Feasibility of the CLIC metrological reference network

T. Touzé, Université de Paris-Est, Marne-La-Vallée, France
CERN, Geneva, Switzerland

Abstract

The CLIC[1] project has imposed pre-alignment tolerances on the transversal and vertical positions of the components of 10 μm along a 200 m sliding window. This specification has led to the concept of overlapping stretched wires being used as pre-alignment references and as the basis of a metrological reference network. In order to demonstrate the feasibility of this concept, the problem has been broken down in terms of the management of coordinate systems. This requires the systematic use of absolute calibrated sensors and CMM[2] measured supports. In addition, a more reliable model of stretched wires has been developed. This paper describes the simulated and experimental results from the 140 m TT1[3] setup.

INTRODUCTION

Before the implementation of the beam based feedback, the components of the CLIC main linac must be pre-aligned according to 3σ tolerances on their transversal and vertical positions of 10 μm along a 200 m sliding window [1].

A pre-alignment strategy has been defined, from the geodetic measurement on the surface to the final positioning in the tunnel [4]. The metrological reference network (MRN) is designed to provide the parameters of the stretched wires modelings, according to which the CLIC components will be pre-aligned. Because of the tight error budget along 200 m, the MRN can be considered as the cornerstone of the pre-alignment strategy.

This paper is going to present the conceptual design of the MRN. It has been split in three main steps: the sensors calibration, the metrology of the supports and the modelings of the sensors measurement references. As this system is now fully determined, it was possible to compute relevant Monte-Carlo simulations.

COORDINATE SYSTEMS INVOLVED IN THE MRN

The overlapping stretched wires is the main concept of the solution proposed by the CERN survey team for the pre-alignment feasibility [2]. But in order to fully determine this principle, it required the analysis of the metrological chain ensuring the overlap. This part is going to describe it, as an introduction for the experimental and simulated results.

Principle of the MRN

The solution proposed by the previous R & D of the CERN survey team to fulfill the requirements consists of overlapping alignment references with redundancy [4] (see the figure 1). This principle is the basis of the MRN. In order to pre-align the CLIC components, the MRN defines the alignment references in a general coordinate system [4]. The geometrical linkage from the references to the components beam axis is ensured by the combination of the SPN[4] [4] and of the fiducialization [4].

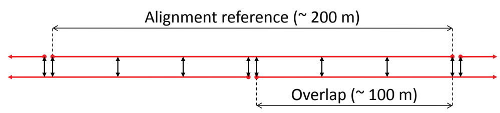

Figure 1: Principle of the overlapping references

Several measurement systems could be applied to the overlapping principle. However the R & D presented in this document are focused on the stretched wires measured by WPS[5] sensors, provided by the manufacturer *Fogale Nanotech*. In order to strengthen the determinism in the MRN, hydrostatic surfaces — measured by *Fogale Nanotech* HLS[6] sensors — and tiltmeters are added.

The starting point of the MRN feasibility studies was the metrological definition of the overlapping wires. Those references are measured by independent sensors that positions and orientations must be known according to each other. The problem remains the same by including in the system the measurements of the HLS and of the tiltmeters.

Metrological plate concept

This statement has led to the concept of metrological plate on which the sensors are fixed. If one considers the plate as an undeformable object, the relative positions and orientations of the sensors, according to each other, are constant. By a high accuracy machining or a high precision calibration of the plate, the knowledge of those relative positions and orientations just depends on the absolute calibrations of the sensors and their possible drifts.

[1]Compact Linear Collider
[2]Coordinates Measuring Machine
[3]Transfer Tunnel 1
[4]Support Pre-alignment Network
[5]Wire Positioning System
[6]Hydrostatic Levelling System

A design of such plates has been made in 2006 for a pre-alignment facility in the TT1. It has been updated many times. The last version, installed in 2009, includes three balls isostatic interfaces for the WPS and tiltmeters centerings [6]. The plates are made of invar[7] and have been measured in the CERN metrological laboratory by a 6 µm uncertainty CMM (2σ).

