9th Edit. of the Mech. Eng. Des. of Synchrotron Radiat. Equip. and Instrum. Conf. MEDSI2016, Barcelona, Spain JACoW Publishing
ISBN: 978-3-95450-188-5 doi:10.18429/JACoW-MEDSI2016-MOPE15

CAM MOVER ALIGNMENT SYSTEM POSITIONING WITH WIRE POSITION SENSOR FEEDBACK FOR CLIC

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Abstract

Compact Linear Collider (CLIC) is a study of an electron-positron collider with nominal energy of 3 TeV and luminosity of $2 \cdot 10^{34}$ $cm^{-2}s^{-1}$. The luminosity goal leads to stringent alignment requirements for single quadrupole magnets. Vertical and lateral offset deviations with regards to a given orbit reference in both ends of a quadrupole shall be below 1 µm and quadrupole roll deviation shall be below 100 µrad. Translation in the direction of particle beam is not controlled but mechanically locked.

A parallel kinematic platform based on cam movers was chosen as system for detailed studies. Earlier studies have shown that cam movers can reach the CLIC requirements through an iterative process. The paper presents new modular off-the-shelf control electronics and software including three optional positioning algorithms based on iterations as well as a more advanced algorithm which can reach target position in one movement. The advanced algorithm reads wire position sensors (WPS), calculates quadrupole orientation based on the readings and updates the remaining trajectory during motion. All of the optional positioning methods reach the CLIC positioning requirements within minutes.

INTRODUCTION

CLIC final stage nominal energy is so high that two 21-km-long main linacs are needed, even though a very high acceleration of 100 MV/m is foreseen. Both main linacs are composed of 2.01-m-long modules. The modules are composed of either accelerating structures (AS), main beam quadrupoles (MBQ) or a combination of the two. There are four different types of MBQ which differ from each other only by length. Type 1 is the shortest and type 4 is the longest MBQ. The lengths are 420 mm, 920 mm, 1420 mm and 1915 mm. [1, pp. 393]

Each MBQ is equipped with a beam position monitor (BPM). In order to reach the CLIC luminosity target, all MBQ magnetic centres have to be within 17 µm and all BPMs within 14 µm from straight line fit on any sliding window of 200 m along the linacs, as shown in Fig. 1. The requirements include uncertainties related to linking the MBQ magnetic centre to the alignment sensors, uncertainties of the alignment sensors themselves as well as positioning accuracy of the alignment stage of a single MBQ. The maximum contribution of single MBQ misalignment is defined as ± 1 µm in transversal (x) and vertical (y) offset with regards to a given orbit reference with ± 3 mm travel in each end of the MBQ. In addition, maximum deviation in rotation around the beam (roll) is 100 µrad.

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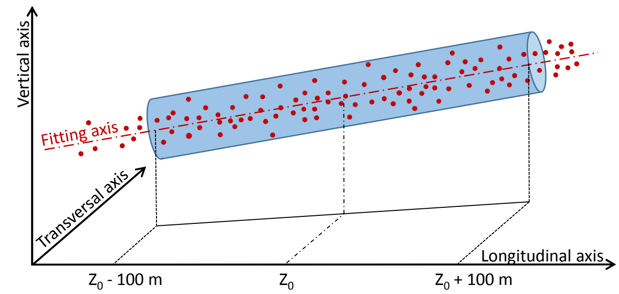

Figure 1: Objectives of CLIC active pre-alignment. [1, pp. 602]

It was demonstrated in an earlier study that the CLIC positioning requirement is reached when a mock-up girder with dummy weights, simulating type 4 MBQ and stabilisation system, is aligned using a parallel kinematics machine (PKM) based on cam movers [2]. In this paper, the same PKM and girder are used but the control electronics have been replaced. The new electronics allowed more advanced motion control. Four different positioning algorithms were developed. They are presented and compared.

The type 4 cam movers and the test setup are presented in the next section. Then, the new control electronics are introduced. Next, the positioning algorithms are described, followed by test results and comparison. Finally, conclusions are drawn.

TEST SETUP

Left side of Fig. 2 shows CLIC type 4 MBQ together with a system that stabilizes its mechanical vibrations. The combination weighs 570 kg. It is mounted on five cam movers which control five degrees of freedom (DOF). Only translation in the direction of beam is not controlled but rather blocked mechanically. The five DOFs are measured redundantly with two stretched wires and two wire position sensors (WPS) around each wire, manufactured by Fogale Nanotech and measuring both x- and y-offsets with 0.1 µm resolution.

