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CLIC main beam quadrupole active pre-alignment based on cam movers

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Abstract:

Compact Linear Collider (CLIC) is a study for a future 48 km long linear electron-positron collider in the multi TeV range. Its target luminosity can only be reached if the main beam quadrupoles (MB quads) are actively pre-aligned within 17 µm in sliding windows of 200 m with respect to a straight reference line. In addition to the positioning requirement, the pre-alignment system has to provide a rigid support for the nano-stabilization system to ensure that the first eigenfrequency is above 100 Hz.

Re-adjustment based on cam movers was chosen for detailed studies to meet the stringent pre-alignment requirements. There are four different types of MB quads in CLIC. Their lengths and masses vary so that at least two types of cam movers have to be developed. The validation of the cams with less stringent space restrictions has proceeded to a test setup in 5 degrees of freedom (DOF). Prototypes of the more demanding, smaller cams have been manufactured and they are under tests in 1 DOF. This paper describes the challenges, test methods and results as well as current status of development of both cam based system types.

1-Introduction

To meet the CLIC pre-alignment target, each MB quad should be actively re-adjusted with micrometric precision in 5 DOF. Only the movement along the beam line direction will not be controlled but mechanically blocked. There will be four different MB quad types and in total more than 4000 MB quad units in CLIC [1]. All MB quad types have the same width, approximately 500 mm. Type 1 MB quad is the shortest (420 mm, 300 kg) and type 4 is the longest (1915 mm, 800 kg) [2, 3]. Because the MB quad types are so different, at least two different actuator types needed to be developed.

Cam movers are actuators in which translation is realized by rotating an eccentric camshaft. They have been successfully deployed in several synchrotrons and light sources and they were originally developed at SLAC. The starting point for CLIC was the design used in the Swiss Light Source (SLS) at the Paul Scherrer Institute (PSI) [4].

This paper first introduces the operating principle of a cam mover and the two different mover types that have been thus far developed and tested at CERN. Then, a cam mover based 5 DOF mock-up and its control algorithms are presented. The current status of both cam mover based systems (type 1 and 4) is presented and discussed before conclusions.

2-Cam mover

There is a bearing and bearing housing around the eccentric part of the shaft of a cam mover to interface with the cam follower (load). The cam follower trajectory is sinusoidal as a function of the camshaft orientation, the stroke being twice the eccentricity of the camshaft.

The MB quad pre-alignment project was started by validating the cam mover concept in a dedicated 1 DOF mock-up. The tested actuator was a further developed version of the PSI design. [5].

The cam mover design was then optimized together with the company ZTS VVU Kosice which also manufactured 6 actuators; 5 for a 5 DOF mock-up (to simulate type 4 MB quad adjusting, presented in next section) and one spare. These cam movers are hereafter called ZCM (ZTS cam mover). They have a stroke of 10 mm and theoretical worst case resolution of 0.03 µm. All ZCM's were tested and calibrated in the 1 DOF mock-up. Their repeatability throughout the whole movement range is below 1 µm. With a reduced stroke of ±3 mm, their repeatability is below 0.3 µm. [2]

ZCMs are too big for the pre-alignment of type 1 MB quads so a new design was needed. In the ZCM, high re-adjustment resolution is achieved by having two gearboxes in series, thus high gear ratio. However, in the type 1 design, CCM (Compact cam mover) hereafter, there was not enough space for two gearboxes so high resolution had to be realized in another way.

Cam mover resolution can be increased by reducing the eccentricity, by increasing the gear ratio or by improving the stepper motor's resolution. The effect of eccentricity in the resolution is rather low and some margin is preferable so it was not open for optimization. Several stepper motor and gearbox combinations were studied to find a suitable solution. In addition to relatively high gear ratio, the gearbox had to be self-locking and preferably with negligible backlash.

An Oriental Motor PK564PMA-A7 stepper motor with 1000 steps per revolution was chosen. An off-the-shelf gearbox to match the requirements was not found. The company Davall Gears manufactured custom gearboxes based on their Spriradrive® technology which met all requirements and have gear ratio 90:1. This means theoretical worst case resolution of 0.35 µm.

Figure 1 is a photograph of a ZTM and figure 2 shows a CCM.

Figure 1 ZCM (ZTS cam mover)

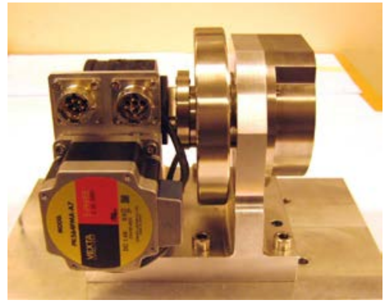

Figure 2 CCM (Compact Cam Mover)

3-5 DOF mock-up

5 DOF mock-up was built for the final validation of cam mover based pre-alignment system for type 4 MB quads. Figure 3 is a photograph of the mock-up. It consists of a specially designed rigid chassis which lays on 5 ZCMs through interfaces. There are 3 ZCMs under one end of the chassis, one of them with a horizontal, one with a 45° angle and one with a -45° angle interface. The remaining 2 ZCMs are under the other end of the chassis, with 45° and -45° interfaces.