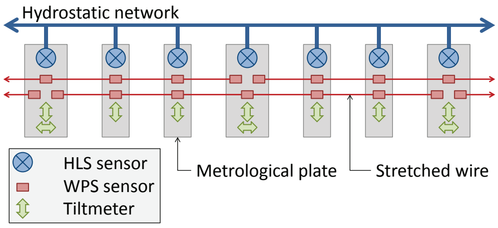

Figure 2: The metrological reference network

Hence, the MRN is composed by calibrated metrological plates on which tiltmeters, WPS and HLS sensors are fixed (see the figure 2). The overlapping stretched wires and the hydrostatic surfaces are observed by sensors fixed to different metrological plates.

Metrological chain

Let us consider W as a point of a stretched wire measured by a WPS sensor. If the zero and the measurement axis of the sensor have been defined with respect to a three balls interface, W is known in the balls system (see the figure 3). The CMM provides the coordinates of all the balls in the plate system. By usual vectorial operations, one can build the interfaces coordinate systems and deduce their transformations to the plate system. W is defined with respect to the metrological plate. How this point can be expressed in the general coordinate system ?

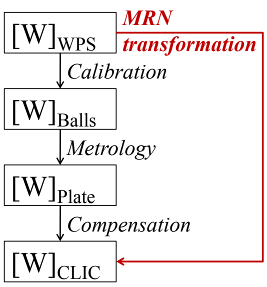

Figure 3: Metrological chain of the MRN

First of all, the CLIC longitudinal alignment specifications are less critical, so it is not necessary to dispose of high precision values for the longitudional position, the pitch and the yaw of the plates in the general coordinate system. According to the TT1 simulations, those parameters can be deduced from the usual alignment method with 0.2 mm and 1 mrad standard-deviations for, respectively the longitudinal and both of the rotations [7].

Then, each plate is supporting one tiltmeter from which the roll can be deduced. This step will be described in the last part of this paper.

Finally, each wire and each hydrostatic surface are measured in several points corresponding to different metrological plates. In other words, a relationship can be written between the points W in the plates system, the transformations from the plates to the general coordinate system and the modeling of the wire. The same can be done considering the hydrostatic surfaces. Those relationships allow a least square adjustment from which the transversal and the vertical positions of the plates, as much as the parameters of the stretched wire and the hydrostatic surfaces, are deduced.

SENSORS AND PLATES CALIBRATIONS

In this part, the developments made to clarify the two first steps of the metrological chain are going to be presented. The main effort has been done on a new interface for the WPS and their calibration bench.

Metrology of the plates

The CMM provides the coordinates, in the plate system, of the centers of $1\frac{1}{2}$" and $3\frac{1}{2}$" diameter survey reflectors, as well as those of the 8 mm diameter ceramic balls constituting the isostatic WPS and tiltmeters interfaces. The zeros of the HLS are measured according to the $3\frac{1}{2}$" diameter survey reflectors that can fit on their tops. The position of the WPS zeros is measured with respect to the three balls interfaces. The plate CMM measurement deals with the second step of the metrological chain (see the figure 3) which consists of the definition of the sensors interfaces according to the plate system.

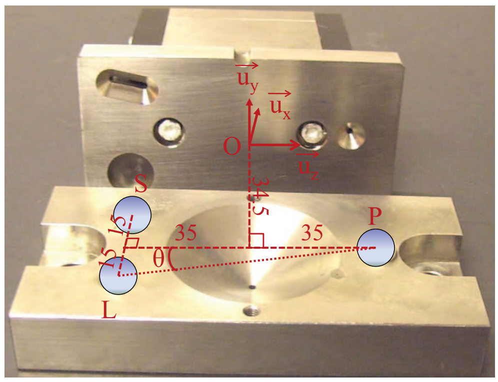

Figure 4: WPS 3 balls interface (distances in mm)

