MICROMETRIC PROPAGATION OF ERROR USING OVERLAPPING STRETCHED WIRES FOR THE CLIC PREALIGNMENT

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Abstract

The geodetic network for the Compact LInear Collider (CLIC) will consist of a combination of overlapping wires stretched in parallel and Wire Positioning Sensors (WPS). Such a configuration will limit the propagation of errors (maximum deviation w.r.t. a fit line) below 10 µm over 200 m. These first results were obtained through simulations in 2009, with hypotheses remaining to be validated. New experimental results have been obtained allowing to reconsider the accuracy of WPS sensors and the knowledge of stretched wires.

This paper presents the experimental results obtained on dedicated calibration benches and on a test facility made of three overlapping stretched wires over a length of 140 m including WPS sensors measurements. It confirms the possibility to have a propagation of error below 10 µm using overlapping stretched wires combined with WPS sensors.

INTRODUCTION

An active pre-alignment of the CLIC components will be needed, prior to the injection of the pilot beam, within a few micrometres overs sliding windows of 200 m, in order to implement beam based alignment and beam based feedback [1]. The determination of the position will be carried out by WPS sensors attached to the components, measuring transverse offsets w.r.t. a network of overlapping stretched wires propagating the smooth reference of alignment through 25 km of linacs and BDS [2]. The adjustment will be performed by actuators located below the components to be aligned.

In 2009, Monte Carlo simulations of the effects of such pre-alignment configuration on the beam emittance were carried out [3]. More particularly, the offsets of the coordinates of the network points in the linac tunnel were studied. It was shown that the maximum deviation of such coordinates along the tunnel fits between ± 1mm along 25 km. Some hypotheses were not validated at that time: 5 µm uncertainty concerning the calibration of the WPS sensors, 5 µm uncertainty concerning the stability of the wire [4].

This paper presents the progress achieved since 2009. It first recaps the general strategy concerning the sensors and their associated transformations, with the uncertainty of measurement achieved. Then it considers a 140 m facility of overlapping wires, comparing the experimental results to the simulations, before extrapolating over kilometres.

METROLOGICAL PLATES TO LIMIT PROPAGATION OF ERROR

Introduction of the Strategy of Prealignment

The shape of a stretched wire is mathematically known and can be modelled by a straight line in the horizontal plane and a catenary curve in the vertical plane. The accuracy of such a modelling plays a key role in the pre-alignment of the CLIC components. As it is not possible to stretch a single wire over kilometres, 200 m long overlapping wires have been proposed. Two series of wires are set in parallel with an overlap of 100 m (see Figure 1). The metrological plates, located at each extremity of wires, combined with intermediary metrological plates for redundancy, are equipped with WPS sensors and provide wire-to-wire distances to limit the propagation of error.

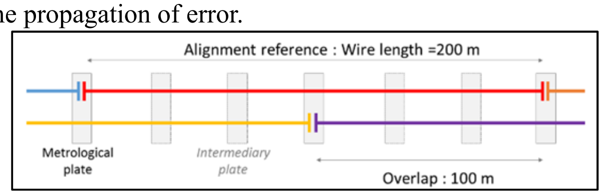

Figure 1: Configuration of overlapping stretched wires.

Such an assembly of metrological plates and parallel wires allows to determine a straight reference of alignment in the general coordinate system.

All CLIC components are equipped with WPS sensors measuring radial and vertical offsets w.r.t. this straight reference of alignment, defining the position of components in the tunnel general coordinate system [5][6].

The Metrological Plates

The metrological plates are a key component of such a strategy (Figure 2).

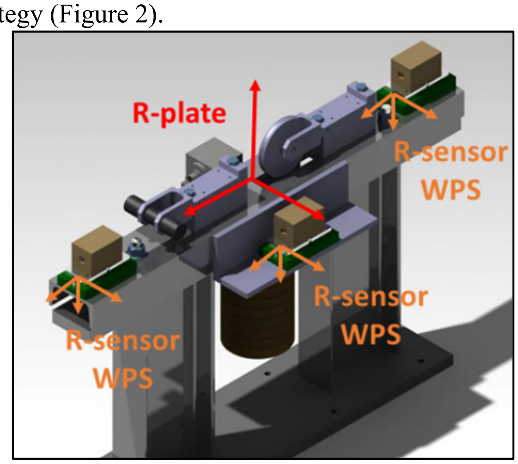

Figure 2 : Design of a metrological plate.

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They consist of 2 or 3 WPS sensors performing radial and vertical offset measurements w.r.t. the two parallel wires, with a micrometric accuracy. These readings correspond to the coordinates of the wire in the sensor system (R-sensor WPS), determined during the calibration process using absolute and linearity benches, at an accuracy better than 5 µm [2]. This value takes also in account the uncertainty of the shape of the wire. The sensor system is defined by a 3 balls kinematic mount. The 3D position of these 8 mm diameter ceramic spheres (grade 40), was measured by a 3D Coordinate Measuring Machine, with a Maximum Permissible Error for length measurement (MPEE) of 0.3 µm + 1 ppm, in the referential frame of the metrological plates (R-plate). A 3D transformation from the sensor coordinate system to the plate coordinate system can be deduced.

