FREQUENCY SCANNING INTERFEROMETRY FOR CLIC COMPONENT FIDUCIALISATION

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Abstract

We present a strategy for the fiducialisation of CLIC's Main Beam Quadrupole (MBQ) magnets using Frequency Scanning Interferometry (FSI). We have developed complementary device for a commercial FSI system to enable coordinate determination via multilateration. Using spherical high index glass retroreflectors with a wide acceptance angle, we optimise the geometry of measurement stations with respect to fiducials -- thus improving the precision of coordinates. We demonstrate through simulations that the 10 µm uncertainty required in the vertical and lateral axes for the fiducialisation of the MBQ can be attained using FSI multilateration.

INTRODUCTION

One of the main technical challenges of the Compact Linear Collider (CLIC) study is the tight pre-alignment requirements of its 3,992 beam-focussing MBQs. For the determination of the position of the magnetic axis of each MBQ with respect to external targets, a 10 µm (1 σ) error budget is specified in the CLIC conceptual design report [1]. This process, also known as fiducialisation, is very important because the magnetic axis of these magnets will not be accessible during alignment in the accelerator tunnel. Instead, the external alignment targets (fiducials) will be used for the alignment of the magnets.

The Leitz Infinity Coordinate Measuring Machine (CMM) is the preferred instrument for fiducialisation due to its low measurement uncertainty. This CMM has Maximum Permissible Error of length measurement ($E_{L,MPE}$) of only 0.3 µm + 1 ppm, making it the most accurate in its class.

The Leitz Infinity has a couple of drawbacks. First is its limited measurement volume of 1200 mm X 1000 mm X 700 mm whereas some MBQs will have a length of 1850 mm. Secondly, it can only perform measurements in a fixed location in a metrology lab, whereas some measurements will be needed in the accelerator tunnel.

The Particle Accelerator Components' Metrology and Alignment to the Nanometre scale (PACMAN) project is a study at CERN that seeks to develop portable fiducialisation solutions [2]. FSI is a high accuracy absolute distance measurement technique which will be combined with multilateration to produce a portable coordinate measurement system. Our goal in PACMAN is to meet the measurement uncertainty requirements for the fiducialisation of CLIC's MBQs using FSI multilateration. We present the status of our developments that make multilateration measurements with FSI possible. We also demonstrate via simulation, the feasibility of multilateration for CLIC MBQ fiducialisation.

HARDWARE AND DEVELOPMENTS

Absolute Multiline Technology

We are using Absolute Multiline Technology which is manufactured by Etalon AG [3] for our research. It is the only commercial FSI system in the world and has measurement uncertainty of 0.5 µm per metre at 2 σ. Our version of the system can perform up to 8 distance measurements simultaneously, with the potential of being scaled up to 100. This is a unique characteristic compared to other distance measurement systems.

The Absolute Multiline measures absolute distances between the tip of an optical fibre and a retroreflector. Unfortunately, this system cannot directly measure absolute distances between defined points of interest. Furthermore, the system cannot measure distances in different directions from the same point whereas this is necessary for multilateration. The reason for this is that the fibre tip which is housed inside a collimator does not have an external reference. The collimator is necessary to collimate light to the retroreflector and focus down the retroreflected beam back into the optical fibre.

FSI Optical Fibre Tip Localization

We have developed a first prototype for localizing the Absolute Multiline optical fibre tip; thus opening up FSI to a host of metrology applications -- notably multilateration.

The prototype consists of a reference sphere into which we have inserted the FSI collimator as shown in Fig. 1. The goal is to determine the position of the fibre tip with respect to the centre of the sphere and in so doing, also to the surface of the sphere.

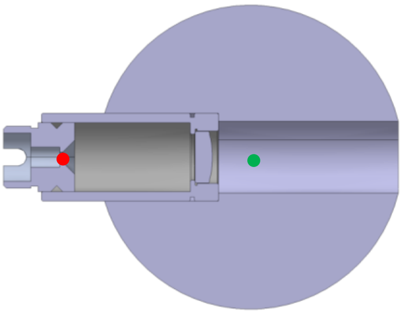

Figure 1: Cross section of FSI collimator [4] coupled to the reference sphere. The red dot is the position of the optical fibre tip; the green dot is the centre of the sphere.

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Our reference sphere has a nominal diameter of 38.1 mm ± 0.5 µm and a sphericity of ± 0.5 µm. We chose this diameter to be the same as commercial spherically mounted retroreflectors -- this allows us to use the same support for both. In so doing, we can perform interstation observations leading to stronger multilateration networks.