Let us consider the case of the three balls non-redundant isostatic interface of the WPS (see the fi-

[7] Invar (FeNi36) is a nickel steel alloy. Its coefficient of thermal expansion is 1.2 $ppm \cdot K^{-1}$

gure 4). The ball P gives the position of the sensor. It is locking its position. Because it is free along an axis, the L ball is locking the pitch and yaw. As S is in contact against a surface, it fixes the last degree of freedom of the system, the roll. The interface coordinate system is built with respect to the kinematic effects of each point [7].

The interface coordinate system is defined by an origin O and an orthonormal basis $(\overrightarrow{u_x}, \overrightarrow{u_y}, \overrightarrow{u_z})$ (see the figure 4). The vertical axis $\overrightarrow{u_y}$ is orthogonal with the plan of the three balls. The longitudinal axis $\overrightarrow{u_z}$ is given by the balls locked in position and axis.

$$\left\{ \begin{array}{lcl} T & = & [O]_{plate} \\ R & = & \left[\begin{array}{ccc} \overrightarrow{u_x} & \overrightarrow{u_y} & \overrightarrow{u_z} \end{array} \right] \\ & = & R_z(\alpha_z) \times R_y(\alpha_y) \times R_x(\alpha_x) \end{array} \right. \quad (1)$$

The 3D transformation from the interface to the plate coordinate system is given by a translation and a rotation matrices T and R which are directly obtained by the vectorial operations [7] (see the relationship 1). Then the rotation matrix is the product of three elementary rotations α_z, α_y and α_x around, respectively, the longitudinal, transversal and vertical axis.

HLS offset calibration

The HLS sensor provides the distance from its electrical zero to the hydrostatic surface. In order to be able to apply this measurement, the HLS electrical zero must be defined with respect to the plate. The calibration sketched on the figure 5 gives the distance from the electrical zero to the center of a Taylor sphere on the top of the HLS [5].

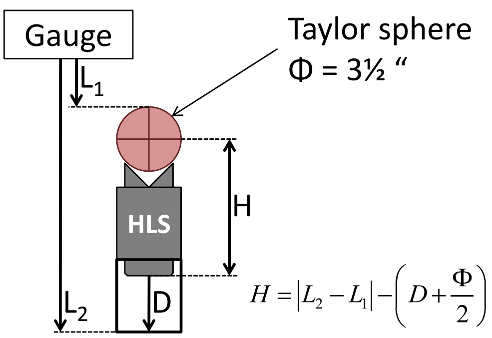

Figure 5: Calibration of the HLS offset

$$\varepsilon = (D + H) \cdot (1 - \cos\beta) \quad (2)$$

The measurement axis of the HLS sensor is assumed to be the same as the vertical direction of the plate coordinate system. The assembly of the HLS makes the distance H (see the figure 5) equal to 123 mm ± 50 µm. Considering a HLS reading of 10 mm (the longest it can achieve), a 0.3° non-verticality angle β will induce an error ε of 2 µm on the vertical distance from the Taylor center to the water surface (see the equation 2). Such an angle can be easily avoided by a control of the plate's orientation during installation with a reasonably accurate levelling system. This definition of the measurement axis of the HLS can be considered as efficient enough.

The seven HLS installed in the TT1 have been calibrated. As the gauge has been checked in the CERN metrological laboratory [7], those calibrations have been simulated by the Monte-Carlo method, assuming a Gaussian behavior with a 1 µm standard deviation on the HLS measurements [7]. According to a χ^2 Pierson's test, all the seven simulated offsets have a 0.9 µm standard deviation Gaussian distribution [7]. But it is not yet possible to claim the accuracy of the HLS sensors is 0.9 µm. Further tests have to be done.

