ISSUES AND FEASIBILITY DEMONSTRATION OF CLIC SUPPORTING SYSTEM CHAIN ACTIVE PRE-ALIGNMENT USING A MULTI-MODULE TEST SETUP (MOCK-UP)

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Abstract

The implementation study of the CLIC (Compact LInear Collider) is under way at CERN with a focus on the challenging issues. The pre-alignment precision and accuracy requirements are part of these technical challenges: the permissible transverse position errors of the linac components are typically 14 micrometers over sliding windows of 200m. To validate the proposed methods and strategies, the Large Scale Metrology section at CERN has performed campaigns of measurements on the CLIC Two Beam Test Modules, focusing inter alia on the alignment performance of the CLIC "snake"- girders configuration and the Main Beam Quadrupoles supporting structures.

This paper describes the activities and results of tests which were performed on the test mock-up for the qualification of the CLIC supporting system chain for active pre-alignment. The lessons learnt ("know how"), the issues encountered in the girder position determination as well as the behaviour of the mechanical components are presented.

INTRODUCTION

The most critical CLIC components need to be pre-aligned within 14 µm rms with respect to a straight reference line along a sliding window of 200 m [1, pp.602].

A system based on supporting structures (girders and cradles) linked together and equipped with linear actuators is being tested. A special test mock-up was built at CERN (Fig.1) to demonstrate the feasibility of remote active pre-alignment within the required tight tolerances.

The main components of the CLIC mock-up were machined with high accuracy and measured at a micrometric uncertainty of measurement using 3D Coordinate Measuring Machines, to determine the position of the mechanical reference axis/zero of the components with respect to external alignment references called fiducials (fiducialisation process [2]). To provide the real time position feedback of the supporting structures - their cradles were equipped with high precision Wire Positioning Sensors (WPS). As the position of the mechanical interface of the sensors was measured within a few micrometres with respect to the mean axes of the supports, the readings of the sensor allow the determination of the real position of the girder mean axis (and of the RF components installed on the girders) w.r.t. reference line established in tunnel or laboratory coordinate system. If needed, a re-adjustment is performed with the actuators.

All tests and measurements were performed in a climatised laboratory at 20°C. The algorithms were implemented inside a specially designed software (using Matlab and LabView) to examine the system behaviour during repositioning and verify the performance of active alignment.

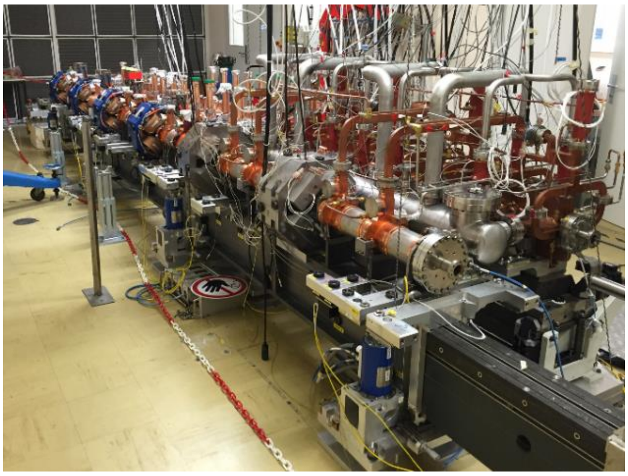

Figure 1. CLIC test module mock-up

CLIC SUPPORTING SYSTEM CHAIN

"Snake"-type girders configuration

All CLIC RF components will be installed on modular girders, which will be used as a support for RF components' pre-alignment [3]. Motorization will be installed at one side of a girder (MASTER cradle) and the non-motorized side (SLAVE cradle) is left to be driven by the adjacent girder (Fig. 2). This solution smooths out "naturally" the pre-alignment of adjacent girders [3, 4].

