CLIC PRE-ALIGNMENT STRATEGY: FINAL PROPOSAL AND ASSOCIATED RESULTS

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Abstract

A Project Implementation Plan for the Compact LInear Collier (CLIC) is under preparation for consideration by the European Strategy Update process. The document will integrate all changes and improvements since the Conceptual Design Report submitted in 2012. One of the technical challenges covered is the pre-alignment of CLIC. This paper presents the final chosen strategy and more particularly the configuration of alignment sensors defined following the results obtained on different test setups. It proposes two methods for the fiducialisation of the components, based on the results obtained in the PACMAN* project combined with R&D on an adjustment platform. The paper concludes with an estimation of the budget of error for the pre-alignment stage.

INTRODUCTION

The pre-alignment of the CLIC project, more particularly of the accelerator components of the Main Linac (ML) and Beam Delivery System (BDS) is a key contributor to the emittance growth. Micrometric tolerances of pre-alignment are requested before inserting the first pilot beam in order to implement beam-based alignment and beam based feedbacks. This technical challenge was tackled many years ago and a first solution was presented in the Conceptual Design Report [1]. Since 2012, deeper studies have been carried out on fiducialisation and initial alignment of the components, leading to a change of strategy for this step to gain accuracy, efficiency and flexibility concerning the location of measurements. We now have a better knowledge of the sensor configuration needed to perform such a pre-alignment. Two solutions of supporting and micrometric adjustment were validated successfully on dedicated test setups. We also have a better understanding of the accuracy that can be reached all along the kilometres of accelerator with simulations, confirmed by experimental results. This paper will first detail the final pre-alignment configuration chosen, by recalling the requirements and the strategy proposed following the results obtained on different test setups. Then, we will lay the emphasis on two methods proposed for the fiducialisation and initial alignment of the accelerator components, before presenting the overall budget of error for such a pre-alignment.

REQUIREMENTS AND STRATEGY OF ALIGNMENT

Requirements

The CLIC accelerator will consist of more than 50 km of ML and BDS in a 3 TeV configuration and 11 km in a 380 GeV configuration. Main Beam (MB) and Drive beam (DB) production must not be overlooked: the length of the injector tunnels for the 3 TeV option would be more than 100 km (40 km for the 380 GeV).

CLIC survey and alignment will consist in aligning all these areas, within a defined budget of error. Concerning the BDS and ML, this budget is allocated for the absolute positioning of the components' reference axes, e.g. magnetic axis for quadrupole (Quad), RF axis for Accelerating Structures (AS) and electrical zero for a Beam Position Monitor (BPM) [1]. For all the other areas, such a budget concerns the determination of the position of the cryostat fiducials (and not the reference axis).

Table 1: alignment requirements

Area	Total budget of error
Main linac (BPM, AS)	± 14 µm over 200 m
Main linac (MB Quad)	± 17 µm over 200 m
Main linac (DB Quad)	± 20 µm over 200 m
BDS quadrupoles	± 10 µm over 500 m
All other areas	± 0.1 mm over 150 m

Strategy of alignment

To achieve such requirements, a coordinate system (CERN coordinate system: CCS) combined with a geodetic reference frame (CGRF) has to be defined. A geodetic model built from astro-zenithal, GPS and gravimetric measurements has to be provided as well. Geodetic pillars, closed from shafts linking the surface to the underground tunnel, are determined and the surface reference is transferred via the shafts within an uncertainty of measurement of ± 1 mm (combination of optical and mechanical measurements). An underground geodetic network, consisting of points sealed in the floor every 50 m, being the backbone of measurements in all the areas, is then determined [2].

