ALIGNMENT METHODS DEVELOPED FOR THE VALIDATION OF THE THERMAL AND MECHANICAL BEHAVIOUR OF THE TWO BEAM TEST MODULES FOR THE CLIC PROJECT

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Abstract

CLIC (Compact LInear Collider) project will consist of more than 20 000 two meters long modules. A test setup made of three modules is being built at CERN to validate the assembly and integration of all components and technical systems in the crowded environment of a module and to validate the short range strategy of pre-alignment. The test setup has been installed in a room equipped with a sophisticated system of ventilation able to reproduce the environmental conditions of the CLIC tunnel, including the longitudinal air flow. Some of the components have been equipped with electrical heaters to simulate the power dissipation, combined with a water cooling system integrated in the RF components. Using these installations, in order to have a better understanding of the thermal and mechanical behaviour of a module under different operation modes, machine cycles have been simulated; the misalignment of the components and their supports has been observed. This paper describes the measurements methods developed for such a project and the results obtained.

INTRODUCTION

CLIC is a study for a multi-TeV electron-positron collider to study high energy physics beyond the capabilities of the current colliders (LHC). For a 3 TeV centre of mass energy, the length of CLIC will be of the order of 50 km. The two main linacs of CLIC will consist of 20 000 modules with a length of 2 m [1]. Modules are a key assembly of the project, integrating different types of components: RF components, quadrupoles, BPM. The components will need to be aligned along two parallel beams: the Drive Beam (DB) and the Main Beam (MB), with a very tight budget of errors, ranging from 14 µm to 100 µm with respect to a straight line of reference in the tunnel over 200 m [2]. Two Beam Test Modules (TBTM) are under installation in a dedicated laboratory with 3 major objectives:

- The validation of the assembly and integration of all components (including associated technical systems as alignment, vacuum, stabilization and nano-positioning, etc.) in the crowded environment of the module,
- The validation of the short range strategy of pre-alignment, including the fiducialisation of the components,
- A better understanding of the thermal and mechanical behaviour of a module under different operating modes.

This last point is addressed in this paper, with the results of the first tests performed on one module. The machine start-up procedure has been reproduced and the misalignment of the components and their supports studied.

The paper will first recall the strategy of short range alignment of the components. Secondly, the module and laboratory environment will be introduced, before detailing the methods of measurements developed to control and study the impact of operating modes on the alignment of the components. Thirdly, the results of such measurements will be presented and analysed.

STRATEGY OF SHORT RANGE ALIGNMENT OF THE COMPONENTS

As the alignment tolerances of the module components are very tight, the following strategy has been proposed in the Conceptual Design Report [1] for the short range alignment of the components [2]:

- Taking into account the number and size of components to be aligned, in order to ease the problem, components are pre-aligned on supporting girders (length of each girder ~2 m)
- The external surfaces of RF components that have cylindrical interfaces (Power Extraction Transfer Structure (PETS) and Accelerating Structures (AS)) will be fastened on V-shaped supports located on the girder. DB quadrupoles are aligned with respect to the mean axis of the V-shaped supports of the girder.
- The V-shaped supports will be manufactured in such a way that their mean axis is included in a cylinder with a radius of a few micrometres.
- To perform their alignment on the girder (or at least to control it for the RF components), all the components have been fiducialised: the position of their reference axis has been determined within a few micrometres precision and accuracy with respect to external targets installed on their outer surface.

MODULE COMPONENTS AND THEIR ALIGNMENT

Introduction

The full module assembly consists of 8 AS along the MB side, and 2 PETS plus 2 quadrupoles along the DB side (see Fig. 1).

