is based on the propagation of uncertainty theorem. Let us define:

- σ_{x_sh} and σ_{y_sh}: precision of x_sh and y_sh,
- p_i: i^th parameter that has an effect on x_sh and y_sh,
- σ_{p_i}: precision of p_i.

If all parameters p_i are independent, then following relationships can be written:

$$\sigma_{x_\mathrm{sh}}^2 = \sum_{i=1}^{n} \left(\frac{\partial x_\mathrm{sh}}{\partial p_i}\right)^2 \cdot \sigma_{p_i}^2$$

$$\sigma_{y_\mathrm{sh}}^2 = \sum_{i=1}^{n} \left(\frac{\partial y_\mathrm{sh}}{\partial p_i}\right)^2 \cdot \sigma_{p_i}^2$$

Based on these equations, simulations were made with $d_1 = 80\,\mathrm{mm}$, $d_2 = 20\,\mathrm{mm}$, $f = 20\,\mathrm{mm}$, $\beta_\mathrm{x} = 45°$, $\beta_\mathrm{y} = 90°$ and a CCD range of measurement of $\pm 2.5\,\mathrm{mm}$. As a result, it was found that shutter position has to be repeatable within $12\,\mu\mathrm{m}$ and shutter angular orientation within $0.2\,\mathrm{mrad}$.

Several comments should be made about these simulation results. First of all, five variables are supposed to be independent (d_1,d_2,f,β_{x} and β_{y}). However, if it is assumed that d_1 and f are independent, then there is only one possible choice for d_2 in order to have a sharp image. Thus, only four independent variables remain.

Moreover, in the simulation, it was assumed that each sum term $\left(\frac{\partial x_{\mathrm{sh}}}{\partial p_i}\right)^2 \cdot \sigma_{p_i}^2$ and $\left(\frac{\partial y_{\mathrm{sh}}}{\partial p_i}\right)^2 \cdot \sigma_{p_i}^2$ had to be equal to $1\ \mu\mathrm{m}^2$. In reality, requirements are higher: Each sum $\sigma_{x_{\mathrm{sh}}}^2$ or $\sigma_{y_{\mathrm{sh}}}^2$ has to be equal to $1\ \mu\mathrm{m}^2$. Since each sum has four terms, $\left(\frac{\partial x_{\mathrm{sh}}}{\partial p_i}\right)^2 \cdot \sigma_{p_i}^2$ and $\left(\frac{\partial y_{\mathrm{sh}}}{\partial p_i}\right)^2 \cdot \sigma_{p_i}^2$ have to be equal to $0.25\ \mu\mathrm{m}^2$.

With these new assumptions and if the same parameter values are kept, shutter position would have to be repeatable within $4\ \mu\mathrm{m}$ and shutter angular orientation within $0.06\ \mathrm{mrad}$.

However, in the lab, the used hardware and configuration had different characteristics than those considered during the theoretical study. Indeed, following parameter values were registered: $d_1 = 190\ \mathrm{mm}$, $f = 25.08\ \mathrm{mm}$, $\beta_{\mathrm{x}} = 84°$, $\beta_{\mathrm{y}} = 90°$ and a CCD range of measurement of $\pm 2.304\ \mathrm{mm}$. With these characteristics, shutter position has to be repeatable within $6\ \mu\mathrm{m}$ and shutter angular orientation within $1.3\ \mathrm{mrad}$. The most challenging requirement would certainly be the first one. Indeed, between two series of measurements, each shutter is closed and opened. The very tight precision ($6\ \mu\mathrm{m}$) requires a huge effort in mechanics in order to place each time the shutter at the same position.

STUDY OF KEY-PARAMETERS

In order to meet CLIC-project requirements, many challenges have to be taken up. Indeed, λ-sensors are subject to several constraints: measurement repeatability has to be $1\ \mu\mathrm{m}$, measurement accuracy $5\ \mu\mathrm{m}$ and measurement range $\pm\ 3\ \mathrm{mm}$. Moreover, the sensor has to be compact (max: $10\ \mathrm{cm} \times 10\ \mathrm{cm} \times 10\ \mathrm{cm}$). Besides, the distance sensor to laser beam has to remain small because of integration into the pipe. The development of such a sensor requires an analysis of each part of the alignment system in terms of measurement accuracy, precision and repeatability. Table 1 gives an overview of relevant parameters with the corresponding challenges and their solutions.

Until now, the study has remained at theoretical level. In order to have a better understanding of the influence of these parameters on measurement precision and repeatability, first simple experiments were undertaken.

FIRST EXPERIMENTS AND RESULTS

Objective

The objective of the experiment is to study measurement precision and repeatability with a camera that moves perpendicular to the laser beam over a small distance ($50\ \mu\mathrm{m}$).

Configuration

The experimental setup is shown in Figure 4 and comprises four main steps:

- Beam production and orientation done by laser, optical fibre and collimator,
- Beam interruption done by shutter,
- Data acquisition done by CCD/lens assembly, hereinafter referred to as "camera",
- Data processing done by computer.