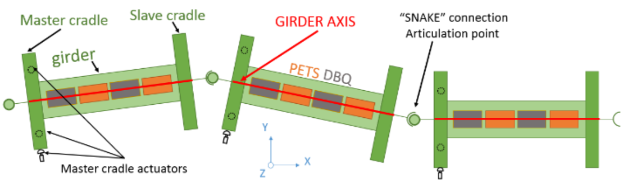

Figure 2. "Snake"-type girders configuration

MASTER cradles

Only the MASTER cradle has an impact on the active pre-alignment process. The actuators control the X-Y position as well as the roll of a cradle, resulting in a 3 DOF mechanism [4] (Fig. 3).

Articulation point

The SLAVE cradle is attached mechanically to the MASTER side, by a flexural 'Articulation point', role of which is to allow through elasticity the roll-yaw-pitch rotations while rigidly keep X and Y shifts of the two neighbouring cradles (Fig. 2) [3, 4]. A combination of cradles MASTER-SLAVE-MASTER allows girder position control in 5 DOF.

The MASTER-SLAVE connection accuracy plays a very important role in the "snake"-type girder configuration – the interconnection offset error after pre-alignment should be lower than 10 µm rms [3].

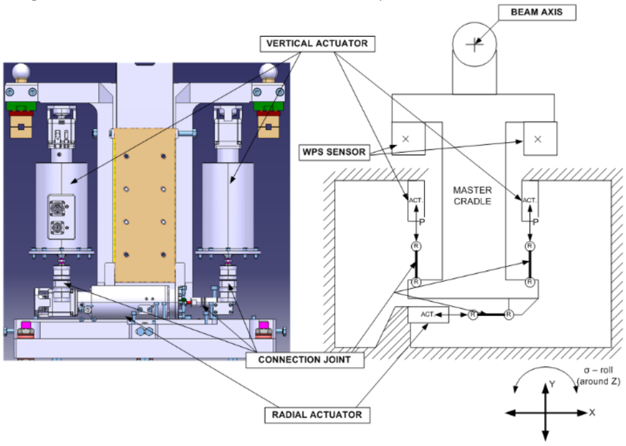

Figure 3. Master cradle schema – 3 DOF mechanism

CERN CLIC MOCK-UP

The CLIC conceptual design assumes modular construction of the linac. In order to accommodate all the defined configurations – five types of modules are needed [1, pp. 392]. Type-0 (T0) modules contain only Accelerating Structures (AS) along the Main Beam (MB) line. Modules 1-4 (T1 - T4) include Main Beam Quadrupoles (MBQ) of variable length. The Drive Beam (DB) lines of all T0 - T4 modules contain two Drive Beam Quadrupoles (DBQ) and one or two Power Extraction and Transfer Structures (PETS).

The special CLIC mock-up built at CERN consists of four CLIC two-beam modules in configuration ***T4-T0-T0-T1***. All modules include supporting girders: DB1 - DB4 for Drive Beam and MB2 - MB4 for the Main Beam (Fig.4). The Main Beam Quadrupoles of modules T4, T1 (Fig. 4 – dashed line) have not been deployed yet.

Each module is equipped with two 'Artificial' cradles to support capacitive and optical WPS sensors. The 'Artificial' cradles were implemented due to problems with the position stability of MASTER and SLAVE cradles, which will be described in the next chapter.

Each girder includes four WPS sensors: two capacitive and two optical [5]. The amount of four sensors was chosen to increase data redundancy, perform intercomparison tests and for a better understanding of feedback data during the alignment tests. Currently, all the sensors are ready to provide absolute reference values. The absolute calibration accuracy of capacitive WPS sensors is 5 µm, compared to a 10 µm accuracy for the optical WPS [5].

At each extremity of the mock-up, stable reference plates were installed (***REF. Plate A, B***, Fig. 4). The plates' role is to provide local (laboratory) absolute position reference to the module strings. The reference plates are equipped with capacitive and optical WPS sensors to provide the position of the wires (***WIRE DB1-2, WIRE MB1-2***, Fig. 4) stretched along the DB and MB girders.