The initial alignment of the accelerators is performed w.r.t. the initial geodetic network for all the areas except ML and BDS. For these two specific areas, an additional network is put into place: the Metrological Reference

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*PACMAN is an acronym for a study on Particle Accelerator Components' Metrology and Alignment to the Nanometre scale

Network (MRN) consisting of overlapping stretched wires and metrological plates. The MRN propagates the absolute reference from shaft to shaft. The metrological plates are equipped with Hydrostatic Levelling Sensors (HLS) and Wire Positioning Sensors (WPS): WPS measure transverse offsets w.r.t. the stretched wire with a micrometric accuracy [3], HLS measure a vertical distance w.r.t. a water surface, providing a vertical reference to model the catenary of the wire [4]. By adding an inclinometer on the metrological plate, it was demonstrated that one could determine the distance between two wires with an accuracy of 5 µm [5].

In order to facilitate the pre-alignment process, several components of different types are pre-aligned on a common girder assembly. The girder assembly is then actively pre-aligned using WPS installed on the girder assembly via a cradle and performing offset measurements w.r.t. a wire of the MRN network. This proximity network, made of pre-alignment sensors on girder assemblies, is named Support Pre-alignment Network (SPN), see Fig.1.

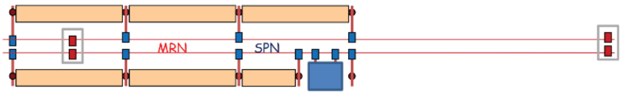

Figure 1: SPN and MRN configuration proposed in CDR

New results were obtained concerning the definition of the two networks: SPN and MRN, on three different test setups named Two Beam Test Modules (TBTM), TT1 and CLEX test setups.

TESTS SETUPS AND ASSOCIATED RESULTS

Two Beam Test Modules

CLIC will consist of a chain of 2 m long modules made of different types of components resting on their associated supports. Each module includes components of two beams:

- the DB with power extraction and transfer structures, and two DB Quads
- the MB consisting of AS and MB Quads with a length depending on the type of module.

The TBTM consists of two type 0 modules (no quadrupoles, four AS) and one type 1 module (one 0.5 m long MB Quad and three AS) (see Fig. 2).

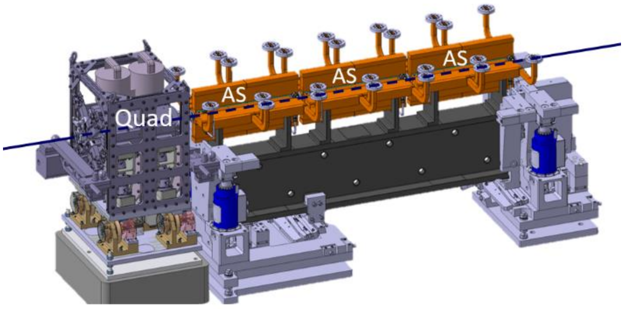

Figure 2: MB side of type 1 module

The different options of support were validated and described in previous papers [6, 7]. On the MB side, AS are installed on V-shaped supports, machined to a micrometric accuracy. Girders on the MB and DB sides are inter-linked by an articulation point allowing a natural smoothing of the girder ("snake configuration") and limiting the number of Degrees of Freedom (DOF) between girders to three. Each girder is equipped with two cradles at its extremities: one master cradle and one slave cradle (see Fig. 3). The master cradle is supported by three linear actuators (two vertical actuators to perform the vertical translation and roll rotation and one horizontal actuator) and is equipped with pre-alignment sensors. The slave cradle is only equipped with pre-alignment sensors. Slave and master cradles between adjacent girders are interlinked in such a way that the slave cradles follow the master cradle transverse displacements, but not the roll. Such a displacement is performed around a virtual articulation point, which is the interpolated section of the mean axes of the V-shaped supports of two adjacent girders. Such a point can be manually adjusted within a 10 µm accuracy using laser tracker measurements during the fiducialisation process of girders.

Previous tests showed that the two extremity cradles on which the pre-alignment sensors were installed needed to be part of the girder (from the same material).