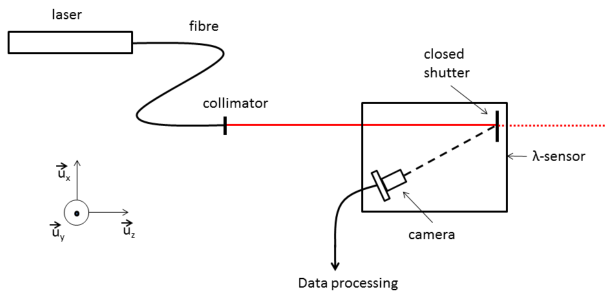

Figure 4: Top view of the experimental setup

The laser beam passes through the optical fibre and propagates from the collimator to the closed shutter. The laser spot formed on the surface of the shutter is captured by the camera. The images are sent to the computer for data processing. For each image, the laser spot centre is computed by means of two-dimensional Gaussian matching[7]. An average over all computed points is done and gives an estimation of the spot centre position.

The camera is placed on a micrometric stage that can be moved manually in $\vec{u}_{\mathrm{x}}$ direction from $0\ \mu\mathrm{m}$ to $50\ \mu\mathrm{m}$ with a step of $10\ \mu\mathrm{m}$. The shutter is placed at a distance of $2000\ \mathrm{mm}$ from the collimator. The camera lens is placed at a distance of $190\ \mathrm{mm}$ from the shutter with an angle $\beta_{\mathrm{x}} = 84°$ and an angle $\beta_{\mathrm{y}} = 90°$. The room temperature is 22°.

Hardware characteristics

The laser is HeNe with a wavelength $\lambda = 633\ \mathrm{nm}$. Its pointing stability is better than $0.03\ \mathrm{mrad}$ after 30 min and its long-term drift $\pm 2\%$ per hour. Moreover, the noise (rms) is less than 1% and the noise frequency 30 Hz to $10\ \mathrm{MHz}$.

The focal length of the camera lens is $f = 25.08\ \mathrm{mm}$. The CDD is 1/3" CMOS with a resolution of 1280×1024 and a pixel size of $3.6\ \mu\mathrm{m}$.

Protocol

The camera does two round-trips in $\vec{u}_{\mathrm{x}}$ direction (radial) between $x = 0\ \mu\mathrm{m}$ and $x = 50\ \mu\mathrm{m}$ with a step of $10\ \mu\mathrm{m}$. This means that the camera 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 four data points (crosses) per x-value (see Figures 5 - 8).

Table 1: Parameters, challenges and solutions

Parameters	**Challenges**	**Solutions**
Beam straightness	Air molecules or temperature gradient change refraction index and cause beam distortion	Use of vacuum pipe Use of stationary waves[6] or continuous air flow in order to stabilise the beam
Shutter surface	If too flat, shutter like a mirror, if too rough, blurred image	Optimal order of magnitude for roughness: laser wavelength
Shutter orientation	Wrong orientation after opening/closing	Improve shutter stability after opening/closing
Spatial resolution	Limited by Rayleigh criterion (order of magnitude = $\frac{0.61 \cdot \text{laser wavelength}}{\text{numerical aperture}}$) and CCD resolution (order of magnitude = pixel size)	Compromise between both factors (best spatial resolution achievable = half laser wavelength)
	Limited by Gaussian matching algorithm and target detection algorithm	Compromise between both algorithms

Each time, 40 images are captured. For each image, the laser spot centre is computed by means of two-dimensional Gaussian matching. Then, the mean and the standard deviation of the spot centre are calculated over 40 measurements.

Observation and interpretation

Figure 5 and Figure 6 present the radial (x-position) and the vertical (y-position) coordinates of the spot centre on the shutter centred around the mean value with respect to the (x-position) of the camera. It can be seen that all values remain in the interval $[-4\ \mu\mathrm{m}, +4\ \mu\mathrm{m}]$ for x and $[-3\ \mu\mathrm{m}, +3\ \mu\mathrm{m}]$ for y. This difference could be explained by the fact that moving along $\overrightarrow{u}_{\mathrm{x}}$ creates more uncertainty for the radial than the vertical coordinate. Moreover, the values obtained at both ends ($x = 0\ \mu\mathrm{m}$ and $x = 50\ \mu\mathrm{m}$) are slightly larger than those in the middle. This could be caused by the backlash within the micrometric stage.