CLIC MOCK-UP MODULES VALIDATION AND ENCOUNTERED ISSUES

Cradle-Girder compatibility

The initial design of CLIC mock-up assumed supporting girders manufactured of silicon-carbide (SiC) with cradles in aluminium. This approach was tested during measurement campaigns in 2014 and 2015 including the thermal cycle tests to verify the supporting structures' behaviour in varying temperature. The main conclusion of the tests was that fiducialisation of interconnected components (cradle-girder-cradle) is lost after several temperature cycles. The environment temperature was changed several times from ~20°C to ~40°C, resulting in displacements of cradles w.r.t. girder at the level of tens of micrometres (depending on the measured module). The important difference in thermal expansion coefficients of both materials (Al = ~23µm/m/°C, SiC = ~3 µm/m/°C),

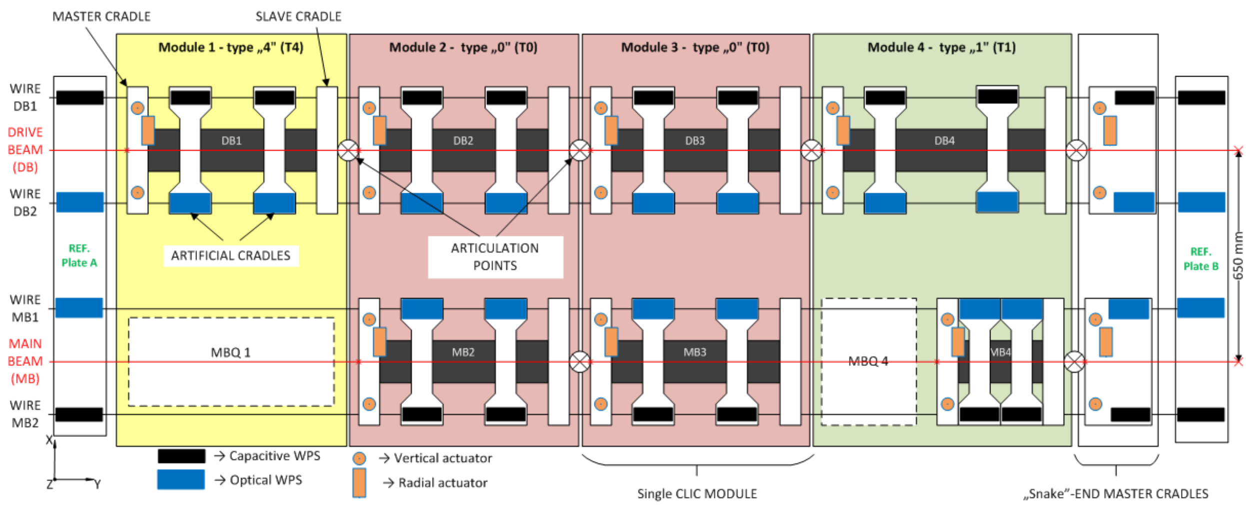

Figure 4. Test module mock-up schematic view

combined with temperature changes, caused shifts of the rigidly connected Al-SiC components [6].

