

# DRIVE BEAM QUADRUPOLES FOR THE CLIC PROJECT: A NOVEL METHOD OF FIDUCIALISATION AND A NEW MICROMETRIC ADJUSTMENT SYSTEM

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## Abstract

CLIC (Compact Linear Collider) Drive Beam (DB) Decelerator will generate RF power to accelerate the colliding beams. One key component of the decelerator is the Drive Beam quadrupole (DBQ). More than 40 000 DBQ will have to be pre-aligned within a challenging precision and accuracy: the magnetic axis of each DBQ will have to be positioned in a cylinder with a radius of 20  $\mu\text{m}$ , over a sliding window of 200 m along the 20 km of linacs. The current strategy of pre-alignment foresees: first to perform the fiducialisation of the DBQ, e.g. determining the position of the magnetic axis of each quadrupole with respect to external alignment targets, second to pre-align two DBQ on a common support, third to align the support once transported in the tunnel. In order to make the strategy easier, we propose a novel method of fiducialisation based on a combination of laser tracker, 3D coordinate Measuring Machine (CMM) and Wire Positioning Sensors (WPS) measurements. The method is described and the results of its cross-comparison with the standard method of fiducialisation are shown. We also propose a new adjustment system to pre-align the DBQ on their supports according to 5 degrees of freedom. The conceptual design of the system is introduced, as well as the results during the validation of the prototype.

## INTRODUCTION

In the CLIC DB decelerator, more than 40 000 quadrupoles (DBQ) are foreseen to steer the beam. In order to send the first pilot beams in the decelerator and perform beam based alignment, a high precision mechanical pre-alignment of the quadrupoles is required [1]. As a matter of fact, for a sliding window of 200 m along the 20 km of linac, the standard deviations of the transverse position of the magnetic axis of each DBQ with respect to a straight line fit must be less than 20  $\mu\text{m}$  [2]. Each CLIC linac will consist of more than 10 000 modules, with a length of 2 m. Each module will contain two DBQ, supported on the same girder. Consequently, two DBQ will have to be pre-aligned in the referential frame of a girder. Each girder will be equipped with position sensors and will be supported by actuators allowing its micrometric remote adjustment. Each position sensor will provide horizontal and vertical offsets with respect to a straight alignment reference at an accuracy of 5  $\mu\text{m}$  [3]. The alignment of each DBQ on the girder will consist of two steps: the determination of the

magnetic axis of the quadrupole in the referential frame of the DBQ (fiducialisation process) and the adjustment of the quadrupole on the girder in such a way that its magnetic axis is at its theoretical position within a few micrometres in the referential frame of the girder, e.g. with respect also to the second DBQ [4].

In this paper, a new method of fiducialisation is described based on a combination of capacitive based Wire Positioning Sensors (cWPS), AT401 measurements and CMM measurements. The results obtained on DBQ are introduced and discussed, as well as the results of the comparison between this new method and the standard one.

The paper introduces also a high precision solution of micrometric adjustment of the DBQ, detailing the results obtained on standalone regulation units and on the prototype.

## A NOVEL METHOD OF FIDUCIALISATION

### Introduction

The use of an oscillating stretched wire is one the possibility to determine the magnetic axis of a quadrupole using the Faraday's law of induction. The wire is centred and aligned in the quadrupole by finding the position that minimizes the oscillation amplitude. The two translations (horizontal and vertical: Y and Z according to Figure 1) are put in place by looking at the first resonance and applying a co-directional movement, while the two rotations (pitch and yaw: rotations around Y and Z) are put in place by looking at the second resonance and applying a counter-direction movement [5].