The reference sphere is made of white alumina ceramic (Al_2O_3). With a coefficient of thermal expansion of $8.1 \cdot 10^{-6} K^{-1}$, it is more thermally stable than more common materials such as stainless steel ($18 \cdot 10^{-6} K^{-1}$) and aluminium ($23 \cdot 10^{-6} K^{-1}$). The use of white ceramic spheres means that the system can be measured by QDaedalus micro-triangulation system which uses similar targets [2]. This way, FSI can potentially be used as a scale for micro-triangulation.

In coupling the collimator to the sphere, there is an offset of the fibre tip with respect to the centre of the sphere. This can be split into two components, one along and the other perpendicular to the measurement beam.

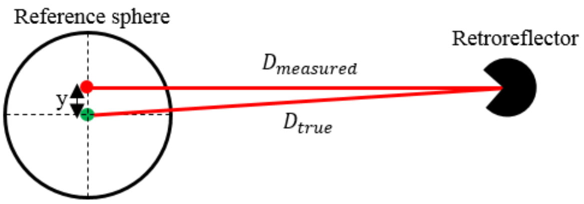

Figure 2: Cross section showing a *y* offset of the optical fibre tip with respect to the centre of the sphere perpendicular to the beam line

Assuming the beam is perfectly aligned to the retroreflector, the *y* offset only introduces a cosine error whose impact is negligible and reduces with increasing distance (See Fig. 3).

Given a measured distance in the presence of a perpendicular offset, *y*, the true distance can be calculated using the Pythagorean theorem as shown in Eq. 1.

$$D_{true} = \sqrt{D_{measured}^2 + y^2} \tag{1}$$

The difference E_y, between the measured distance and the true distance can therefore be calculated using Eq. 2. This Equation is used to calculate the error in Fig. 3.

$$E_y = D_{measured} - \sqrt{D_{measured}^2 + y^2} \tag{2}$$

A more serious error due to the offset perpendicular to the beam is the sine error. We found that the collimator we inserted into the reference sphere can tolerate retroreflector lateral misalignments of ± 1.5 mm for a 12.7 mm diameter open-air corner cube. The presence of a perpendicular offset, introduces uncertainty in the measured distance which depends on the pointing accuracy of the measurement beam to the retroreflector. Given that the true distance between reference sphere and retroreflector centres remains unchanged, we can use Eq. 3 to Eq. 5 to ascertain the impact of pointing accuracy on the measured distance in the presence of a *y* offset.

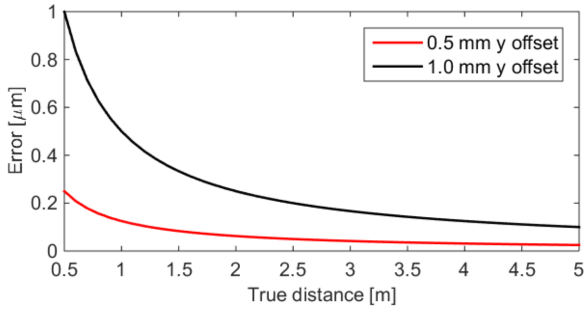

Figure 3: The cosine error introduced by 0.5 mm and 1.0 mm perpendicular offset has little impact on distance.

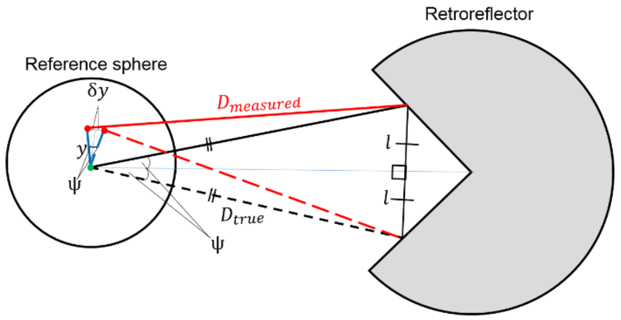

Figure 4: Relationship of the sine error, δy, the *y* offset perpendicular to the beam and a pointing offset, *l*.

Based on Fig. 4, the rotation angle ψ, due to a pointing offset *l*, is related to the true distance D_{true}, by Eq. 3.

$$sin\psi = \left(\frac{l}{D_{true}}\right) \tag{3}$$

The sine error δy, the perpendicular offset *y*, and the rotation angle ψ, are related as shown in Eq. 4 (small-angle approximation).

$$\delta y \approx y sin\psi \tag{4}$$

Merging Eq. 3 and Eq. 4 shows that the sine error is inversely proportional to the true distance between the reference sphere and retroreflector. However, it is directly proportional to the pointing offset and the perpendicular offset (See Eq. 5).

$$\delta y \approx y\left(\frac{l}{D_{true}}\right) \tag{5}$$

In Fig. 5, we show that the ±sine error due a ±1.5 mm pointing offset in the presence of 1 mm *y* offset is significant. However, it reduces with distance.