Actual type 4 MBQ prototype together with its stabilization system has not been built. Therefore, a mock-up girder was used in the alignment study. Right side of Fig. 2 shows the girder, mounted on CLIC type 4 cam movers (ZCM), manufactured by ZTS VVU Kosice. The same setup was used also previous study [2]. The girder weighs 185 kg. In the previous study, 590 kg of dummy weights were installed on top of the girder, resulting in total load of 775 kg and it was seen to make positioning more difficult. This time, only the girder was installed due to lack of time. Two stretched wires and four WPS sensors are used to measure the girder position.

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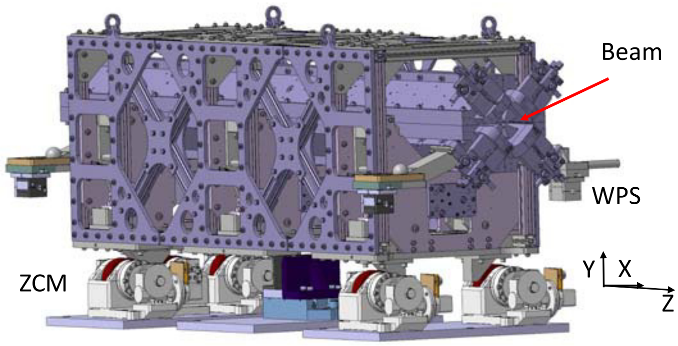

Figure 2: Type 4 MBQ and stabilisation system mounted on cam movers (left) and test setup including ZCMs, follower girder and local coordinate system (right).

Least squares algorithm is used to calculate the controlled five DOFs from the redundant data. The girder position can be thus measured with the uncertainty of approximately 5 µm in absolute and 1 µm in relative but the measurement system is not within the scope of this paper. The goal was to show that the girder can be positioned within 1 µm in offsets and 100 µrad in roll from an alignment sensor feedback. The accuracy of the feedback is not relevant.

CONTROL ELECTRONICS

ZCMs were delivered with dedicated control electronics. Previous study, demonstrating the positioning capability of a PKM based on ZCMs with an iterative algorithm, was conducted using the dedicated electronics crate. There are, however, some drawbacks with this setup. Firstly, it is only possible to set a target angle and parameters of trapezoidal motion profile of the ZCMs. It is not possible to adapt the trajectory during motion. Secondly, the crate is error prone. This prevented long test runs.

In order to exploit the full potential of the ZCMs, new control electronics crate based on commercial, off-the-shelf components was developed in-house. The goal was also that the same control crate could be used to control other cam mover prototypes with small adaptations. National Instruments (NI) cRIO-9068 was chosen as the controller as the hardware setup can be adapted by changing the standardized C modules. Plenty of different modules are available, manufactured by NI and other companies.

This study was carried out with a configuration of five C modules. Two SEA 9521 BiSS interface modules were used to acquire the five absolute encoders. Two SISU-1004 stepper interface modules were used to send steps to the motor drives. In addition, an NI-9207 module was used for fast acquisition of four WPS sensors.

The new electronics enable three software layers. User interface is a regular LabVIEW program running on a host computer. All calculations (kinematics, measurement data processing, trajectory generation) are done in the cRIO-9068 processor and the program is written in LabVIEW Real-Time. Low level program is running on LabVIEW FPGA and it reads the WPSs and encoders as well as sends step signals to stepper motor drives.

POSITIONING ALGORITHMS

CLIC alignment requirement is set for MBQ magnetic centre. In this study, it is assumed that the magnetic centre is coincident to the beam which goes through the MBQ, as indicated in the left side of Fig. 2. The beam line does not exist in the mock-up girder. Therefore, both the positioning algorithms and the WPS readings are transformed to a theoretical beam line which is floating on top of the girder at the same height compared to the ZCMs as in the left side of Fig. 2 and which is rigidly attached to the girder.

The ZCMs are calibrated in a separate setup. The girder has a reference position approximately in the mid-travel in 5 DOF. The ZCMs are driven to the angles corresponding to this reference position. Girder position is then measured and all movements are relative to this reference position. NI SoftMotion is used in motion control of the setup.

Four positioning algorithms were developed and compared. The first one is called Synchronous PTP (point-to-point) and it is the simplest one. Target girder position is transformed to relative motor steps of each ZCM based on a kinematic model. Trajectory is not pre-defined but SoftMotion makes sure that all five cams start and stop at the same time. After the movement is finished, the position is measured with the WPSs. The target position is compared to the measured position and if the deviation is too high, it is added to the target. A new movement is performed and the procedure is repeated. This is done until the target position is reached within limits. This is called iterative approach.