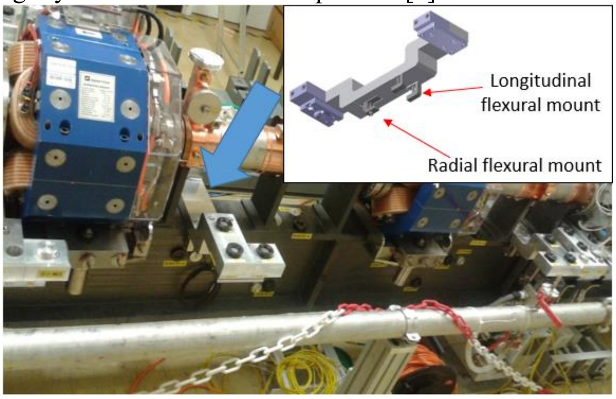

Figure 5. ‘Artificial’ cradle

As the cradles’ role is to support the WPS sensors used for girder position computation – each cradle position change caused errors in calculations. This imposes the re-fiducialisation of the girder-cradle connection. To be able to continue the tests with the CLIC mock-up without re-fiducialising the modules frequently - the ‘Artificial’ cradle was designed to anticipate the thermal effects on cradle positions. The ‘Artificial’ cradle (Fig. 5) consists of one rigid and two flexural girder mounts – in radial and longitudinal directions. The task of the flexures is to deform elastically with the thermal expansion/contraction of the girder, to achieve repeatability of the position at the same temperatures.

All mock-up modules were equipped with the ‘Artificial’ cradles and re-measured in-situ using AT 401 laser tracker. The tracker measurements of ‘Artificial’ cradles connect the coordinate frame of the girder, previously measured by CMM with the coordinate frames of the newly installed cradles measured by AT401. The in-situ fiducialisation accuracy was estimated to be 20 µm (based on least square fit calculations of the measured values and the instrument’s accuracy).

Articulation point

The articulation point interconnecting the MASTER and SLAVE cradles was designed as a flexural assembly, which allows roll-yaw-pitch rotations with its elasticity while rigidly preventing X and Y shifts of two neighbouring cradles (Fig. 6, Fig. 2).

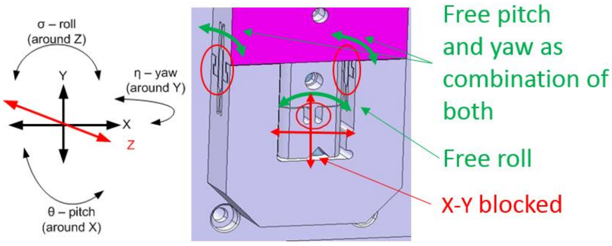

Figure 6. Articulation point

The initial tests of articulation point kinematics showed good behaviour in terms of movements and appropriate DOF transfer from MASTER to SLAVE cradle. However the alignment between both cradles did not meet the requirements for all module interconnections. The initial design of articulation point assumed its alignment using precisely machined pin-holes and positioning w.r.t. cradles by pins (Fig. 7). Some of the interconnections were misaligned by more than 100 µm due to the problems of cradles-articulation point machining and assembly tolerances.

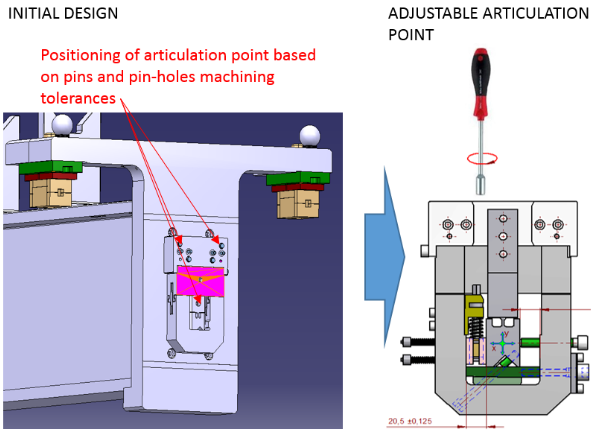

Figure 7. Articulation point – adjustable solution

Based on the initial test experience – the second generation of articulation points was designed (Fig. 7 – right side). The new design enables the possibility of in-situ adjustment of the MASTER-SLAVE cradles to fulfil 10 µm intra-alignment requirement. The adjustment mechanism was implemented as wedge-based, ±0.25mm X-Y stroke regulation, which in most of cases was sufficient to compensate for the machining tolerance errors.