Once the wire is located at the magnetic axis, its position has to be transferred and determined with respect to external alignment fiducials (fiducialisation process). Later, during the installation process, these fiducials will allow the accurate positioning of the magnetic axis of the quadrupole. This transfer of reference is performed using Laser Tracker (LTD500) measurements. The wire is stretched by a motor coupled to a tension gauge and positioned by displacements tables located at each extremity. The wire oscillations are controlled by opto-couplers. The wire is "driven" through two ceramic balls in such a way that it is always re-installed the same way (in vertical and horizontal) with respect to the displacement tables' reference frame at the micrometre level. As it is not possible to measure directly with a laser tracker these ceramic balls, two 1.5" fiducials have been

added on each side close to the ceramic balls. The position of these targets has been determined within a micrometric uncertainty of measurement with respect to the ceramic balls, thus with respect to the stretched wire.

Such a fiducialisation strategy appeared to have a very good precision, within a few micrometres, but there were some doubts concerning the accuracy, estimated at 40 micrometres, with no possibility to cross-check the measurements. A novel method of fiducialisation is proposed to perform such cross-checks, using capacitive Wire Positioning Sensors (cWPS) to determine the position of the wire coupled with AT401 measurements linking the position of cWPS with respect to the external fiducials on the DBQ. The devices used: cWPS and AT401 are described in the next chapters, as well as the results obtained.

### *cWPS sensors*

cWPS are manufactured by Fogale Nanotech [6]. They perform transverse offsets measurements with respect to a conductive wire, without any contact, at a sub-micrometric resolution. They have been upgraded by CERN to improve their precision and accuracy.

First, each sensor has been equipped with a kinematic mount (cone, oblique chamfer and plane), allowing only one position when installed on a support consisting of 3 ceramic spheres. Such kinematic mount and 3 spheres interface, coupled with efficient solutions of fastening, provide repeatability and reproducibility less than 1  $\mu\text{m}$  in the dismantling and remounting of the sensor [7][8].

Second, each sensor has been calibrated with such a kinematic mount on a dedicated bench. The position reference during the calibration process is provided by a displacement table with a 50 nm resolution along the 2 transverse directions. The sensor is displaced over its whole range (10x10 mm), by steps of 0.1 mm, the stretched wire being kept at a stable position during the whole process of measurements. Then, polynomials are computed providing the offsets in horizontal and vertical in mm in function of the vertical and horizontal readings in Volts. The process of calibration is performed in such a way that the mechanical zero of each sensor is the same for a given position of the reference wire, guaranteeing the interchangeability of all the sensors from the same batch, e.g. that two different sensors installed on the same 3 spheres interface will read the same transverse offsets with respect to a static stretched wire within 1  $\mu\text{m}$  repeatability.

Third, each sensor is calibrated using an “absolute” calibration bench, e.g. the position of its zero is known within a 5  $\mu\text{m}$  accuracy in its coordinate system, materialized by a 3 spheres interface [9].

### *AT401*

The absolute tracker AT401 is manufactured by Hexagon metrology. It integrates an Absolute Distance Meter based on the polarization modulation technology, insensitive to both long distances and environmental influence, with an uncertainty of measurement of  $\pm 10 \mu\text{m}$

per meter over a range of 25 m. The angle measurement accuracy is claimed to be 0.5 " at 1  $\sigma$ , according to ISO 17123-3 [10].

### *Description of the new proposal*

The new system of fiducialisation consists of 2 cWPS sensors and a bench. The 2 cWPS determine the position of the wire without any contact, at micrometric precision and accuracy. The dedicated bench, rigid and stable along time, is equipped with a lot of fiducials and two 3 spheres interfaces for cWPS. The bench has been designed in such a way that the DBQ can be inserted in between the two cWPS interfaces. The position of the spheres of the cWPS interfaces has been measured with respect to the fiducials of the bench in the metrology laboratory, with a 3D Coordinate Measuring Machine having an uncertainty of measurement of 0.3  $\mu\text{m}$  + 1 ppm (MPPE, ISO 10360-2). Such a bench allows the determination of the position of the cWPS with respect to the fiducials of the DBQ using an AT401.