WPS offset calibration

The WPS sensor provides the transversal and vertical positions of the wire with respect to its electrical zero. The sensors readings can be considered as the position of a point of a wire in a coordinate system which has to be defined according to the three balls system. The interface coordinate system is built in order to have the six degrees of freedom close to zero. The pitch and the yaw can be neglected if both of them are smaller than 1° [5]. The longitudinal position is assumed to be zero. There are still two remaining translations — the transversal and vertical —and one rotation — the roll.

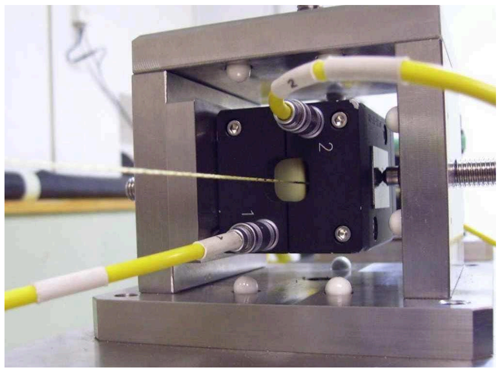

Figure 6: WPS offset calibration bench

A calibration bench has been designed to measure the transversal and the vertical offsets of the WPS sensor. The references used for the calibration are the coordinates of the balls which have been measured in Germany on a 0.6 µm standard deviation CMM [7]. The sensor measures one single constant point of a wire on four different known interfaces (see the figure 6). The transversal and the vertical offsets of the sensor can be computed from the observations. Monte-

Carlo simulations have also been made on seventeen calibrated sensors. The standard deviation of both of those parameters are respectively 1.7 µm in transversal and 0.9 µm in vertical [7].

The calibration required thirty-six centerings per sensor, on side and upside-down interfaces [7]. A value of the repeatability of all the sensors has been deduced (see the table 1). The mean repeatabilities are, respectively, 1.1 µm in transversal and 0.7 µm in vertical [7].

Table 1: Repeatability of the WPS

Repeatability	**Transversal**	**Vertical**
Minimum	0.6 µm	0.5 µm
Mean	1.1 µm	0.7 µm
Median	1.0 µm	0.7 µm
Maximum	1.8 µm	1.0 µm
STD	0.4 µm	0.1 µm

Unfortunately, the bench is unable to provide an accurate values of the WPS roll. The residuals of the calibration are submitted to this parameter. The biggest ones were, depending of the sensor, between 25 µm and 47 µm. This problem will be solved as soon as a linearity calibration bench, that is adapted to the three balls interface, is ready at CERN. In other words, the accuracy of the WPS has actually been improved to the detriment of its precision.

RESULTS OF THE TT1 FACILITY

The TT1 facility design is close to the MRN principle. It has to provides the parameters of the stretched wires, in order to use them in the next CLIC prealignment steps to position the components.

$$\begin{bmatrix} X \\ Y \\ Z \end{bmatrix} = T + k \cdot R \times \begin{bmatrix} x \\ y \\ z \end{bmatrix} = \begin{bmatrix} f(Z) \\ g(Z) \\ Z \end{bmatrix} \tag{3}$$

This principle can be written in one equation (see the equation 3). On one hand, there are the coordinates of wires and hydrostatic network in the general system. On the other hand, there are the coordinates of the same points in the plate system. The relationship between those two systems is given by an unknown transformation and the modelings of the wires and hydrostatic network.

Tiltmeters and vertical deflection

Let us introduce $\vec{\zeta}$ as the vector of the vertical direction in one point with a norm equal to 1. A double-axis tiltmeter provides the angles θ_x and θ_y as describe on the figure 7. The coordinates of the vertical vector can be deduced in the tiltmeter system from its measurements (see the equation 4).