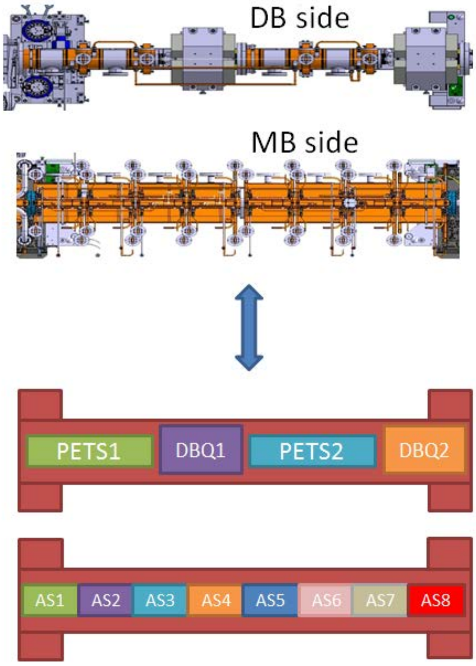

Fig. 1: configuration of the components inside the module

Alignment of PETS components

Each PETS is an assembly of 3 mechanical parts measured in the metrology laboratory via Coordinate Measuring Machine (CMM) and linked by non-rigid tanks. 4 supports for alignment targets (fiducials) with a diameter 0.5''have been glued on each mechanical part [3]. The position of these fiducials with respect to the mean mechanical axis of each part has been determined by measurements performed on the Leitz Infinity machine (Maximum Permissible Error of 0.3 µm + 1 ppm). The assembly of the 3 parts has been controlled using the Leitz Infinity machine and a Multi Gage Romer arm, after each step: the pairing process, the tack welding and welding. A difference of 10 µm between CMM and Romer arm measurements has been found, which is very satisfactory taking into account the uncertainty of measurement of the Romer arm of the order of 10 µm. A misalignment of 80 µm has been found for each assembly (considering a global budget of error of 100 µm).

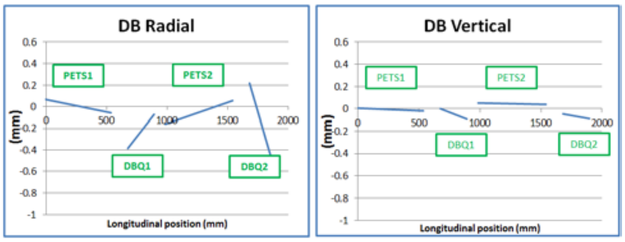

Fig. 2: horizontal and vertical position of the DB components w.r.t the mean axis of the V-shaped supports

Once measured, PETS have been fastened on the V-shaped supports of the girder. The position of their mean axis with respect to the mean axis of the V-shaped supports is shown Fig. 2.

Alignment of DB quadrupole components

Dummy DB quadrupoles (of similar weight and dimensions) have been manufactured. They have been equipped with 6 supports for 1.5'' fiducials. The position of the fiducials has been measured with respect to the beam pipe axis, using the Leitz Infinity machine.

A dedicated supporting system located beneath the DB quadrupoles has been designed for the adjustment of the quadrupoles at their theoretical position with respect to the mean axis of the girder. The adjustment resolution of the system did not have a satisfactory resolution [2], and the DB quadrupole could not be put in place as wanted: it took several hours to adjust the quadrupoles at an accuracy of 20 µm with respect to its nominal position. A new system, introduced in [4] will solve the problem allowing a micrometric adjustment of the quadrupoles along 5 DOF. The position of the DB quadrupoles with respect to the mean axis of the V-shaped supports is shown Fig. 2. The misalignments are far above the initial 20 µm: a degradation of the alignment has occurred due to a bad fastening of the quadrupoles on the girders.

Alignment of AS components

One accelerating structure consists of 28 cells brazed together. Then four accelerating structures are brazed together to become a stack with a length of 1 m. Each cell has been controlled in the metrological laboratory using Leitz Infinity CMM, then their assembly has undergone the same measurements. The centre of each cell has been determined and the mean axis of each structure has been computed. 4 supports of 0.5'' fiducials have been glued on the manifolds and their position has been measured (Leitz Infinity CMM) with respect to the mean axis of each AS. The position of the fiducials of each stack has then been measured in metrology. After transport, each stack has been fastened on the V-shaped supports of the MB girder and the position of each mean axis of structure has been determined using AT401 measurements on the fiducials.

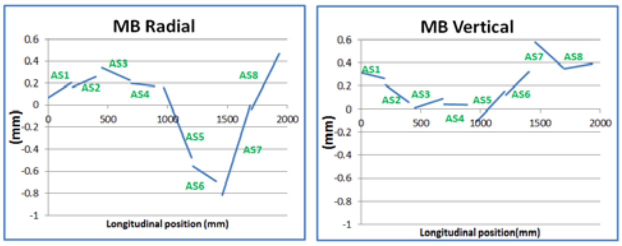

Fig. 3: horizontal and vertical position of the MB components w.r.t the mean axis of the V-shaped supports

The position of the mean axis of each structure is shown on Fig. 3. The first stack has a maximum alignment default of 0.19 mm in horizontal and 0.19 mm in vertical, while the second stack has a maximum alignment default of 0.85 mm in horizontal and 0.70 mm in vertical [5] [6].