Alignment of components on the girder

To achieve the proper alignment of RF components on the SiC girders - the CLIC design foresees so called V-shaped supports providing repeatable and precise interface to AS and PETS [1, pp. 404-406]. The mean axes of the V-shaped supports of the girder should be included in a cylindrical tolerance zone of 10 µm diameter. The possibility of reaching such tight machining tolerance was confirmed during measurements on the CLIC mock-up [3]. On the other hand, the RF components should be machined in a way which provides alignment of ±14 µm for AS and ±100 µm for PETS, w.r.t. V-support mean axis.

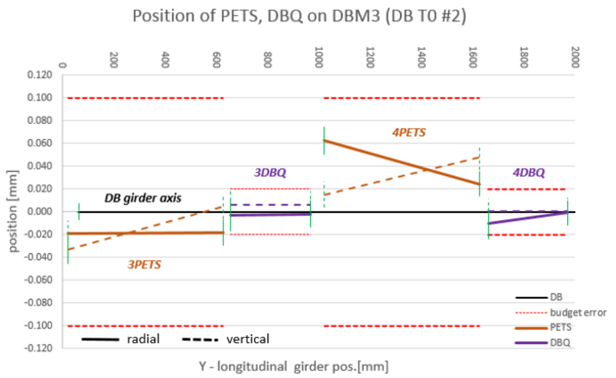

Figure 8. PETS, DBQ on DB3 girder

The measurements of PETS alignment on mock-up showed that their mean-axes positions are always in tolerance. Maximum observed misalignment was below 80 µm (Fig. 8).

For AS, there is still a need to improve their production technology. In the best case, the AS misalignment w.r.t. V-support's (girder) mean axis is 60 µm (Fig. 9), which does not comply with the CLIC requirements.

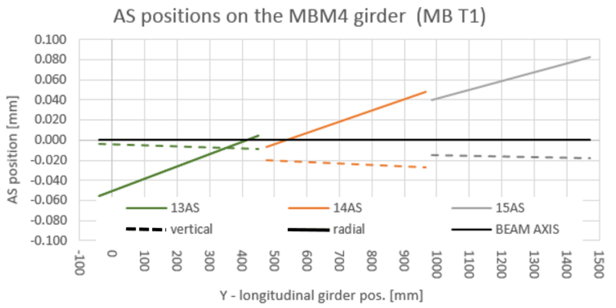

Figure 9. AS on MB4 girder

Currently, the other possibilities of mechanical pre-adjustment of AS and PETS on the girders are studied.

CLIC MOCK-UP ACTIVE ALIGNMENT

The "snake" structure can be pre-aligned by setting each girder mean axis position (using motorized MASTER cradles) in one line w.r.t. reference line established in the tunnel or laboratory coordinate system

Determination of the girder axis position

The CLIC mock-up modules (Fig. 4) consist of four DB girders (DB1 - DB4) and three MB girders (MB2 - MB4). Girders DB1 - DB4 are connected in "snake"-type structure using articulation points. For MB, only MB2 and MB3 are connected together.

The four wires (***WIRE MB1-2, WIRE DB1-2***) stretched along the MB and DB girder chains serve as straight line references, linked by WPS sensor readings to laboratory coordinate system established with use of reference plates (***Ref. Plate A, Ref. Plate B***). The WPS sensors provide observations of wire position w.r.t. reference plates and w.r.t. mean axes of the girders.

The least mean square fitting method is used to compute the coordinates of each girder mean axis. Separately for each MB and DB girders string, the set of observation equations are created and resolved basing on WPS sensors observations, components' fiducialisation data, sensors calibration and stretched wire model. For the least square method calculations purposes, the following 'a priori' accuracies were considered:

- Girder fiducialisation accuracy → 20 µm. This value had to be established so high due to problems with cradle alignment and temporary solution of 'Artificial' cradles in-situ fiducialisation;
- Reference plate fiducialisation → 1 µm (CMM fiducialisation uncertainty of measurement);
- WPS sensor absolute accuracy of 5 µm for capacitive WPS and 10 µm optical WPS.