We performed two experiments to assess the impact of pointing accuracy on the repeatability of distance measurements performed with our prototype. For the first experiment, we deliberately varied the alignment accuracy while for the second, we aimed for the best possible alignment.

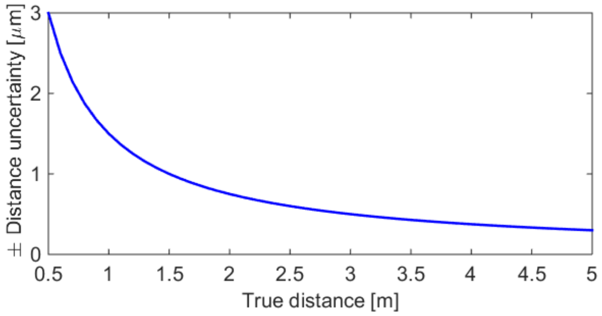

Figure 5: Distance uncertainty due to sine error in the presence of a 1 mm perpendicular *y* offset and a ±1.5 mm pointing offset.

The collimator in the sphere was pointed by hand towards a 12.7 mm diameter open air corner cube retroreflector with the aid of a red guide laser. The guide laser forms a bright focussed central spot when well aligned and a more scattered spot when not. Good alignment was confirmed by ensuring that we consistently achieved the highest reflected intensity readings.

We performed both experiments at two distances of 311 mm and 994 mm to assess the impact distance had on the repeatability of the measurements. For each setup, the beam was misaligned and then realigned 36 times. The standard deviations obtained for each alignment setup and distance are shown in Table 1.

Table 1: Repeatability achieved using the prototype reference sphere.

Pointing Accuracy	Distance [mm]	std [µm]	Distance [mm]	std [µm]
Poor	311	2.9	994	1.9
Good	311	0.8	994	0.5

With careful alignment, we demonstrated that we can achieve a repeatability of under 1 µm (1 σ). The corresponding range between the maximum and minimum distance for the 36 repeat measurements was 2.5 µm and 2.9 µm for the longer and shorter distance.

For the poor alignment, we achieved a standard deviation of under 3 µm over both distances with a range of 5.9 µm and 9.8 µm for the longer and shorter distance.

From these experiments, we see that both the standard deviation and range are better with good pointing accuracy. We also see that the uncertainty is greater for shorter distances despite the fact that the uncertainty of Absolute Multiline Technology increases with distance. Both these observations agree with our theoretical analysis of the effects of sine error in our design.

Figure 6: *x* offset along the measurement beam line.

The offset along the beam, if not compensated would introduce a systematic error in the distance measured equal to the offset itself. Fortunately, it can easily be calibrated by a host of methods, such those for determining the zero-point correction for Electro-optical distance-meters.

A simple calibration procedure could involve arranging 3 supports in a straight line and making 3 distance measurements with a single reference sphere and corner cube of the same diameter. One measurement between the two supports at extremes of the setup would be required, followed by one for each of the two shorter distances. The sum of the two shorter distances should equal the longer distance; if not, the difference would represent the offset along the beam. Alternatively, this offset can be added as one additional unknown for each reference sphere in a multilateration network. This way, it can be solved for as part of the least squares adjustment routine as is the case for retroreflector offsets.

Figure 7. Prototype for localizing the FSI optical fibre tip consisting of a reference sphere and kinematic mount.

We have also developed a kinematic support to complement the reference sphere. The kinematic mount consists of three, 6 mm diameter alumina spheres fixed on an anodized aluminium base (See Fig. 7). The base spheres have limited friction with the reference sphere which slides seamlessly within the support. The support consists of a bracket to secure the reference sphere on the 3 base spheres allowing various mounting possibilities.

High Refractive Index Glass Retroreflectors

We have elected to use high index glass retroreflectors for this study. To this end, we have developed our own targets in conjunction with external companies. These are 12.7 mm spheres with a sphericity of 63 nm made of high refractive index Tantalum flint (TAFD55) glass. The advantage of using these spheres rather than traditional corner cube retroreflectors is the fact that they have an unlimited acceptance angle. This characteristic allows flexibility in the positioning of measurement stations which in turn enables us to design more precise multilateration networks.