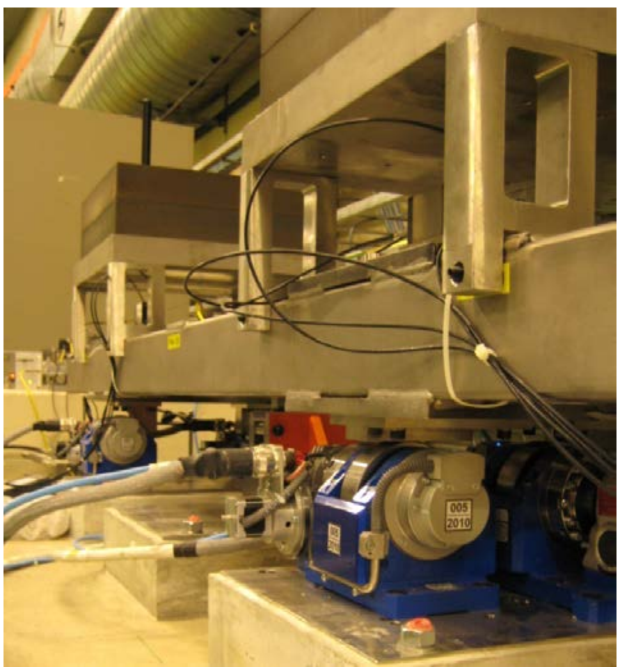

Figure 3 5 DOF mock-up.

Figure 4 shows the 5 DOF mock-up's coordinate system. The chassis' translations along x- and y-axes as well as rotations around the same axes are measured using two WPSs (Wire Position Sensor) installed around a stretched wire. WPS measures relative offset to the wire with 0.1 µm resolution in x and y directions. Roll (rotation around z-axis) is measured with a high resolution inclinometer. There is also another stretched wire and two WPSs installed around it to have redundancy in measurements. [2]

Before installation of the 5 DOF mock-up, the chassis was measured in a CMM (Coordinate Measuring Machine). Therefore all the sensor and interface positions are known within the accuracy of 6 µm in the chassis coordinate system. There are also fiducials in mounted in the chassis so that the chassis' position can be measured in absolute coordinate system in the future.

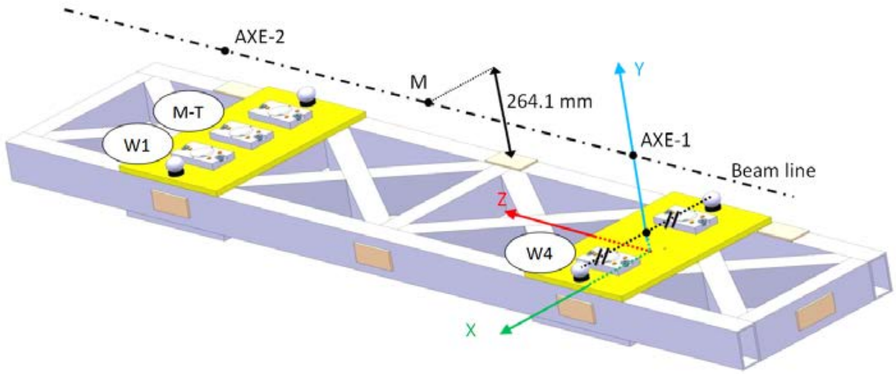

Figure 4 5 DOF mock-up coordinate system.

The chassis is moved relative to a nominal position using the 5 ZCMs. The chassis is in nominal position when the ZCMs from number 1 to 5 are oriented in angles -45°, -135°, -135°, -45° and 0° respectively. If the chassis were positioned in absolute movements, the beam line misalignments in the nominal position should be close to zero or at least they should be accurately known in the absolute coordinate system. But to validate the cam mover based system, movements relative to the nominal position were enough. The above mentioned nominal cam angles were chosen to have the most simple calculations in the control algorithm.

The 5 DOF mock-up re-positioning algorithms are based on Dr. Andreas Streun's formulas which are described in his article [6]. The article gives tools to calculate required cam angles to have required misalignments in point M in the chassis coordinate system visible in the Figure 4. The dashed line containing points M, AXE-1 and AXE-2 is imaginary beam line which is the actual object to be pre-aligned.

Streun's formulas were adapted to the 5 DOF mock-up and they act as a core of the re-positioning algorithm. User inputs are x- and y-displacements in points AXE-1 and AXE-2 as well as roll of the chassis. The user inputs are transformed to 5 misalignments in point M (all DOFs except translation in z-direction because it is mechanically blocked). Then required cam angles are calculated and the cams are turned to these angles.

After re-positioning, the readings of the two WPSs (W1 and W4 in figure 4) are transformed to x- and y-displacements at points AXE-1 and AXE-2. The inclinometer provides directly the relative chassis roll. The effect of roll is taken into consideration in the transformations. This way the required and measured chassis displacements can be compared and the system's positioning precision can be estimated.