MASTER cradle control algorithm

The MASTER cradle motion is based on two vertical and one radial actuator, which are installed on the supporting plates fixed to the ground. The cradle is connected to the actuators by flexible connection joints (Fig. 3), allowing only a coarse pre-adjustement of cradles during assembly. Due to possible machining errors of the actuator supports, adjustment tolerances of flexural connection joints, settling errors of supporting plates and possible ground motions, it is not possible to create reliable inverse kinematics, based on the geometry of cradle suspension for open loop control. To avoid the suspension components' constraints, the closed loop control method was chosen for active pre-alignment. The algorithm converts the current position and rotation error of MASTER cradle into approximated displacements of actuators, basing on nominal geometry of cradle suspension. The algorithm needs several steps (typically 3 for errors lower than 0.5mm) for successful approximation to the requested (target) position within 10 µm [4].

Control system architecture

Control and Data Acquisition System is built using National Instruments CompactRIO 9082 Real-Time Platform (Fig. 10). DAQ modules NI9209, NI9207 and NI9216 are used for the read-out of the analog signals from the cWPS and PT100 temperature probes. The link with oWPS sensors is established by Ethernet data connection. The RS232 connection is used to communicate with actuator drivers, called (from the manufacturers' names): ZTS NEW, ZTS OLD and Microcontrole. Each module configuration and basic data processing are performed using built-in CompactRIO FPGA.

Main application is hosted on the CompactRIO platform where the information obtained from the WPS sensors is converted to the real-time position of the beam axis and roll of each CLIC girder. This information is compared with the desired set points specified by the user, which makes it a closed loop control system. The error obtained at each iteration of the algorithm enables the computation of actuator movements required for the alignment of the structures.

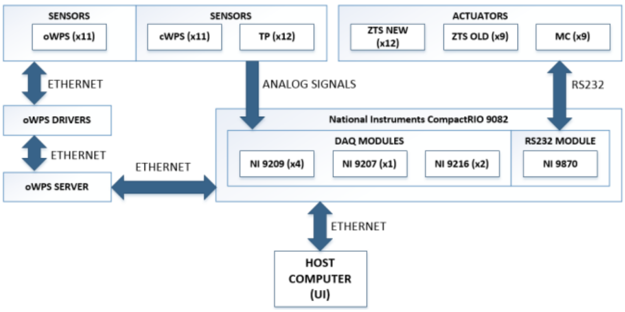

Figure 10. Control system architecture

The User Interface is provided by means of external Host Computer running executable LabVIEW application. The communication is established over the Ethernet protocol using Network Shared Variables. User can access raw and converted data from each sensor in addition to the interface for the automatic alignment of the structure.

Active alignment test

Tests were performed on the "snake"-structure of three Drive Beam girders DB2 - DB4 (Fig. 4) as the longest accessible string. The DB1 girder was excluded from measurements as its fiducialisation was not finished.

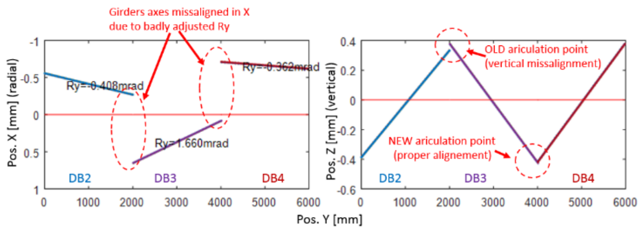

Figure 11. DB girders misaligned - mean axes positions

The girders (DB2 - DB4) were misaligned in random directions with a maximum position error of 0.3 – 0.8mm. The roll (Ry) of the girders was set in range of -0.4 mrad to 1.6 mrad. Figure 11 shows the initial roll and X, Z position components of girders' mean axes before the test. The "0" position of X, Z is the laboratory beam reference line.

The regulation algorithm was launched, generating the sets of commands for MASTER cradles' actuators. Each algorithm iteration was performed every ~25s, to provide a better view for the sensors signal stabilisation (Fig. 12: ***DBn_IN_X, DBn_IN_Z*** represents the girder mean axis coordinate at the MASTER cradle).