Alignment of the girder

Once the components are aligned on top of the girders, the alignment of the components comes to the alignment of the girders. A snake configuration of the girders is proposed guaranteeing a natural smoothing of the alignment of the components and no important offsets as it could be the case if the girders were aligned independently. Module supporting girders will be interlinked by an articulation point defined geometrically as the intersection of the V-shaped supports' mean axis of two adjacent girders. The girders components are aligned once the articulation points are aligned with respect to a straight reference of alignment.

Each girder will be equipped with a master and a slave cradles. Two adjacent girders will be linked respectively by their master and slave cradles. The master cradle will host the pre-alignment sensors and will be supported by actuators, allowing displacements according to 3 Degrees of Freedom (DOF): horizontal, vertical displacements and roll (displacement around beam axis). The articulation point linking both cradles is designed in such a way that only the horizontal and vertical displacements will be transferred from the master to the slave cradle, and not the roll.

Such an alignment can be performed only if the position of the sensors interface located on the cradles has been measured at the best possible accuracy with respect to the mean axis of the V-shaped supports. These measurements have been performed on the Olivetti CMM (uncertainty of measurement of ± 6 µm, at 3σ) that has a limited length of measurements of 1.6 m. The position of the fiducials on the girders has been measured within the uncertainty of measurement of the CMM, but not the sensors interfaces, where an accuracy of 20 µm in their determination is estimated [7].

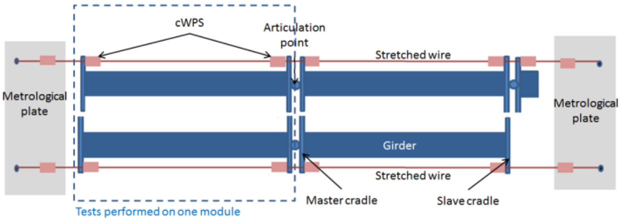

Fig.4: Module configuration (top view)

To get more redundancy concerning the determination of the position of the girders, all the cradles (master and slave) have been equipped with pre-alignment sensors (see Fig. 4). Two reference alignment plates, independent from the module, provide the reference of alignment, as foreseen in the tunnel.

PREPARATION OF THE THERMO-MECHANICAL TESTS

Description of the experimental test area

The Two Beam Test Modules have been installed in a room where the tunnel environment can be reproduced by an air conditioning and ventilation system. Temperatures from 20 °C to 40 °C can be carried out, with a longitudinal air speed (as foreseen in the CLIC tunnel) from 0.3 to 0.8 m/s.

In order to reproduce the estimated power dissipation occurring in the module, all the components have been equipped with electric heaters associated with a control system allowing to regulate separately the heat power per type of components (PETS, DB quadrupole, AS). Straight tubular heaters have been associated to RF components, providing a maximum powering of 6.1 kW for AS and 2.2 kW for PETS; cartridge heaters have been coupled with DB quadrupoles providing a maximum powering of 3.2 kW, while silicon rubber heaters have been associated with compact loads for a maximum power of 1 kW [8].

A cooling system has been integrated in the RF structures (and not in the DB quadrupole), providing the adjustment of temperature of each component via a control cooling system.

Description of the duty cycles

Different operating scenarios are planned to be simulated on the module: nominal operation, AS breakdown, PETS breakdown. This paper concerns the first test performed: the reproduction of the nominal operation, with the powering of components. In this scenario, the DB quadrupoles are powered with no active beams. Then, the Drive Beam is activated and once the Drive Beam is in steady state, the Main Beam is activated [9].

In order to simulate this scenario, 4 states have been defined:

- Zero position
- Power-up of DB quadrupole
- Unloaded conditions (RF inside cavity but no beam)
- Loaded conditions (RF + beam inside the cavity decreasing energy)

The position of the components and their supporting girders will be determined for each state. Transient measurements will be performed as well every 1°C to study the transition between two operating sates.

METHODS OF MEASUREMENTS

Introduction

A combination of two different means of measurements are planned to be used for the tests: capacitive based Wire Positioning Sensors (cWPS) coupled to each cradle (with roll measurements carried out by inclinometers) and AT401 measurements performed on the fiducials of girders, components and metrological plates.

cWPS are fastened within a micrometric repeatability on their kinematic interface located on each cradle [10]. The position of each kinematic interface has been determined with respect to the mean axis of the V-shaped supports with an accuracy estimated at 20 µm. The zero of each sensor has been determined at an accuracy estimated below 5 µm in the referential frame of the sensor (its kinematic interface). Once the sensor is fastened on its interface, its horizontal and vertical readings coupled with CMM measurements provide the position of the mean axis of the V-shaped supports with respect to the stretched wire.