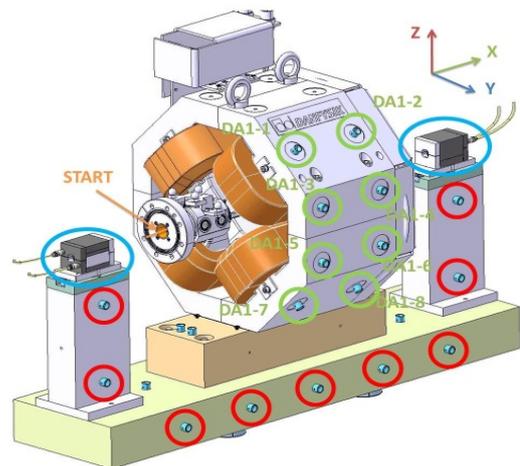


Figure 1: New proposal of fiducialisation

A budget of error of 7.2  $\mu\text{m}$  has been estimated concerning this new method of fiducialisation [2].

In order to validate such a proposal, measurements have been carried out on a real DBQ to be installed in the CLIC Experimental area (CLEX).

### *Fiducialisation results obtained with the new proposal and inter-comparison*

The repeatability of the method itself has been performed on 3 different types of wires: a Copper-Beryllium wire manufactured in 2003 (Cu-Be 2003), a Copper Beryllium wire manufacture in 2013 (Cu-Be 2013), a Copper-Niobium wire (Cu-Nb) with a 0.1 mm diameter. Measurements were performed over respectively 5 sets of Cu-Be 2003, 4 sets of Cu-Be 2013 and 4 sets of Cu-Nb. Each time, the DBQ was reinstalled on its support. Then, once the wire was located at the magnetic axis, the cWPS sensors were reinstalled on their kinematic mount and the measurements of sensors were performed, combined with AT401 measurements. Prior to

these measurements, cWPS had been calibrated with respect to the 3 types of wires, as the type of wire has an impact on the calibration of the sensor [4].

The position of the wire (materializing the entrance and exit of magnetic axis of DBQ) has been determined for the 13 sets of measurements. In order to compare the different sets of measurements, best fits have been carried out using the fiducials located on the bench. Considering two clouds of measurements points, the second cloud of points was translated and rotated (via a 3D similitude) in such a way that the distances between the points of the two clouds were minimized by least square adjustment method.

The standard deviation of the best fits performed of the 13 sets on the DBQ fiducials is presented in the Table 1 below and is very satisfactory. Only the results concerning the transverse position of the wire are introduced as the longitudinal position has no micrometric requirement in its determination. This shows that the 3 types of wire have no impact on the determination of the magnetic centre, and that the repeatability of measurements of AT401 and cWPS is better than 5  $\mu\text{m}$  [11].

Table 1: standard value of the coordinates of entrance and exit points of the DBQ magnetic axis after best fit

Std dev. of coordinates	Y ( $\mu\text{m}$ )	Z ( $\mu\text{m}$ )
Entrance of magnetic axis	4	4
Exit of magnetic axis	4	5

Considering the very good repeatability, the results of the new method of fiducialisation have been cross-checked with the results obtained by the standard fiducialisation method, using an AT401 instead of the LTD500. The position of the wire at the entrance and exit of the DBQ has been computed for each method, with the same micrometric order of repeatability of measurements. In order to cross-check the methods, a best fit has been carried out, and the offsets in the position of magnetic axis between both methods are shown in Table 2.

Table 2: offsets between the coordinates of entrance and exit points of the magnetic axis calculated by new and standard methods

Offset	Y ( $\mu\text{m}$ )	Z ( $\mu\text{m}$ )
Entrance of magnetic axis	26	3
Exit of magnetic axis	27	1

There is a very good matching between both methods in vertical, but not in horizontal, where a systematism of 27  $\mu\text{m}$  appears. Several hypotheses could explain such a value: an error in the CMM measurements linking the ceramic balls centring the stretched wire to the fiducials considered for the standard method or a systematism in the measurements performed by the AT401. Some incoherencies have been recorded between measurements performed on 0.5'' targets and measurements performed on 1.5'' targets using this instrument. Investigations are

under way to have a better understanding of the origin of the problem [11].