The 5 DOF mock-up still contains many unknown parameters, for example exact longitudinal position of the chassis. Therefore the required re-positioning precision cannot be achieved in one movement. However, it is achieved with an automated iterative process. This means that after a movement, the displacement errors are measured, then added to the user input and finally the cams are rotated again. This is repeated until the x- and y-displacement errors in points AXE-1 and AXE-2 are less than 1 µm and roll error is less than 5 µrad.

4-Current status

This section presents the current status and latest results of both type 4 and type 1 MB quad pre-alignment systems.

The 5 DOF mock-up has been extensively tested, with and without additional loads (visible in figure 3) which simulate the quadrupole's weight. In this section, displacement accuracy means the deviation between a reference displacement and a measured one (both relative to the nominal position).

Displacement accuracy depends heavily on the length and complexity of displacement. With simple movements where only one translation or rotation is applied while other degrees of freedom are kept in the nominal position and that are smaller than 0.5 mm (or 0.5 mrad) from the nominal position, the displacement accuracies are in the order of 10-20 µm and µrad (first iteration).

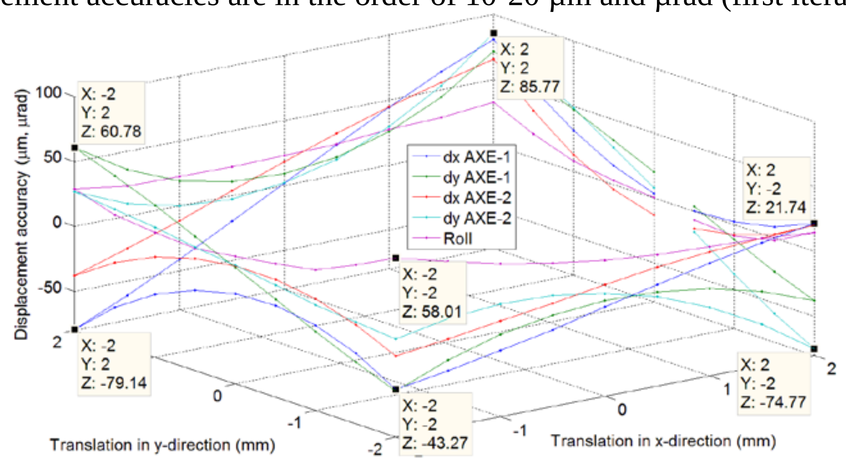

Figure 5 Displacement accuracies as functions of target positions.

With more complex movements, the accuracy was significantly worse. A good example of this is shown in figure 5 which plots the accuracies as functions of target displacements. It can be seen that with combined 2 mm x-direction and 2 mm y-direction translation, the deviation grows to over 80 µm in the y-direction in the point AXE-2. The load weight has an effect of approximately 20 µm in y-direction translation accuracy and less in other degrees of freedom.

The system's movement resolution is below 1 µm everywhere in the movement range. Repeatability is below 5 µm for AXE-1 and AXE-2 displacements and below 5 µrad for roll.

The correct position was found in 3 to 5 iterations without the load weight. But adding the load made a big difference in this matter. The amount of iterations needed grew to 5 with simple movements and to over 10 with more complex movements. Even orientations which were not achievable were found. An improvement in the iteration algorithm solved the problem caused by load. Now most orientations are reached in below 10 iterations and so far all orientations have been achievable.

A CCM prototype was manufactured and installed in the 1 DOF mock-up. The first tests showed great results but then the pinion of the gearbox broke down. The mock-up's construction causes some sticking which causes high momentary torque in the gearbox. This was not taken into consideration and the tests have to be restarted. Also a new, more robust pinion is being designed for the gearbox.

5-Conclusions

The 5 DOF mock-up showed that a cam mover based system meets precision requirements using an iterative process in the case of CLIC type 4 MB quad.

There are two ways to improve the type 4 cam mover re-positioning system. Firstly, the mathematical model can be made more accurate, either by optimizing parameters (e.g. by taking into account cam mover hysteresis) or by making a look-up table based on test data. Secondly, the iteration algorithm could potentially be improved. Especially when reaching the 1 µm level, too abrupt motion in one direction causes a movement of similar size in another direction so the algorithm has to be smooth. With faster data acquisition electronics, it might even be possible to realize real-time position control.

The 5 DOF mock-up is now being dismantled. The ZCM bearings will be changed to another type and afterwards the mock-up will be rebuilt and re-tested. The mock-up's natural frequencies will also be measured and these results will finally determine whether the system is applicable or not.

Designing a cam mover for the type 1 pre-alignment system has proven to be challenging due to the additional size restrictions. The CCM development will continue in parallel with two slightly different gearbox designs. The only difference is the pinion's material. The original bronze pinion is with negligible backlash but it is, as seen, fragile. The new design is with steel pinion which makes the gearbox capable of handling over two times more torque, but it has more backlash (corresponding to up to 7 µm translation in the worst case). 5 DOF tests are required to learn whether it is possible to eliminate the effect of backlash using sophisticated control algorithms.

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