AT401, manufactured by Hexagon Metrology is a laser tracker performing angle and distance measurements, with an uncertainty of distance measurement claimed at ± 10 µm per meter over a range of 25m, and an angle measurement accuracy claimed to be 0.5'' at 1 σ according to ISA 17123-3 [11].

As both AT401 and cWPS allow the determination of the position of the girders, the coordinates of the entrance and exit points of the girders have been compared to check their coherence. Differences between 10 µm on the coordinates of the entrance and exit points were computed [2].

Sensors measurements

During the thermo-mechanical tests, cWPS were installed on the master and slave cradles of the transport sides of the girders. As an inter-comparison was under way with sensors developed by NIKHEF on the non-transport side, no redundancy could be obtained through the sensors readings. The roll angle was given by an inclinometer installed on each master cradle, providing relative measurements only. See Fig. 5.

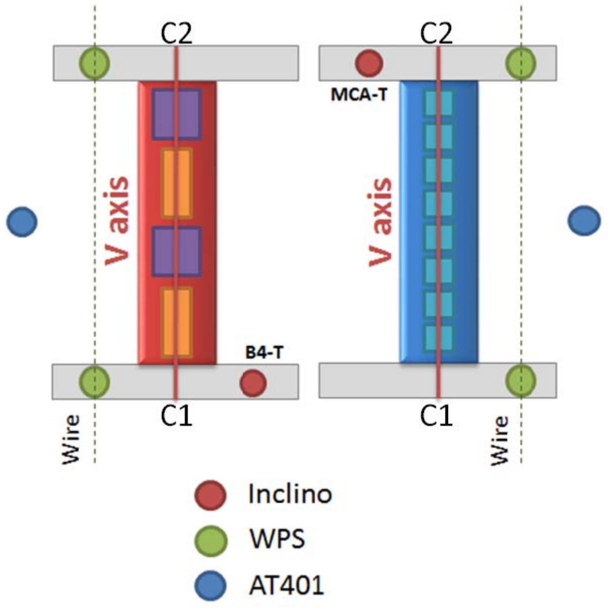

Fig. 5: Configuration of the sensors and AT401 in the module

cWPS readings are validated by horizontal and vertical displacements of the wire: considering the relative displacements performed on the extremities of the wire and the longitudinal position of each sensor, the new theoretical readings of the sensor can be computed and compared with the real offsets measured after displacement. The readings of cWPS coupled with CMM measurements of the girder, cradle and sensors interfaces allow the determination of the mean axis of the V-shaped supports (C1C2) that will be used in the calculations presented later in this paper.

Tests performed by varying the longitudinal air flow in the room have shown that the air flow had no impact on the readings of cWPS sensors [12].

AT401 measurements

A dedicated method of measurement has been implemented and validated to determine the position of the fiducials of the components at the highest accuracy and precision. A network of fiducials has been installed in the experimental area, on the walls and ceilings and determined with respect to the metrological plates used as reference of alignment. Specific care has been brought to the measurements [13]:

- Nobody was allowed in the room during the measurements (except the persons in charge of the alignment measurements)
- A heavy tripod was used to support the AT401 for a better stability, and the duration of one station had to be lower than 45 minutes
- The AT401 was warmed-up 4 hours before the first measurements.
- During the measurements process, all the measurements were performed back side and front side, and integrated over at least 5 seconds. 3 closures were carried out during the network, the girder or the component measurements, e.g. the first point of each set of measurements was measured again at the end of the session. If an offset above 15 µm was found, all the measurements were deleted and started again. To shorten the measurements process, the fiducials located on the girder have been considered as reference (as determined at a high accuracy through CMM measurements, taking into account the low thermal expansion coefficient of the girder in silicon carbide): best fits were performed taking into reference the measurements performed in the metrology laboratory at 20°C to check the coherence of the thermal expansion coefficient.

Strategy of measurements

The strategy of measurements has been prepared without knowing the order of displacements to be monitored. Finite Element Model (FEM) has been prepared with ANSYS to simulate such displacements, but the corresponding data were ready during the measurements process.