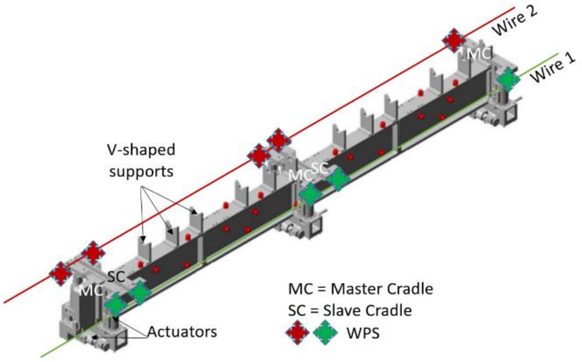

Figure 3: Configuration of sensors studied on TBTM

Simulations were carried out based on such a configuration for the SPN, considering an accuracy of measurement of 5 µm for capacitive-based WPS sensors (cWPS), and 10 µrad for inclinometers. The results shown in Table 2 were obtained.

Table 2: girders position simulations

Configuration	**Radial precision**	**Vertical precision**
Two wires (4 WPS)	10 µm	7 µm
One wire (2 WPS) + 1 inclinometer	12 µm	10 µm

The configuration with two wires is very interesting for its redundancy, especially concerning the roll measurement, and allows fault detection. The performed tests showed that it was difficult to develop, install and calibrate an absolute inclinometer within a µrad uncertainty of measurement, and that it was far more accurate to use two parallel wires, stretched on both sides of the modules, measured by two WPS. We propose to implement a 2 wires / 4 WPS configuration.

CLEX test setup

Only one module was installed in CLEX, so it was not possible to validate active pre-alignment with snake configuration between several modules. Nevertheless, it demonstrated that the beam had no impact on the sensor's noise signal. It showed, as well, that some improvements were still necessary to avoid a coupling between the DB and MB supports: while displacing the MB girder, we were also moving the DB girder, PETS and AS being linked by two rigid RF waveguides.

In CLEX, we had installed two MRN plates on both sides of the modules, considered as the reference of alignment. W.r.t this alignment reference, the module was actively pre-aligned successfully within a few micrometres [6]. The two girders were positioned according to the requested positions during physics tests.

TT1 test setup

In this old transfer tunnel, located 10 m underground, three overlapping wires of different lengths (50 m, 90 m, 140 m) have been installed, with 7 metrological plates equipped with WPS and HLS sensors (see Fig. 4) – 1 plate every 25 m. The objective of this facility is to determine the positions of the seven plates in the general coordinate system of the tunnel using the redundancy of measurements provided by the sensors. Radial standard deviations for these plates' positions were below 7 µm (12 µm in vertical). Simulations performed on such a configuration showed a very good correlation with the results [5].

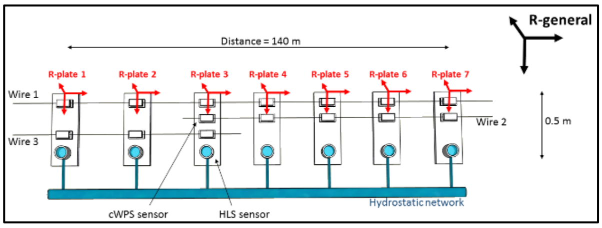

Figure 4: Configuration of metrological plates

This allowed extrapolating such a configuration over 25 km of linacs [5], considering a shaft every 2.5 km. A radial propagation below 1.1 mm along 25 km is obtained and a relative precision for each plate below 7 µm for overlapping wires lengths of 200 m, below 12 µm for overlapping wire lengths of 400 m [5]. In vertical, such an extrapolation is far more complicated, as the equipotential surface of gravity can no longer be approximated to an ellipsoid.

Adjustment solution

Once the position of all the girders or assemblies is determined in the tunnel's general reference frame, the adjustment phase can take place. The requirements were the following: a travel above ±3 mm, resolution below 0.5 µm and repeatability of displacement below 1 µm. Two adjustment solutions were studied:

- One based on cam movers, allowing to displace each support independently according to 5 DOF
- One based on linear actuators, supporting each cradle, according to 3 DOF.