### Other associated results

Another test has been performed in order to have a better knowledge of the determination of the magnetic axis: the impact of the current in the position of the magnetic axis inside the DBQ. The measurements performed show that the position of the magnetic axis changes for values of current inferior to 50 A, and that the offsets have to be taken into account. As a matter of fact, the DBQ will be used with a current of 4A in CLEX: this corresponds to an offset of 20  $\mu\text{m}$  in vertical and more than 40  $\mu\text{m}$  (see figure 2) with respect to determinations of magnetic axis performed on a quadrupole with a current above 50 A.

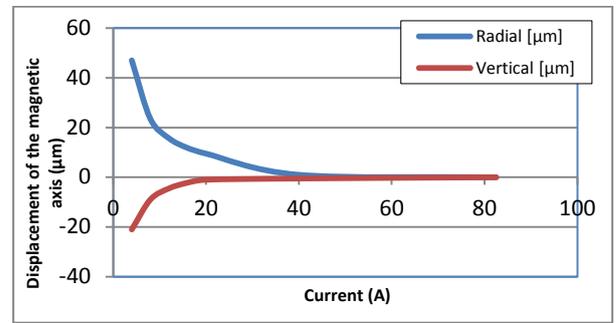


Figure 2: position of the magnetic axis according to the current

The acquisition up to 100 Hz of cWPS sensors have been carried out using NI hardware. NI hardware consists of a Compact DAQ 8-slot Ethernet chassis (NI cDAQ-9188) integrating 2 RTD Analog Input modules (NI9217) for the acquisition of temperature probes and 1 Voltage/current Analog Input module (NI9207) for the acquisition of WPS sensors.

### Conclusion

The new method of fiducialisation has a very good repeatability in the determination of the DBQ magnetic axis, within a few micrometres. Cross-check measurements performed with the standard method show that there is a systematism in the horizontal determination of the position of the stretched wire for one of the two methods, under investigation. The very good results obtained using a combination of cWPS sensors and AT401 measurements confirm the micrometric accuracy and precision of both devices.

The fiducialisation is not the only step on which one can act to gain accuracy in the pre-alignment. As a matter of fact, once the position of the components to be aligned on the same support is known at the micrometres, a micrometric adjustment of these components is necessary. The mechanical solutions using shims tested on the Two Beam Module have not fulfilled these requirements of adjustment [4]. In the next chapter, a new 5 Degrees Of Freedom (DOF) adjustment solution is proposed, based

on flexural joints, wedge actuators and differential thread screws.

## 5 DOF ADJUSTMENT SYSTEM

### Requirements

The requirements to fulfil the micrometric adjustment of the DBQ are the following:

- Adjustment according to 5 DOF (Y & Z translations and 3 rotations),
- Stroke:  $\pm 1$  mm in Y and Z (X blocked)  
 $\pm 4$  mrad in all rotations,
- Resolution  $< 5 \mu\text{m}$ ,
- The solution proposed must fit in the very tight available space (height of 15 mm above the girder),
- User access on the outer side of the module,
- Load 170 kg.

### Description of the solution

The solution has been designed in such way that the regulation knobs are all located on the same side. See figure 3. A girder mounting chassis is fixed rigidly to the girder. Then, the upper plate on which is screwed the DBQ can be adjusted according to 5 DOF with respect to the girder chassis by performing a combination of vertical and horizontal displacements. The upper plate is fixed longitudinally with respect to the girder chassis [12].