The position of the components located on the girders has been determined using AT401 measurements, as there are no sensors coupled to the components. Six stations were necessary to measure the fiducials with redundancy: 2 stations were needed on the DB side as the visibility of fiducials was very good (all fiducials could be measured from the two stations), which was not the case of the MB where 4 stations were needed. During transient states, it appeared that faster measurements were needed, leading to a new strategy of measurements.

In order to shorten the measurement time to determine the position of the fiducials, one station has been proposed on each side of the module. To solve the visibility problem on the MB side, additional fiducials have been glued on the accelerating structures; their position has been determined with respect to the mean axis of the component, using the other fiducials. Several repeatability tests have been carried out to validate this new strategy considering three sets of measurements performed from 3 different stations. The reference axes of the AS have been determined with a standard deviation of 3.5 µm and a maximum error of 11 µm [14]. This strategy of measurements with one station has been kept for the thermo-mechanical tests as it is less time consuming, with the drawback of being less accurate and offering less possibilities of control (see configuration Fig. 3).

The position of the girders in the general referential system has been computed continuously using cWPS sensors fastened on the cradles of the girders.

MISALIGNMENTS OF COMPONENTS AND SUPPORTS DURING THERMO-MECHANICAL TESTS

Stabilization period

Before performing measurements to determine the misalignment of components and supports during thermo-mechanical tests, it was very important to define when the steady state was obtained after each cycle. cWPS allowing continuous measurements could provide such information. The duration of stabilization between two states was determined according to the sensors readings. Figure 4 consists of three graphs showing data between the two first states: the zero position and the powering of DB quadrupoles. The top graph presents the readings of temperature probes installed on DB quadrupoles, PETS and AS components recorded to reach the first step “water + DBQ” from a zero position. The middle graph presents the cWPS readings located on the cradles of DB girders and the bottom graph presents the cWPS readings located on the cradles of MB girders.

It is clearly visible on Fig.6 that the mechanical constants (transient time of the girder to reach the first steady state) are two times longer than thermal constants (temperature of the components). As the MB girder has no heated component during that state, no significant impact is seen by the sensors.

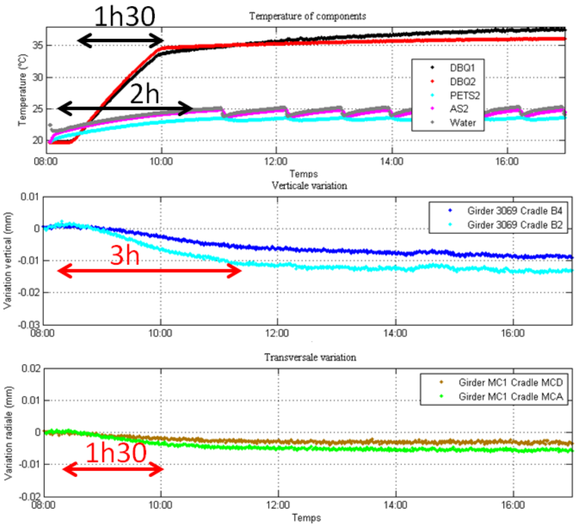

Fig. 6: temperature versus cWPS readings

Misalignments of components

The relative displacement of each reference axis of components has been determined at the end of each phase with respect to the previous position of the components in the girder referential frame. Tables 1 and 2 show the vertical and horizontal displacements of DB Quadrupoles and PETS components measured with respect to the mean axis of the V-shaped supports of the DB girder. Tables 3 and 4 show the vertical and horizontal displacements of AS components measured with respect to the mean axis of the V-shaped supports of the MB girder.

Table 1: vertical offsets w.r.t. previous state (DB side)

	PETS1 (µm)	**DBQ1** (µm)	**PETS2** (µm)	**DBQ2** (µm)
Water + DBQ	-1	41	0	45
Unloaded	11	-2	19	-12
Loaded	-4	3	0	2

Table 2: horizontal offsets w.r.t. previous state (DB side)

	PETS1 (µm)	**DBQ1** (µm)	**PETS2** (µm)	**DBQ2** (µm)
Water + DBQ	8	1	4	15
Unloaded	3	7	7	1
Loaded	-5	-5	-8	-9

Table 3: vertical offsets w.r.t. previous state (MB side)

	AS 1	AS 2	AS 3	AS 4	AS 5	AS 6	AS 7	AS 8
Water + DBQ	7	9	12	15	11	13	14	8
Unloaded	8	5	11	10	8	9	4	6
Loaded	-8	-5	-3	-7	0	1	4	4

Table 4: horizontal offsets w.r.t. previous state (MB side)

	AS 1	AS 2	AS 3	AS 4	AS 5	AS 6	AS 7	AS 8
Water + DBQ	7	3	1	0	-7	-6	-7	-9
Unloaded	2	3	2	3	4	3	-1	-3
Loaded	3	7	6	6	7	10	9	8

Considering the uncertainty of measurement of AT401 combined with the strategy of measurements estimated at an accuracy of 10 µm, only a few data (above 10 µm) in the tables can be considered.