The last transformation from the metrological plates to the tunnel general coordinate system can be deduced using a least square adjustment from the parameters of the stretched wires (origin point, linear coefficient and sag). As a matter of fact, the points measured by the WPS sensors installed on the same wire are constrained by the stretched wire modelling.

The concept of the overlapping stretched wire can be improved by adding a hydrostatic network measured with Hydrostatic Levelling Sensors (HLS) in order to strengthen the vertical direction. Such HLS sensors are used to determine the sag of the wire: a catenary can be computed within a micrometric accuracy knowing at least the difference of height between 3 points of the catenary. However, such a hydrostatic system has drawbacks. The free water surface follows the equipotential of gravity. To align the components w.r.t. a straight line, it is then needed to determine the relative vertical deflection along the hydraulic network [7]. On top of this, sensor readings need also to be corrected from tidal effects (moon, sun, sea influences) [8].

SIMULATIONS & ASSOCIATED RESULTS OVER 140 M

Introduction of the 140 m Facility

To validate such a concept of the overlapping wires, a facility has been installed in an old and stable tunnel named TT1. Seven metrological plates were installed along 140 m, equipped with HLS and WPS sensors (Figure 3).

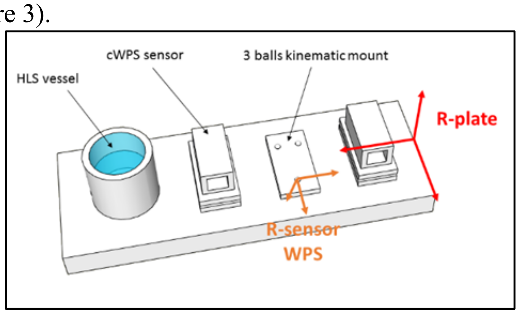

Figure 3 : Configuration of TT1 metrological plate.

Three overlapping wires of different lengths (50 m, 90 m and 140 m) were installed, as well as a hydrostatic network (Figure 4). The distance between the parallel wires is approximately 7 cm.

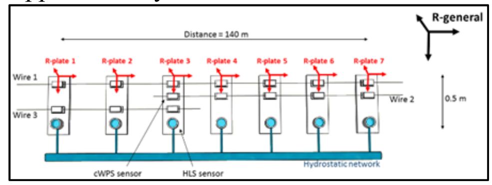

Figure 4 : Configuration of the 140 m facility.

Hypotheses Considered for the Calculation

The objective of the calculation is to determine the position of the 7 plates in the general coordinate system of the tunnel, using the redundant observations given by the WPS and HLS along the 3 wires and the hydrostatic network.

The 6 parameters of Helmert transformation (translation and rotation, [9]) from R-plate-1 to R-general was fixed (fixed point), as well as the radial translation and the roll parameters of the plate 7 (orientation point). The pitch and yaw angles of all the plates, plus their longitudinal position were considered known from the traditional geodetic measurements achieved before, with a few tenths of milliradian precision for the angles, and a millimetric precision for the longitudinal position.

Apart the position of the plates (radial and vertical translation plus roll from R-plate to R-general), additional parameters have been considered as unknowns for the calculation: the parametric equation of the stretched wires including the sag and the altitude of the hydrostatic network. This gave a total of 31 adjustable parameters.

Concerning the 37 sensors observations, an average of 600 points was calculated for the 7 HLS and 15 WPS observations (acquisition frequency of 0.5 Hz over a duration of 10 minutes). The WPS and HLS observations followed independent normal distributions with a 5 µm standard deviation. The equipotential surface of gravity has been approximated by an ellipsoid (Geodetic Reference Ellipsoid GRS-80 [10]). The tidal effects were not included in the calculation as negligible during a 10 minutes acquisition.

Results Versus Simulations

The residuals of the adjustment performed follow a normal distribution with a standard deviation of 2.5 µm. A Pearson's chi-squared test [11] confirms the initial hypotheses including accuracies of WPS and HLS sensors (5 µm).

The radial standard deviations of the positions of the 7 plates installed along the tunnel of 140 m expressed in the R-general coordinate system are below 7 µm in radial (1σ). The vertical standard deviations are below 12 µm. This higher value in vertical is due to the uncertainty of the roll transformation of each plate and the configuration of the TT1 metrological plate.

The propagation error in the TT1 layout has been simulated. The variance-covariance matrix for the estimators of parameters was used to calculate the standard errors.

Figure 5 shows the comparison between the precision of computed radial position of the plates (in blue) w.r.t. the simulated one (in red). The correlation between both curves is very good and demonstrates that such simulations can be extended on higher distances.