The configuration of 5 cam movers was validated for two lengths of quadrupoles: 2 m and 0.5 m, where we showed that the position requirements (sensors offsets below 1 µm and roll below 5 µrad) could be met in one movement using feedback from alignment sensors [8-10]. To fulfil the new requirement of a micrometric adjustment in the longitudinal direction, we propose to add a sixth cam mover to the system and reorganize the layout of cam movers. The previous prototypes did not meet the MBQ pre-alignment stage stiffness requirement. A new prototype, taking into consideration both the positioning accuracy and the stiffness, is being built. The results of the new prototype, along with more general discussions about precise multi-axis machines with pre-load, are under analysis (see Fig 5.).

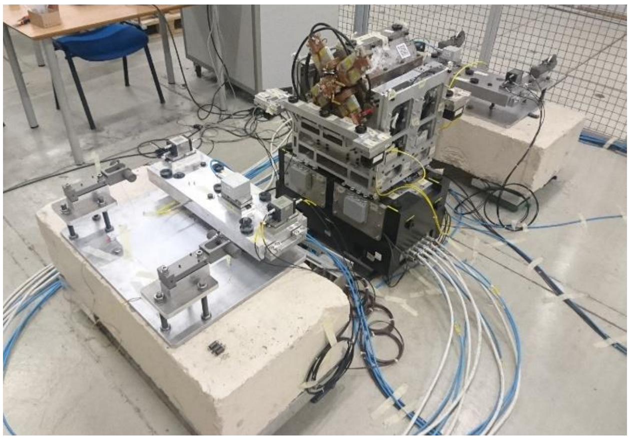

Figure 5: cam mover prototype and its test setup

Final pre-alignment solution

Concerning the position determination, alignment sensors will be installed on cradles; cradles and girders being one block of the same material. Similar configurations are proposed for both options: DB and klystrons, see Fig. 6 and 7.

Concerning the adjustment, the snake configuration using linear actuators will be kept for the DB side where we find only 2m long girders. Cam movers will support the girders and MB quads on the MB side.

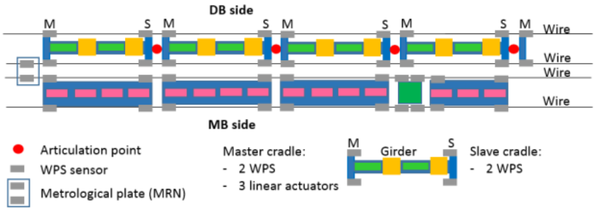

Figure 6: Sensors configuration for DB option

In the klystrons option, the DB side disappears; the only modification concerns the wires' position: vertically instead of on each side of the girder.

Figure 7: Sensors configuration for klystrons option

TWO METHODS FOR THE FIDUCIALISATION AND INITIAL ALIGNMENT OF THE COMPONENTS

PACMAN project and associated results

PACMAN was an Innovative Doctoral Programme funded by EU and the CLIC project, where 10 Early Stage Researchers could work towards a PhD thesis on different fields such as high precision large-scale metrology, metrology, high precision engineering, microwaves and magnetic measurements [11]. The main objective was to develop methods to materialize the reference axes of CLIC components (quadrupoles, BPM, AS) and to measure their position w.r.t. external targets, named fiducials. The developed methods were then validated on a common test setup consisting of real CLIC components in the environment of a 3D Coordinate Measuring Machine (CMM) with an uncertainty of measurement of 0.3 µm + 1 ppm.

We demonstrated that using a CuBe wire made of 98% of Copper and 2% of Beryllium and with a diameter of 0.1 mm, it is possible to materialize the electric centre of BPM and the magnetic axis of a quadrupole with a micrometric repeatability, and an accuracy of a few micrometres [12]. The RF centre of the disk of an AS can also be materialized with the same precision and accuracy [13-15].

Three methods were then developed to measure the position of the wire w.r.t. external fiducials, once the wire is located at the reference axes of the components:

- using a CMM equipped with a confocal sensor,
- building a network to perform Frequency Scanning Interferometry (FSI) for trilateration measurements (see Fig. 8),
- using micro-triangulation (angle measurements).