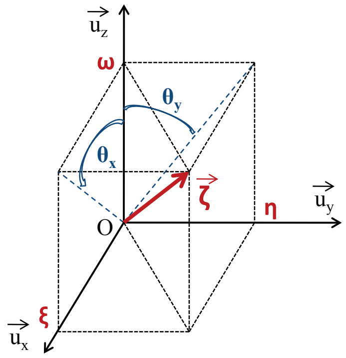

Figure 7: Definition of the tiltmeters angles

$$\begin{cases} \left[\vec{\zeta}\right]_{Incl} = \begin{bmatrix} \xi \\ \eta \\ \omega \end{bmatrix} = \omega \cdot \begin{bmatrix} \tan\theta_x \\ \tan\theta_y \\ 1 \end{bmatrix} \\ \omega = \sqrt{1-\xi^2-\eta^2} = \dfrac{1}{\sqrt{1+\tan^2\theta_x+\tan^2\theta_y}} \end{cases} \tag{4}$$

This is a general definition for the measurements of tiltmeters with respect to the vertical direction and the sensors coordinate systems. Most of the time, this relationship can be simplified and linearized. In order to deduce the roll of the metrological plate from it, on one hand this system must be known according to the plate metrology. On the other hand an equation will be obtained including the coordinates of the vertical direction in the general coordinate system, that is to say the value of the vertical deflection (see the equation 5).

$$\left[\vec{\zeta}\right]_{CLIC} = R \times r \times \rho \times \begin{bmatrix} \omega \cdot \tan\theta_x \\ \omega \cdot \tan\theta_y \\ \omega \end{bmatrix} \tag{5}$$

In the equation 5, the unknown parameter is the roll α_z of the plate (see the equation 1). It is included in the rotation matrix R. The rotation matrices r and ρ belong respectively to the transformation from the tiltmeter three balls interface to the plate system, and from the tiltmeter axis to its interface. They are provided respectively by the CMM measurements and by the tiltmeter calibration.

If tiltmeters are used to deduce the roll of an object in a general coordinate system, it is necessary to solve the equation 5. Hence, it is necessary to know the vertical deflection and to use double-axis tiltmeters. Otherwise it is impossible to obtain the ρ matrix by any calibration process.

Hydrostatic surface modeling

The knowledge of the geoid is not only required for the tiltmeters but also for the hydrostatic network, measured by HLS sensors. The water directly follows the equipotential surface of gravity which is varying in time due to the tides effects [8].

Let us introduce an hydrostatic network, whom center is $C(X_C, Y_C, Z_C)$, in a Cartesian coordinate system. The angle between the vertical axis of the coordinate system and the normal direction of the geoid in C is β_0 (see the figure 8). Because of the tides, the water surface oscillates in time around C by an angle $\Delta\beta(t)$. If one can consider the geoid along the hydrostatic network as a sphere whom radius is c, the equation 6 can be written.

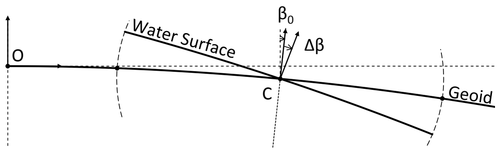

Figure 8: Modeling of an hydrostatic network

$$\begin{cases} \beta = \beta_0 + \Delta\beta(t) \\ \Delta Z = Z - Z_C \\ Y = Y_C - c\cos\beta + \sqrt{c^2 - (\Delta Z + c\sin\beta)^2} \end{cases} \tag{6}$$

In 6, Z and Y respectively the longitudinal and vertical positions of one point of the hydrostatic network. The longitudinal informations Z_C and Z are provided by the survey usual measurements of the facility. $\Delta\beta(t)$ can be obtained by tides prediction or by geophysics high resolution tiltmeters [8]. c and β_0 are given by the geoid modeling. The single undetermined parameter of the hydrostatic network is the height of the center Y_C.

Stretched wires

Two modelings are used for the stretched wires, for both of the horizontal and vertical cases. Let us introduce a wire stretched between two points O and L. $O(x_0, y_0, z_0)$ is considered as the origin of the wire, whereas $L(x_0 + p, y_0 + z, Z_0 + l)$ is its end. When the wire is projected on a horizontal plan, a straight line is obtained.