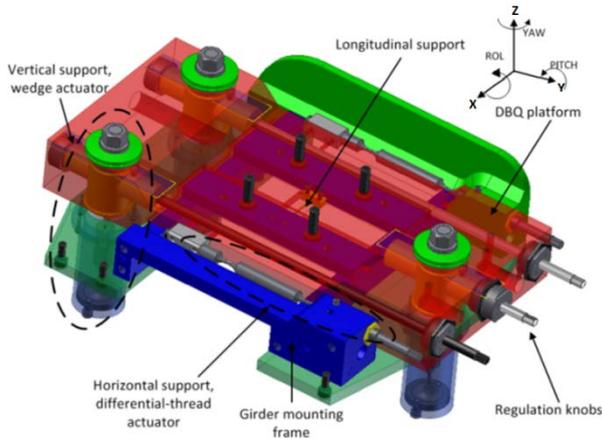


Figure 3: 3D model of 5 DOF adjustment system

The vertical displacements are performed via regulation screws coupled with wedge actuators. 30 mm of wedge displacement correspond to 2 mm of vertical stroke with a resolution of  $2 \mu\text{m}$  (Figure 4 shows the operating principle). The horizontal displacements are performed by a differential thread screw with a stroke of 0.25 mm per revolution. 10 revolutions of screw correspond to 2 mm of horizontal stroke, with a resolution of  $4 \mu\text{m}$ . The vertical and horizontal regulation components are integrated with flexural supports to provide the needed DOF. An additional flexural joint blocks the longitudinal displacement of the upper plate and allows vertical and horizontal translations, plus rotations within the range foreseen.

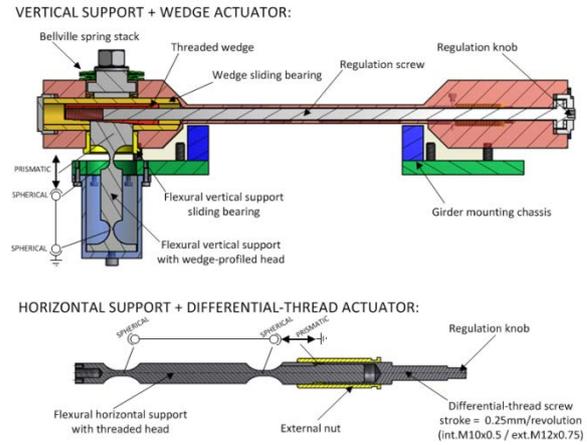


Figure 4: operating principles of vertical and horizontal actuators

### Strategy of development and validation

The design and validation of the concept has undergone three different stages:

- First, one horizontal and one vertical standalone regulation units have been designed, manufactured and tested independently. Once these first concepts validated, the design of the entire 5 DOF adjustment could take place.
- Second, the validation of the prototype with a dummy DBQ, leading to some improvements in the design.
- Third, the validation of final series (2 pieces) to be installed in the CLIC experimental area (CLEX), to adjust DBQ positions.

### Validation of the horizontal and vertical standalone regulation units

An existing test bench developed for the validation of linear actuators has been used, equipped with additional adapters to validate the horizontal and vertical standalone regulation units [13].

The tests performed on the vertical regulation unit showed a stiffness of  $5 \text{ kg}/\mu\text{m}$ . A resolution of regulation below  $1 \mu\text{m}$  was achieved easily within a short regulation time. Repeatability below  $7 \mu\text{m}$  was observed over the whole stroke, with a non-linearity of  $10 \mu\text{m}$  and a backlash of  $15 \mu\text{m}$ . The position was stable along time.

The tests performed on the horizontal regulation unit showed a stiffness of  $2.5 \text{ kg}/\mu\text{m}$ . A resolution of regulation below  $3 \mu\text{m}$  was easily achieved within 5 s. Repeatability below  $20 \mu\text{m}$  was obtained, with a non-linearity of  $10 \mu\text{m}$  and a backlash of  $45 \mu\text{m}$ . It was decided to pre-stress the flexural joints to suppress thread backlash and to increase the threads tolerances.

### Validation of the prototype with a dummy quadrupole

The validation of the prototype has taken place in a room stabilized in temperature. The 5DOF adjustment

system was equipped with potentiometric absolute position sensors on its adjustment screws to monitor the actuator positions. A mock-up of quadrupole, at its nominal load (170 kg) has been installed on top of the support, combined with 2 cWPS sensors and one inclinometer to determine independently the position of the support according to 5 DOF [14].