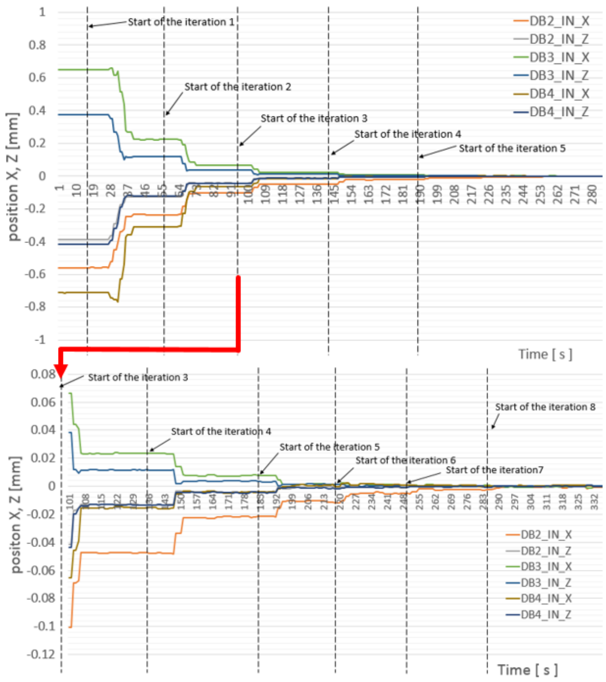

Figure 12. MASTER cradles adjustment iterations

We can see the perfect convergence of the algorithm, reaching the required 10 µm tolerance zone after 4 iterations. The typical stabilizing time of position for single iteration is ~10s, so feasible optimal alignment time to reduce big errors like 0.8 mm is estimated to be below 1 minute.

Trajectory of MASTER cradle during algorithm execution (Fig. 13) is slightly nonlinear only for the first iteration, where the main part of X, Z, Ry errors is reduced and big shifts of actuators are requested. From the 2nd iteration on – the trajectory is smoother.

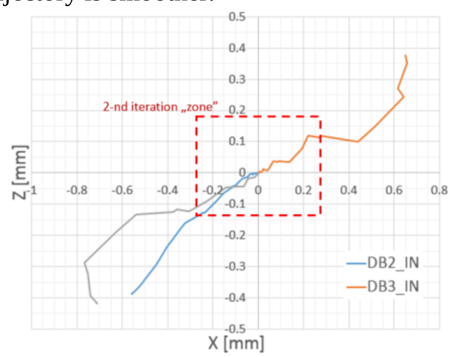

Figure 13. MASTER cradle position change trajectories

The final alignment of the girders DB2 - DB4 is shown on Figure 14. The 10 µm target alignment zone was reached for almost all mean axes, excluding SLAVE cradle side of DB2. DB2 - DB3 interconnection error is caused by machining error of an old type of articulation point interconnecting the girders (60 µm out of tolerance).

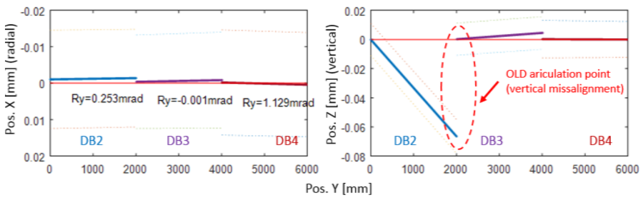

Figure 14. DB girders aligned - mean axes positions

SPECIAL CASE OF MAIN BEAM QUADRUPOLE ALIGNMENT

The Main Beam Quadrupoles (MBQ) were not deployed on the CLIC mock-up, however, the MBQ alignment control algorithm tests were performed on a parallel test stand at CERN. Figure 15 shows the mock-up including the girder, mounted on CLIC type 4 cam movers (CM).