In the vertical direction, the wire modeling is a catenary equation that can be linearized by a second order polynomial [3] (see the figure 9). A point M belongs to the wire if it is in accordance with the equation 7.

$$M(x, y, x) \in \{\mathcal{WIRE}\} \Longleftrightarrow$$

$$\begin{cases} x = x_0 + \dfrac{p(z - z_0)}{l} \\ y = y_0 + \dfrac{4f(z - z_0)^2}{l^2} + \dfrac{(h - 4f)(z - z_0)}{l} \\ z_0 \leq z \leq z_0 + l \end{cases} \tag{7}$$

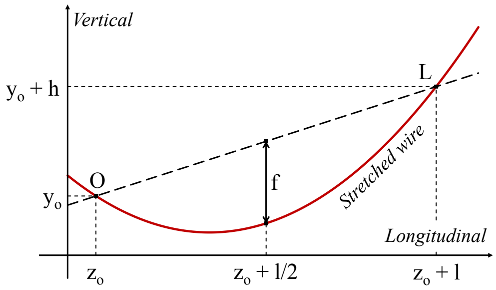

Figure 9: Vertical modeling of a stretched wire

This modeling is reliable if the forces involved in the wire equilibrium are constant in space. The effect of a gravity gradient has been previously studied. It has been demonstrated it can be neglected [2]. However the catenary modeling depends on the ratio between the linear mass of the wire q and its tension T. It has been shown that this ratio was linearly dependent with the relative humidity [6].

If one can accurately model the effect of humidity on the ratio $\frac{q}{T}$ and measure the humidity gradient along the setup, it should be possible to compute corrections of the polynomial modeling of a stretched wire. Seven humidity sensors have been installed along the TT1 facility. The value of this ratio can be obtained by measuring the wire oscillation frequency ϕ [3] (see the equation 8). This measurement can also provide the value of the sag of the wire f. Improvement have to be done to increase the frequency determination precision — 2 mHz — but it is efficient enough to get the sag of the 49 m TT1 wire with a 2.5 µm precision [7].

$$\frac{q}{T} = \frac{8f}{gl^2} = \frac{1}{4l^2\phi^2} \tag{8}$$

The measurement of the wire oscillation frequency has many advantages. It is possible to build a more reliable vertical modeling, to remove the sag from the unknown parameters and to check in real time the state of the wire. Indeed the value of the ratio $\frac{q}{T}$ points out the state of the wire at a precise instant. If this value is abnormally varying, one can expect the wire to break.

Final adjustment

In summer 2009, the measurements of the TT1 facility have been studied during a 33 days period. The precision of the stretched wires and of the hydrostatic network after the final adjustment was 2 µm [6]. As the calibration bench for the WPS offsets was not finished, it was not possible to compute the accuracy of the facility.

All the WPS sensors have been calibrated in November 2009. Hence it was possible to get a value of the TT1 accuracy (see the figure 10). The offsets had an

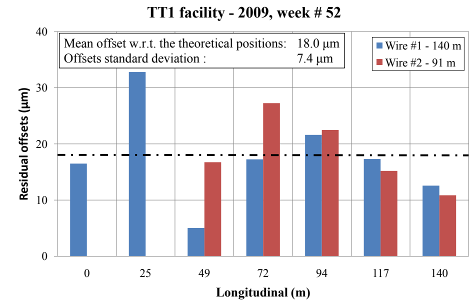

Figure 10: Accuracy after the final adjustment

average value of 18 µm. Gross errors were detected by a norm minimization (instead of a least square adjustment). It was due to unglued ceramic balls. The plates calibrations were lost.

Since then, the TT1 facility did not provide better results, even with an epoxy gluing of the balls, because of the unknown rolls of each WPS and because no high precision model of the TT1 vertical deflection is available. The accuracy of the TT1 facility can only be estimated by Monte-Carlo simulations.