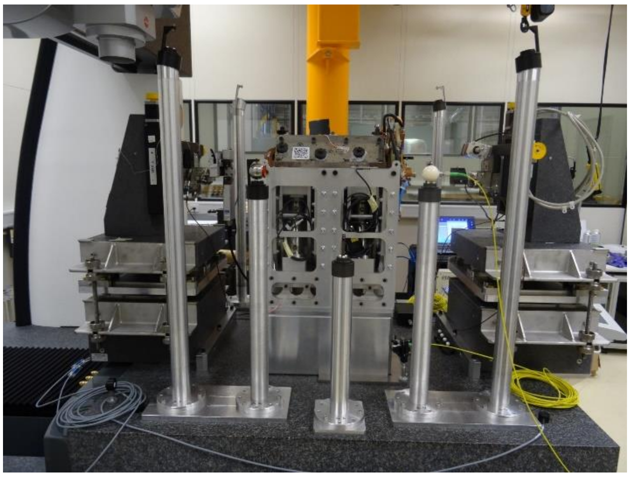

Figure 8: PACMAN bench and FSI heads

Considering CMM measurements as the reference, we showed that by using FSI measurements, we could determine the coordinates of the fiducials w.r.t the stretched wire within 2 µm, and that by using micro-triangulation, we could determine the coordinates and the wire within 15 µm in a configuration that was not optimised at all [13, 14].

5 DOF platform R&D and associated results

A 5 DOF adjustment platform has been developed in the frame of the CLIC project to ease the adjustment of two DB quadrupoles on top of their common girders. Such an adjustment was initially performed using shims and took more than 8 hours, without reaching the final accuracy of 20 µm. A very compact Stewart-type platform (thickness below 2 cm) located between the DBQ and girder was developed. The platform performs readjustments in a radial and vertical direction with a micrometric resolution over a travel of ± 1 mm. The regulation of yaw, pitch and roll rotations is achieved within 20 µrad [16]. Such a platform was used for the adjustment of the DB quadrupoles on their girder located in the CLIC Experimental Area (CLEX) with a great success. The position of the quadrupole was determined by continuous laser tracker measurements and the platform allowed the micrometric adjustment of the quadrupole w.r.t to the girder, within a few micrometres, in less than 10 minutes. It demonstrated to be very stable along time. Then an automatic control was developed, allowing the plugging of temporary motors on the platform instead of an operator acting manually on the adjustment knobs.

Towards new methods of initial alignment and fiducialisation

The methods of fiducialisation and initial alignment developed in the PACMAN project, combined with the 5 DOF adjustment platform, provide new perspectives. In the CDR, the initial alignment of components on the same common support was achieved by the high precision manufacturing of the supports and of the outer surfaces of the components. As an example, girders supporting the RF structures were machined with V-shaped supports at a micrometric accuracy, and the same for the outer diameter cylinder of the RF structures. Concerning the fiducialisation, we had considered at that time a determination of the external targets w.r.t. the mechanical axis (and not the reference axis) of the components.

A new strategy is proposed for the fiducialisation and initial alignment of the components on their common support assembly based on the results introduced in the previous chapters.

The following sequence is proposed:

- An individual fiducialisation of each component is carried out, based on techniques developed in the PACMAN project: stretching a wire to materialize the component's reference axis.
- Each component of the girder assembly is installed on a 5 DOF adjustment platform and is roughly pre-aligned.
- The girder is transferred to a measurement marble equipped with FSI heads, and plug-in motors for adjustment (see Fig. 9).
- The position of each component is determined using the FSI heads, and then plug-in motors are temporarily connected to the 5 DOF adjustment platforms to set the components at their nominal position. Then, the FSI heads measure the components' position again (see Fig. 10). If all the components are at their nominal position on the girder, plug-in motors are disconnected and the girder is stored, being ready for its installation (see Fig. 11). Otherwise, there is an additional iteration of adjustment and position determination.