In order to reach the CLIC luminosity target, all MBQ magnetic centres have to be aligned within 17 µm w.r.t. straight reference line along sliding window of 200m [1, pp. 602]. Vertical and lateral maximum offset deviations of a single quadrupole are defined as ± 1 µm and its roll deviation shall be below 100 µrad [1, pp. 604].

There are four different types of MBQ which differ from each other only by length. Type 1 is the shortest (~0.5 m) and type 4 is the longest one (~2 m).

It was demonstrated in an earlier study that the CLIC positioning requirements are reached when a mock-up girder with dummy weights is aligned using a parallel kinematics machine (PKM) based on cam movers [7]. For the new algorithms test purposes, the same PKM and girder are used but the control electronics has been replaced. The new electronics allows more advanced motion control.

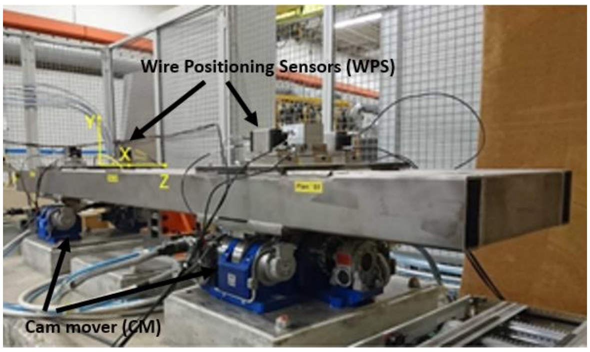

Figure 15. Type 4 MBQ test mock-up

Four positioning algorithms were developed and compared [8]:

- *Synchronous PTP* (point-to-point) - it is the simplest one. Target girder position is transformed to relative motor steps of each CM based on a kinematic model. Trajectory is not pre-defined. Relative moves are repeated until the target position is reached within limits (iterative approach);
- *Straight-line movement* - it is also iterative. Trajectory to the target is calculated before movement and constraints to the trajectory can be applied;
- *Complex movement* - it is a combination of the two first ones;
- *Predictive movement* - the trajectory can be constrained. Before motion, the set of initial points of trajectory is calculated. During motion, the trajectory points are sequentially supplemented and corrected basing on on-line girder position feedback.

Algorithms tests results

All positioning algorithms managed to reach all sequence targets within tolerances. The movement time of Synchronous PTP algorithm (60 – 90 s, Fig.16) is significantly longer than that of the others (30 – 40s) [8].

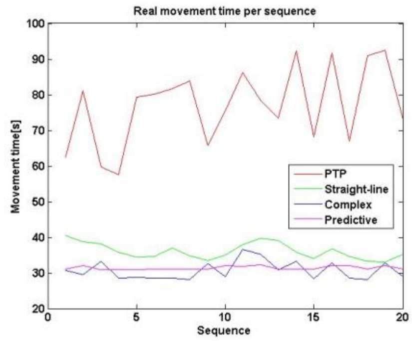

Figure 16. Comparison of execution times of four movement types in 20 test sequences [8]

Figure 16 does not take into account the time it takes to calculate trajectory before movement. This is on average 2 % of the total time for Synchronous PTP and Predictive movements and 5 % for Straight line and Complex movements.

CONCLUSIONS

Closed loop adjustment of "snake"-like girders string shows that absolute active alignment of supporting structures is feasible within the specified accuracy. The tests show that using a cradle/girder geometry combined with fiducialisation data and sensor readings gives satisfying results to calculate actuators response. Thanks to sensors feedback in regulation loop, the influence of all random constraints like ground movements, components machining errors, etc., can be eliminated.

What matters is to ensure that the materials of supporting structures sub-components are compatible, in order to have good performance and geometric stability in temperature and time.

There are still several issues linked with the alignment of the RF structures on the girders, mainly due to manufacturing problems which have to be studied in the future.

The CLIC positioning requirements for the MBQ alignment can be met in one movement by using feedback directly from alignment sensors. This predictive movement was compared to iterative algorithms and it performed well considering both the deviation and the positioning time.

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