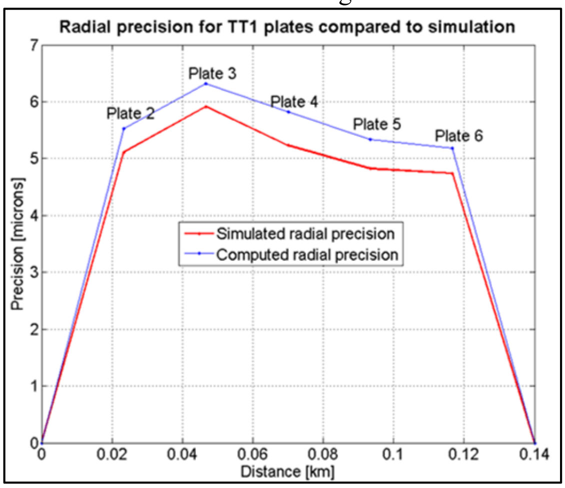

Figure 5: Radial precision for the metrological plate.

SIMULATIONS OVER 25 KM OF LINACS

Hypotheses Considered

Both TT1 simulations and results showed that it is possible to achieve the CLIC pre-alignment requirements over 140 m, and it was decided to extrapolate such results on higher distances. Only radial simulations have been considered. For the vertical simulations, the precision is determined by the knowledge of the equipotential surface of gravity measured with HLS sensors along the tunnel.

For the simulations of the radial propagation errors, the following hypotheses have been considered:

- WPS observations following independent normal distribution with a standard deviation of 5 µm
- Longitudinal positions of WPS sensors known
- The 6 parameters transformation from the first and the last plates to R-general, as well as the pitch and yaw angles are fixed.
- Distance between metrological plates known : 20 m
- Wire length: 200 m
- Longitudinal Distance between the parallel wires : 10 cm
- 11 pits separated by 2.5 km were considered for the calculation (25 km long linac)
- The precision and accuracy at the bottom of each pit are below 2 mm in R-general.

The variance-covariance matrix for the estimators of parameters was used to calculate standard errors.

Simulation Results

Figure 6 presents the radial deviation error over 25 km without and with pits every 2.5 km. With such an overlapping configuration of stretched wires and metrological plates, the radial propagation error along 25 km of tunnel is below 1.1 mm with 11 pits. Without pits, the radial propagation error increases to 6 mm.

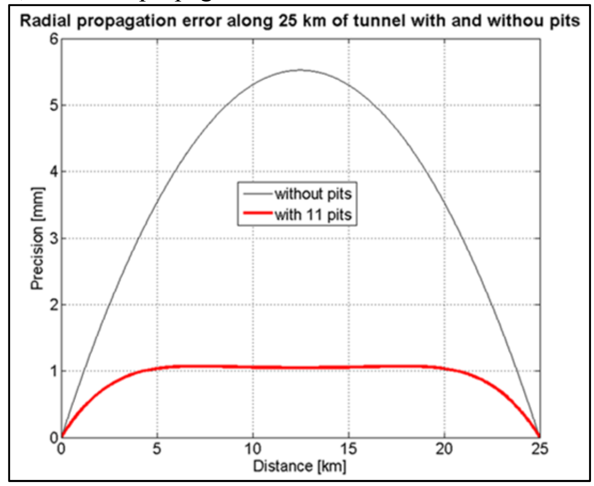

Figure 6: radial propagation error along a 25 km of tunnel with/without pits.

Figure 7 zooms on the relative precision of any part of radial propagation. For a zoom of 200 m, the relative precision (1σ) of components radial positions to the stretched line is below 6 µm.

For a zoom of 400 m, the relative precision of radial positions is about 12 µm, i.e. all the components in this interval are aligned w.r.t. each other within 12 µm.

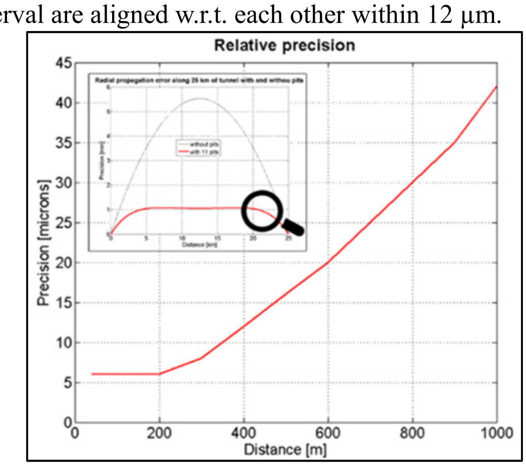

Figure 7: relative precision to the stretched line according to the distance considered.

CONCLUSION

New TT1 results show a very good correlation with the simulated data and confirm the 5 µm accuracy defined for WPS and HLS sensors.

The propagation error over the CLIC collider has been simulated using the variance-covariance matrix as estimator of parameters. For a sliding window of 200 m, the standard deviation of the transverse position of each component w.r.t. a straight line is included in a cylinder with a radius below 7 µm (better than the CLIC requirements). A maximum standard deviation of 1.1 mm was computed along the 25 km of tunnel.

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