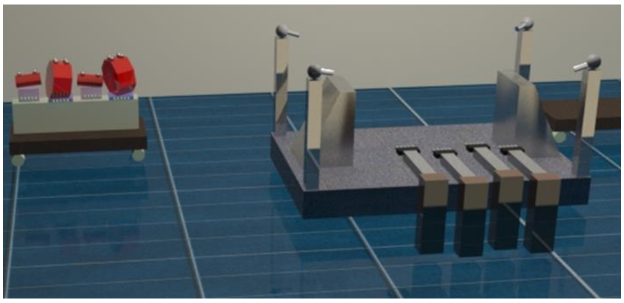

Figure 9: Transfer of a girder assembly to a marble

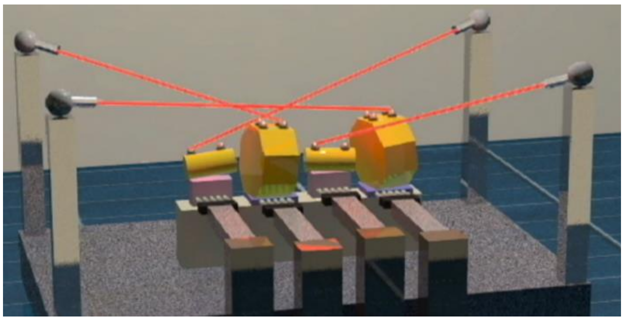

Figure 10: Determination of the components position using FSI heads and readjustment using plug-in system of the 5 DOF adjustment platform

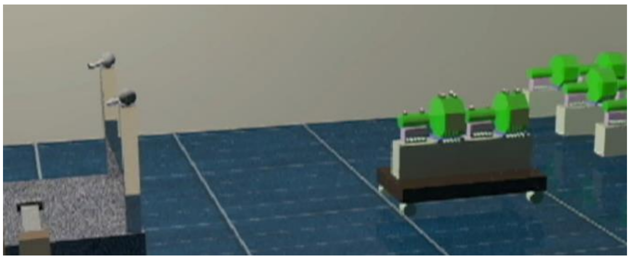

Figure 11: storage of the girder with its aligned components

A second scenario is applicable in case the components were not fiducialised prior to their installation on their common girder assembly. Once the girder is installed on the equipped marble, a wire is stretched through all the components. Each component is adjusted using the 5 DOF adjustment platform below until the wire is located at the reference axis of the component. Once all the reference axes coincide with the wire, the fiducialisation is performed by FSI heads. The positions of all components and girder assembly targets are measured w.r.t. the stretched wire in the girder referential frame.

Such sequences can be fully automatized; they can be performed in the manufacturers' premises, or at CERN metrology labs, or even downstairs in the tunnel, provided the FSI heads are installed on a rigid and portable structure. It allows a gain of accuracy and efficiency (such an initial alignment can be performed within a few minutes) and provides the possibility to perform alignment controls after transport in the tunnel.

OVERALL BUDGET OF ERROR

The recent studies undertaken on several facilities confirm that pre-alignment requirements can be fulfilled in the ML. A combination of WPS and HLS sensors for the determination of the position is proposed, combined with linear actuators or cam movers for the adjustment of the component assembly, with a new scenario for the fiducialisation and initial alignment of the components on their assembly, based on the techniques developed in the PACMAN project. The global error budget is summarized in the table below.

Table 3: new pre-alignment budget of error

Steps	**Components (BPM, quadrupole, AS)**
Fiducialisation	5 µm
Fiducials to pre-alignment sensor interface	5 µm
Pre-alignment sensor accuracy	5 µm
Sensor linearity	5 µm
Straight reference	7 µm (in radial)
TOTAL ERROR BUDGET (rms)	**11 µm (in radial)**

CONCLUSION

The latest results from the PACMAN project and the CLIC test setups confirm that pre-aligning the reference axes of components over 200 m within a few micrometres is achievable. Procedures of fiducialisation and initial alignment of the components on their support assemblies have been simplified and could even be performed in the tunnel once the components are transferred.

One question remains: all these studies were performed at 20°C. The operational temperature of the CLIC accelerator was recently set to 30°C. We need now to understand, model and study the impact of such an operational temperature on all alignment systems to update the procedures of alignment.

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