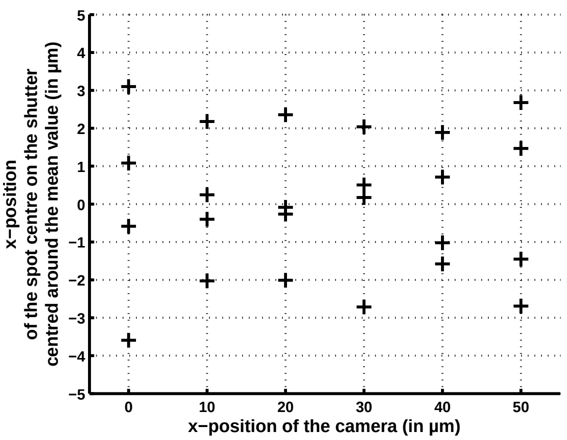

Figure 5: x-position of the spot centre on the shutter centred around the mean value with respect to x-position of the camera

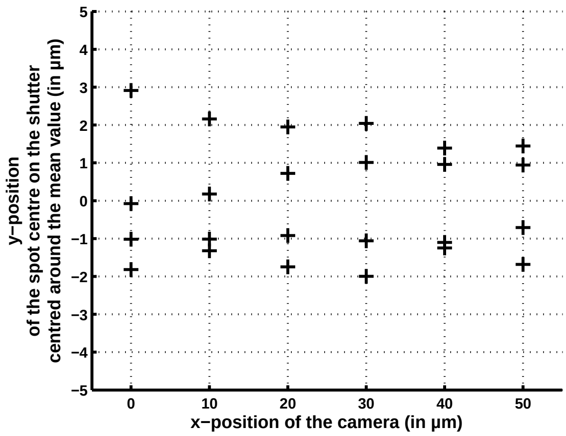

Figure 6: y-position of the spot centre on the shutter centred around the mean value with respect to x-position of the camera

Figure 7 and Figure 8 present the standard deviation over 40 measurements of the radial (x-position) and the vertical (y-position) coordinates of the spot centre on the shutter with respect to the radial (x-position) coordinate of the camera. It can be seen that all values remain smaller than $5\ \mu\mathrm{m}$ for x and $3\ \mu\mathrm{m}$ for y. Moreover, for the vertical coordinate, the majority of the values is smaller than $2\ \mu\mathrm{m}$ or even $1.5\ \mu\mathrm{m}$, which is encouraging for further work.

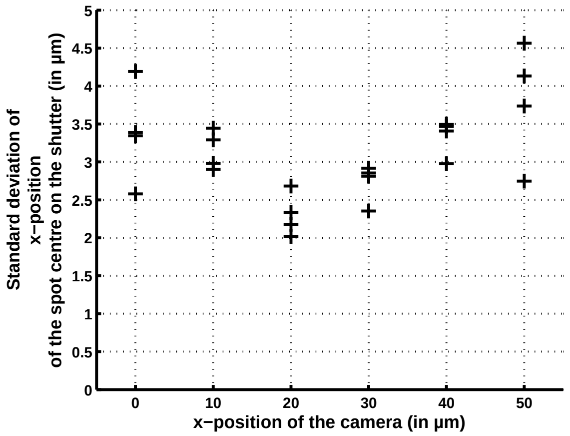

Figure 7: Standard deviation of x-position of the spot centre on the shutter with respect to x-position of the camera

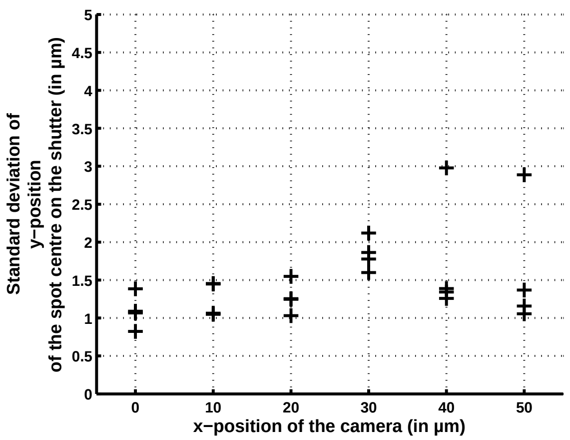

Figure 8: Standard deviation of y-position of the spot centre on the shutter with respect to x-position of the camera

CONCLUSION

A new alignment concept using laser beam as straight line reference has been presented. The physical principles mainly based on geometrical optics were studied and allowed to find mathematical relationships between key parameters (e.g. spot coordinates on shutter with respect to spot coordinates on CCD). Then, the uncertainty propagation theorem was used and simulations were made to investigate on the expectable precision. As a result, it was found that shutter position has to be repeatable within $6\ \mu\mathrm{m}$ and shutter angular orientation within $1.3\ \mathrm{mrad}$ This approach also allowed to point out critical design parameters.

Afterwards, this theoretical background was applied on a series of basic lab experiments at short distance (about $2\ \mathrm{m}$). In a first iteration, a simple measurement approach was chosen to demonstrate the feasibility. These tests implied to gain knowledge mainly on measurement repeatability and precision. Even if these experiments were performed with low cost elements and simple methods, the results were encouraging. A $50\ \mu\mathrm{m}$ camera displacement with a $10\ \mu\mathrm{m}$ step gave a measurement repeatability within an interval of $[-4\ \mu\mathrm{m}, 4\ \mu\mathrm{m}]$ around the mean values. The related standard deviation was computed to be smaller than $5\ \mu\mathrm{m}$. Complementary tests are scheduled in order to validate further system parameters with a higher level of detail. In this scope an automatised micrometric table has been ordered and should contribute to improve the study of the measurement uncertainty of the whole system.

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