The second algorithm is called Straight-line movement and it is also iterative. Trajectory to the target is calculated before movement and constraints to the trajectory can be applied. However, it is not monitored during motion whether the girder follows the trajectory, only between iterations.

The third algorithm is called Complex movement and it is a combination of the two first ones. The trajectory of first iteration (which is assumed to be the longest movement) is calculated in advance like in Straight-line movement. The following iterations (if needed) are using the Synchronous PTP algorithm. This way the trajectory is well defined during the long movement but no slow trajectory calculations are needed for the shorter iterations.

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In the fourth algorithm, called Predictive movement, trajectory can be constrained. Before movement, the trajectory of the first 4 seconds of movement is calculated. This is divided into 40 intermediate points (one every 100 ms). When movement is started, this buffer of points is consumed. When there are less than 10 points left, the girder position is measured, the position error is taken into account and new ten points are calculated to the buffer. This means that during motion, the trajectory is updated every second. In the end of the movement, slow approach is applied. The goal is to have a smooth positioning without overshoot. It was seen in previous study that, especially with the higher load, changing rotation direction of cams caused jumps in position and made it harder to reach the target.

TESTS

Uncertainties in the kinematic model of the 5 DOF setup, e.g. manufacturing tolerances and uncertainties in assembly and ZCM calibration, cause open-loop positioning error. The error increases with increasing distance from the reference position. Positioning is therefore the most dependent on the feedback near maximum travel in each direction and emphasis of tests was there. A test of 136 sequences was repeated using each of the four positioning algorithms. Each test sequence had a target position where the girder was driven directly from the previous target position, without passing by the reference position.

The 96 first test sequences covered different offset combinations near the maximum travels but while roll was kept at zero. The 40 last sequences covered roll targets while other DOFs were kept at zero. For each sequence, the target was considered reached (and parameters were set so that this was always the case) when offset deviations with regards to alignment sensors were below 1 µm and roll deviation below 5 µm. The roll deviation tolerance was kept lower than CLIC requirement because the system can readily handle it.

All positioning algorithms managed to reach all sequence targets within tolerances. Alignment sensor readings were not saved during motion but ten acquisition were saved after each target was reached. Standard deviation of the ten acquisitions was calculated in order to check that the girder was well stabilised to the target position. The difference between performances of movement types can then be evaluated by comparing the time it takes them to position the girder within tolerance.

Fig. 3 shows a 20 sequence slice of the test. It can be seen that the movement time of Synchronous PTP algorithm is significantly longer than that of the others. Fig. 3 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.

After the movement type comparison test, the Predictive movement algorithm was tested with a reduced amount of sequences and three different stop condition parameters: the original, the tightest possible which still reached all positions and a set of parameters which is between them.

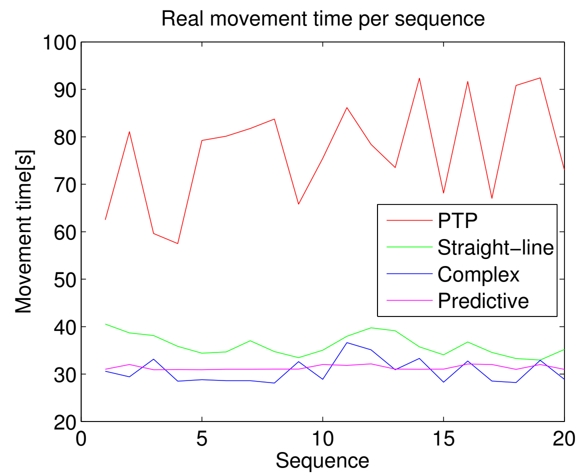

Figure 3: Comparison of execution times of four movement types in 20 test sequences.

Average deviation decreased when stop condition was tightened, but not significantly. A bigger difference can be seen in the maximum deviations, which are approximately 1.0 µm for x-offsets, 0.4 µm for y-offsets and 2.0 µrad for roll with original parameters and 0.5 µm, 0.4 µm and 1.3 µrad correspondingly with the tightest parameters. The positioning takes on average 13 % and up to 65 % longer with the tightest parameters than with the original ones. The parameter set in between is only very little better than the original set but it also takes only 1 % more time on average in positioning.

CONCLUSIONS

It was demonstrated that the CLIC positioning requirements for MBQ alignment stage 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 both in level of deviation and in positioning time. A trade-off between positioning accuracy with regards to feedback and positioning time can be made depending on requirements.

When applied to a specific system, the predictive movement algorithm can be made faster, especially if there is very little play in the cam movers. Then overshoot is allowed and more aggressive trajectory can be applied.

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