The following results have been obtained:

- The long term stability of the support has been confirmed, with no drift or material creeping observed,
- A resolution of translations below  $4\ \mu\text{m}$  has been obtained, and rotations between  $20\text{--}40\ \mu\text{rad}$ .
- The manual adjustment performed to obtain such resolutions took less than 10 minutes following a determined sequence: rough adjustment of angles, rough adjustment of translations, fine adjustment of angles and fine adjustment of translations.
- A second order impact on the vertical axis has been recorded while adjusting the horizontal axis and vice versa.

Such a validation has led to some improvements in the design of the series: tolerances of several parts have been corrected to avoid minor assembly problems; the shape of the vertical flexure has been optimized to increase its stiffness and strength and regulation knobs have been equipped with standard interfaces to have the possibility to connect encoders during the regulation process.

The final support is shown on Figure 5.

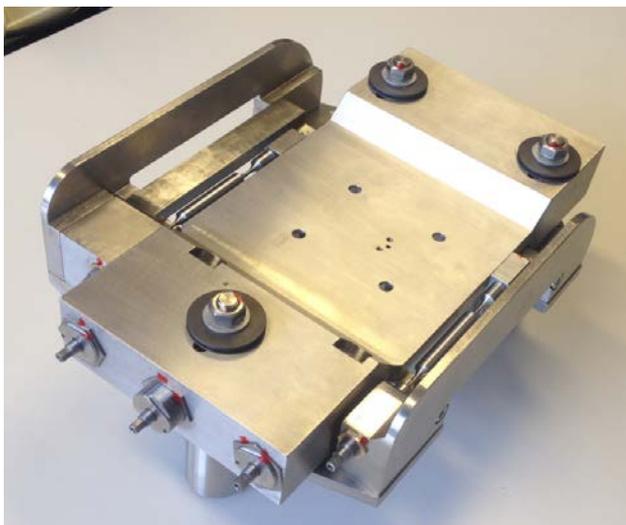


Figure 5: DB quadrupole support

## CONCLUSION

A new method of fiducialisation has been proposed and validated successfully on the DBQ, showing that a budget of error below  $5\ \mu\text{m}$  can be considered to determine the position of a magnetic axis, materialized by a stretched wire, with respect to external alignment fiducials. This new method combines Wire Position Sensors

Measurements, 3D Coordinate Machine Measurements and AT401 measurements.

A new mechanical system allowing a micrometric adjustment of the DBQ according to 5 DOF has been validated successfully, with a resolution of translations below  $4\ \mu\text{m}$  and a resolution of rotations between  $20$  and  $40\ \mu\text{rad}$ .

These two solutions could be combined during the fiducialisation process, leading to a new strategy of pre-alignment more efficient in term of time and accuracy. The two DBQ would be pre-aligned on their common support via the 5 DOF adjustment system. The whole assembly would be installed on a magnetic calibration bench and a wire would be stretched through the two quadrupoles. Instead of displacing the wire to determine the magnetic axis, the quadrupole would be displaced acting on the 5DOF support till the wire is located at the magnetic axis. At the same time, the position of the wire would be measured with respect to fiducials using the new proposal of fiducialisation. Such a method could be extrapolated to other components: the stretched wire could be used to determine the offsets between the zero of BPM and the magnetic axis of the DB quadrupole. If the whole process was done in a 3D CMM, a very good accuracy could be obtained to determine the position of the wire with respect to the external alignment fiducials.

This example is an extrapolation of the PACMAN project [15], a Marie Curie Initial Training Network program, offering 10 PhD subjects to a new generation of scientists in beam instrumentation, metrology, micrometric alignment, magnetic measurements, nano-positioning and high precision engineering. The technical goal of this project is to develop very high accuracy metrology and alignment tools and methods for the fiducialisation of CLIC components as Main Beam quadrupole, BPM and accelerating structures.

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