The TT1 network has been modeled and simulated by the Monte-Carlo method of distribution propagation by using "MatLab". The network has been split in ten steps, from the calibration benches CMM measurements to the final positioning of a point from a stretched wire [7]. Each step is simulated independently. It provides the mean values and the covariance matrix of the simulated parameters which are exported for the next steps.

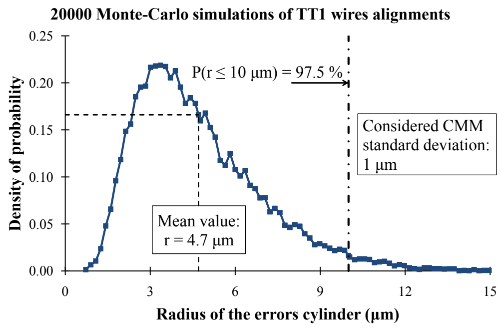

Figure 11: Radius of the 140 m TT1 errors cylinder

The last step of the TT1 simulations consists of the positioning of a point every meter per wire, according to the equation 7. The covariance matrix of the coordinates of those points permits to compute the errors along the 140 m of the TT1. For each simulation, the mean radius of the cylinder that contains all the errors has been computed. Its distribution, considering a 1 µm CMM uncertainty, is presented on the figure 11. The mathematical expectation of the radius, computed from the empirical density of probability, is 4.7 µm. 97.5 % of the 1000 simulated radius are smaller than 10 µm.

CONCLUSION

The experimental results of the TT1 facility are limited by the WPS roll calibration, by the knowledge of the vertical defection and by the CERN's CMM uncertainty (6 µm at 2σ today, 0.4 µm MPE[8] in a few months). However it was possible to simulate those results. Along 140 m, the positions of hundreds of points are defined in a 10 µm error cylinder, in 97.5 % of the simulated cases. This result includes a wire overlap. The ability of the MRN to provide pre-alignment references within the specifications is close to be demonstrated.

Indeed the principle of this network is defined and perfectly determined. The algorithms are written. By solving the limitations of the TT1 precision, it should be possible to demonstrate the accordance between the experimental and simulated results. Then, it will be possible to extrapolate the entire CLIC pre-alignment if plausible values of the tides effects and of the geoid modelings are available. Both of those topics represent huge challenges and further developments have to be done [8].

REFERENCES

[1] D. Schulte, "Pre-alignment needs for CLIC", CLIC Pre-alignment workshop 2009, CERN, Geneva, Switzerland, 2009.

[2] F. Becker, "Définition d'un réseau de référence métrologique pour le positionnement d'un grand accélérateur linéaire", PhD thesis, Université Louis Pasteur, Strasbourg, France, 2003.

[3] H. Mainaud, "Une nouvelle approche métrologique : l'écartométrie biaxiale. Application à l'alignement des accélérateurs de particules", PhD thesis, Université Louis Pasteur, Strasbourg, France, 1996.

[4] H. Mainaud-Durand et al., "CLIC active pre-alignment system: Proposal for CDR and program for TDR", International Workshop on Accelerator Alignment, DESY, Hamburg, Germany, 2010.

[5] A. Herty, "Micron precision calibration methods for alignment sensors in particle accelerators", Master thesis, Nottingham Trent University, England, 2009.

[6] T. Touzé, "Le réseau de propagation du projet CLIC, analyse des données de l'expérience du TT1", Revue XYZ, 122, march 2010.

[7] T. Touzé, "Simulations du réseau métrologique de référence sur 140 m et résultats expérimentaux associés", EDMS document 1086453, CERN, Geneva, Switzerland, 2010.

[8] M. Jones et al., "Latest results from the CLIC geodetic studies", International Workshop on Accelerator Alignment, DESY, Hamburg, Germany, 2010.

[8] Maximum Permissible Error