During the first phase (water cooling + powering of DB quadrupole), the vertical displacements of the two DB quadrupoles are respectively 41 µm and 45 µm. The vertical displacements of AS are also clear. As there was no cooling system for the DB quadrupole, the temperature of the quadrupoles reached 35 °C, at the origin of the vertical displacements. AS were "cooled down" at an average temperature of 25 °C, producing an expansion of the structures.

During the second phase (unloaded conditions), the temperature of PETS and AS increase by 5 °C, with as a consequence an expansion of the components (vertical displacements of 15µm for the PETS and 10 µm for the AS).

During the third phase (loaded conditions), the temperature of AS decrease by 1 °C: a very small misalignment in vertical is observed in the tables.

Horizontal displacements are very small, within a few micrometres, within the uncertainty of measurement of the AT401, which seems logical: a temperature increase of the component should not misalign horizontally its reference axis, as the component is symmetric. The misalignments above 5 µm can be explained by a modification of the contacts points of the components with respect to their support. As an example, the AS has a banana shape of a few tenths of millimetre, and is installed in V-shaped supports. During an expansion, the contact points of the AS are modified, producing roll, and thus a small horizontal displacement.

Misalignments of supports

The misalignment of the supporting girders was monitored continuously by the cWPS sensors and inclinometers. Table 5 summarizes the displacement of entrance and exit points of the DB girder once the steady states were reached.

Table 5: displacements of C1 and C2 (DB side)

	C1 vert (µm)	C2 vert (µm)	C1 hor (µm)	C2 hor (µm)
Water + DBQ	10	16	13	20
Unloaded	5	0	14	4
Loaded	3	2	3	2

Table 6 summarizes the displacements of entrance and exit points of the MB girder once the steady states were reached.

The fact that the sensors are located on the cradle and not on the girder creates an additional uncertainty in the determination of the position of the girder. The cradle is in aluminium, while the girders are in silicon carbide, two materials with different thermal expansion coefficients.

Table 6: displacements of C1 and C2 (MB side)

	C1 vert (µm)	C2 vert (µm)	C1 hor (µm)	C2 h (µm)
Water + DBQ	10	16	13	20
Unloaded	5	0	14	4
Loaded	3	2	3	2

To obtain the value of misalignment of the components in the general referential frame, two values have to be added: the misalignment of the component with respect to the mean axis the V-shaped supports (in tables 1 to 4) and the misalignment of girder in the general referential frame (in tables 5 and 6).

CONCLUSION

One first duty cycle reproducing the machine start-up procedure during nominal operation has been simulated on a CLIC module, by adding heaters to the components. The measurements performed show that it has nearly no impact on the alignment of the components that are cooled down (PETS and AS), and has an impact on the vertical position of the DB quadrupoles that are not cooled down. The strategy of measurements chosen has been a trade-off between the accuracy of measurements needed and the duration of measurements. The misalignments measured of RF components are in the uncertainty of measurements of the methods, within ± 10 µm. A good correlation between the measurements performed and the outcome of the FEM model has been established.

Improvements of the methods of measurements should be undertaken before starting the tests of other duty cycles. First, concerning the sensors measurements, the corrections of thermal expansion of the cradle with respect to the girder should be implemented. The measurements of the mean axis with respect to sensors interface have been performed at 20°C at an accuracy of 20 µm. The uncertainty of measurements should be improved, as the knowledge of the position of sensors interfaces when the temperature varies. Second, concerning the AT401, several improvements are under consideration:

- To increase the number of stations per side by two, e.g. two stations on the DB and two stations on the MB sides.
- To use simultaneously 4 AT401 measuring the position of components
- To equip all the fiducials supports with CCR
- To automatize the process of measurements.

The tests have also shown that a better knowledge of the performance of sensors was needed when the temperature differs from 20°C. Studies of such a characterization will be undertaken using climatic chambers.

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