The disadvantage of using these spheres is the fact they have a low efficiency -- only ≈ 8.38% of the incident beam is retroreflected. We have experimentally demonstrated that the Absolute Multiline can measure to these glass spheres over distances of up to 4.5 m. The intensity performance of these spheres depends on the collimator chosen to equip the fibre end. We found that whilst using collimators with a larger acceptance aperture (Thorlabs F810FC-1500), distance measurements were always possible and the intensity remained more or less constant. We tested several smaller aperture collimators (Thorlabs F280FC-1550), but the ability to perform measurements with them varied with collimator and distance. Only 12.5% of F280FC-1550 collimators tested could consistently measure all distances up to 4.5 m. The explanation for this is the fact that light retroreflected from high index spheres is slightly deflected [6]; larger collimators are more likely to capture slightly diverging rays.

Figure 8: On the right is a 12.7 mm diameter TAFD55 glass retroreflector mounted on the same type of support as a Leica open air corner cube and a white ceramic micro-triangulation target of the same size.

High index glass spheres have a retroreflector offset because the measurement beam propagates through the glass of the sphere. We compared distances measured to these spheres versus those to a traditional corner cube. We found that the offset of the glass spheres remains constant with distance and lateral misalignment. This offset can be solved for by adding it as a constant in the least squares adjustment of a multilateration network.

MULTILATERATION NETWORK SIMULATION

We have designed a multilateration network to demonstrate the feasibility of multilateration for fiducialisation of MBQs. This network is based on a CLIC Type-1 MBQ mounted on a Leitz Infinity CMM as part of the PACMAN final prototype alignment bench shown in Fig. 9 [5].

The magnetic axis of the MBQ is characterised by magnetic measurements and is materialised by a 0.1 mm diameter copper-beryllium stretched wire [5]. Each end of the wire is mounted on two ceramic spheres, the position of which has been determined with respect to external fiducials. This linking measurement was performed at CERN using a Zeiss O-Inspect optical CMM with a repeatability of 2 μm. Our goal is to determine the position of these fiducials with respect to those on the magnet within the same coordinate system using FSI multilateration.

For this simulation, we used 12 measurement stations; 6 on either side of the MBQ. The network consists of 19 fiducials in total; 5 of which are for positioning the wire. 4 fiducials are mounted on top of the granite supports of the wire tensioning system to link the stations on either side of the network. The remaining 10 fiducials are on the magnet; 4 on either side and 2 on top of the magnet.

A total of 170 observations were used to solve for 93 unknowns (x, y, z coordinates) in a totally free (unconstrained) network. One additional unknown was added to the network to solve for the retroreflector offset of the TAFD55 spheres. The observations consist of 150 station to fiducial observations and 20 interstation observations which were added to strengthen the network.

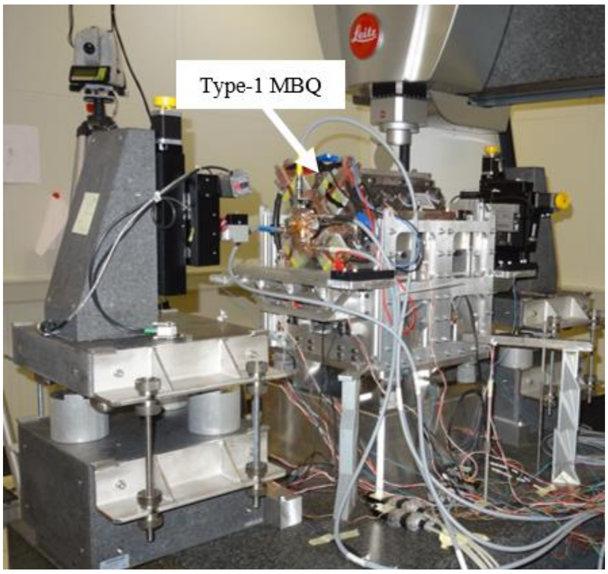

Figure 9: The PACMAN final prototype alignment bench mounted on a Leitz Infinity CMM.

For a full appreciation of the scale of the network, we have plotted measurement stations, fiducials and observations in Fig. 10.

We used LGC++, CERN’s least squares compensation program to solve the network. A modest instrument *a priori* standard deviation of 10 μm was used.

The error budget specified for the MBQ corresponds to the uncertainty perpendicular to the accelerator beam line. As a consequence, we only present the relevant standard deviations in the lateral (Y) and vertical (Z) axes of Fig. 10.

Fig. 11 shows the results of this simulation. We were able to determine the coordinates of all fiducials with a one sigma standard deviation of 5 μm to 10 μm. The retroreflector offset was determined with an uncertainty of 6 μm. These results indicate that we can perform fiducialisation by multilateration to within the uncertainty of the measurement system.

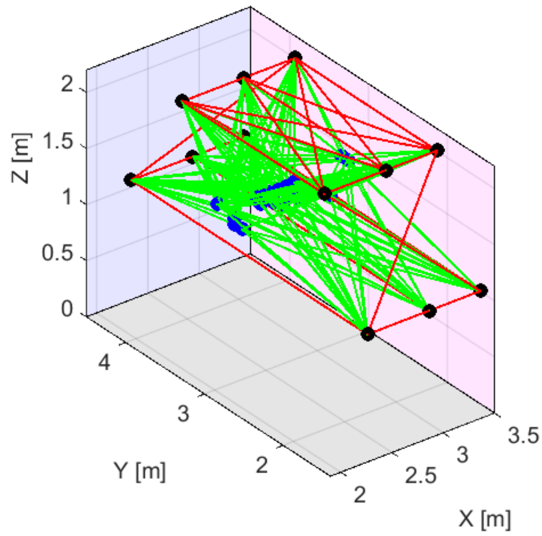

Figure 10: Multilateration network for fiducialisation of the CLIC Type-1 MBQ on the PACMAN bench. The blue circles represent fiducials; the black ones show station positions. The red lines are interstation observations and the green lines are station to fiducial observations.

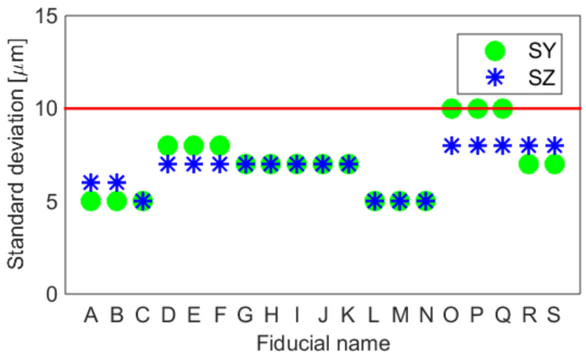

Figure 11: The one sigma standard deviation of coordinates of all fiducials in the network are between 5 and 10 µm.

NEXT STEPS

Our next step is to build a test bench to realise high accuracy coordinate metrology using FSI, high index glass targets and the prototype reference sphere introduced in this paper.

We shall validate our concept by comparing the coordinates determined using this method with more well established instruments such as the Leitz Infinity CMM and QDaedalus micro-triangulation.

We shall explore the possibility of motorizing our solution to improve pointing accuracy and thus reduce the uncertainty due to the sine error inherent in our design. Motorization would also significantly speed up the measurement process.

Commercially available solutions for mounting non-magnetic targets such as corner cubes in ceramic housing lead to a reduced acceptance angle of our high index targets. We are investigating non-destructive means of mounting the TAFD55 spheres in variety of orientations such as on a wall or ceiling without reducing the acceptance angle.

Finally, we intend to apply our developments to the PACMAN final prototype alignment bench for the fiducialisation of CLIC's Type-1 MBQ.

CONCLUSION

We have developed a prototype for localizing the Absolute Multiline fibre tip to allow absolute distance measurements between defined points of interest. This allows us to exploit this technology for multilateration and potentially as a scale for micro-triangulation. First tests show that distances measured with the prototype differ by less than a respectable 3 µm with careful pointing of the laser to the retroreflector.

We have also developed retroreflectors with an almost unlimited acceptance angle based on TAFD55 high index glass. We have shown that the Absolute Multiline can measure to these targets over distances of up to 4.5 m. This will be vital in the realisation of precise FSI multilateration networks.

We have demonstrated through simulations that fiducialisation can be conducted solely by multilateration to within the uncertainty of the measurement setup. Therefore, with a setup which yields a distance uncertainty of 10 µm or less, we can fiducialise CLIC MBQs within the required specifications.

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REFERENCES

[1] M. Aicheler et al., "A Multi-TeV Linear Collider Based on CLIC Technology: CLIC Conceptual Design Report", CERN, Geneva, Switzerland.

[2] S.W. Kamugasa and V. Vlachakis, "PACMAN study of FSI and micro-triangulation," IWAA'14, Beijing, China, October 2014, https://cds.cern.ch

[3] Etalon AG website: http://www.etalon-ag.com

[4] Thorlabs website: https://www.thorlabs.com

[5] H. Mainaud Durand et al., "PACMAN project: A new solution for the high accuracy alignment of accelerator components, 7th International Particle Accelerator Conference, Busan, Korea, 8-13 May 2016.

[6] B. Yang and H. Friedsam, "Ray-tracing studies for a whole-viewing-angle retroreflector." Argonne National Lab. Argonne, Illinois, USA, 1999.