PRE-ALIGNMENT TECHNIQUES DEVELOPMENTS AND MEASUREMENT RESULTS OF THE ELECTROMAGNETIC CENTER OF WARM HIGH-GRADIENT ACCELERATING STRUCTURES

N. Galindo Munoz[*], N. Catalan Lasheras, CERN, Geneva, Switzerland
A. Faus Golfe, LAL, Univ. Paris-Sud, CNRS/IN2P3, Université Paris-Saclay, Orsay, France
V. Boria, Polytechnical University of Valencia, Valencia, Spain

Abstract

In the framework of the PACMAN[†] project [1, 2] we have developed a test set-up to measure the electromagnetic centre of high gradient accelerating structures for alignment purposes. We have demonstrated with previous simulation studies that a resolution of 1 µm is possible [3]. The improvements applied on the technique and on the set-up, calibrations and the equipment instrumentation allows the measurement of the electromagnetic centre, with a final precision of 1.09 µm in the horizontal plane and 0.58 µm in the vertical plane. The experimental measurements and the simulation studies as a support to justify the numbers obtained are presented and discussed.

INTRODUCTION

The Compact Linear Collider (CLIC) [4] main linac uses normal-conducting 12 GHz accelerating structures to reach 3 TeV in a 21 km long linac. The required high gradient of 100 MV/m also generates particularly strong wakefields which need to be addressed during the structure design. Even so, the effects of wakefields in the beam is not negligible and in order to preserve beam emittance, RF structures should be aligned in their girders with an accuracy of 10 µm with respect to its electric centre. The current alignment methodology relies on finding the geometric axes in a 3D Coordinate Measuring Machine (CMM) from the outside references and thanks to an excellent fabrication process of the AS disks with tolerances in the micron level. This paper focuses on the measurement of the electromagnetic axes of the CLIC accelerating structure prototypes by means of electromagnetic measurements and in the controlled metrological environment in order to gain accuracy in the alignment.

At the European Council for Nuclear Research (CERN), we have developed an experimental set-up to measure the electromagnetic centre in the middle cell of the TD24 AS [5], Figure 1. The measurement uses a stretched wire and a vector network analyser (VNA) and has been described and demonstrated in previous publications [6]. We connect the four ports of a VNA to the middle disk of the AS in order to excite the first high order dipole mode. A conductor wire is stretched along the AS and is fixed at both extremes, perturbing the original electromagnetic field by changing transmitted power signals between ports. The perturbation preserves the symmetry and gives the electromagnetic centre when it is minimised.

The AS is moved in two degrees of freedom in the X and Y planes using two linear stages mounted orthogonally. We have observed a linear relationship between the signals measured by the VNA with respect to the position. A LabVIEW post processing is done in order to obtain the position of the stages where the perturbation measured by the VNA is minimized.

The first test performed at constant temperature using the Wakefield Monitor (WFM) [7] signals showed different sensitivities in each plane. After the first iterations of the algorithm, the electromagnetic centre as measured by each port converges into a unique value. However, we find a different value for the centre when using different ports. The difference is in the order of 10-18 µm in both planes.

We have worked on the analysis and simulations to understand the origin of this difference. In this paper we describe the hardware and the methodology updates and present the final results.

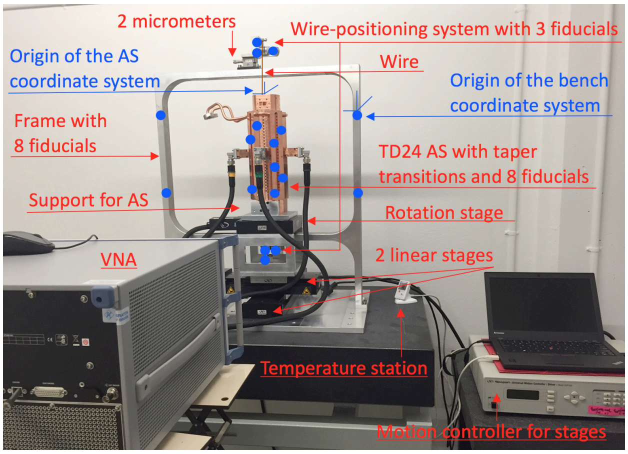

Figure 1: Experimental set-up to measure the electromagnetic centre of the TD24 AS.

UPDATES ON THE TEST SET-UP AND THE MEASUREMENT ALGORITHM

New hardware components of the test bench have been assembled and calibrated in the environment of a CMM with an uncertainty of 0.3 µm. This update involves installing two wire positioning systems with a repeatability of 1.5 µm mounted at both extremes of the frame. Both systems can be equipped with metrological

---

[*] natalia.galindo.munhoz@cern.ch

[†] PACMAN is founded under the European Union's 7th Framework Program Marie Curie Actions, grant PITN-GA-2013-606839

targets. The one at the bottom remains fixed while the one on top seats on two orthogonal micrometres with a resolution of 10 μm to allow positioning the wire in the X and Y planes independently and thus change the wire tilt with respect to the structure. The position of the wire was measured using the targets by the CMM and the tilt between the wire and the baseplate was minimised using the micrometres. The final result localizes the wire in a cylinder with a length of 388 mm and a radius of 11 μm.

At the same time, WFM have been removed and taper transitions with low reflections have been installed in the AS to ensure the symmetry in the middle cell.

The initial methodology was updated by including the virtual port option available in the VNA. This measurement consists on combining two physical ports in one logical port and, since no simultaneous excitation of two ports is done by the VNA, it can be compared with the individual excitation of two physical ports, Figure 2. This measurement has recently been included in the algorithm, resolving $(S_{32}$-$S_{12})+(S_{34}$-$S_{14})$ or $(S_{3A}$-$S_{1A})$ when moving the wire along the X axis, and $(S_{41}$-$S_{21})+(S_{43}$-$S_{23})$ or $(S_{3B}$-$S_{1B})$ when moving the wire along the Y axis.

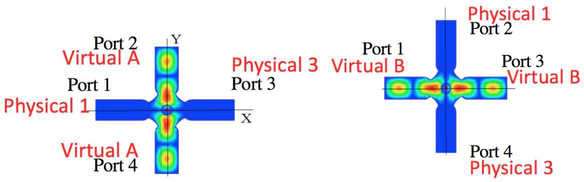

Figure 2: On the left, electromagnetic field excited when measuring the centre and moving the wire in X. On the right, the measurement in Y.

TEST RESULTS AND DISCUSSION

Figure 3 illustrates the two electromagnetic centres, X_1 and X_2, measured by two physical ports in the horizontal plane during seven days of measurements at different conditions. A good correlation is observed between the two centres indicating that the difference is not due to noise. When calculating the measurement precision and, in order to use all data from different runs, we use each independent measurement difference with respect to its average value to calculate the standard deviation. A precision of 1.09 μm is obtained in the horizontal plane and it has a value of 0.58 μm in the vertical plane, both calculated at one sigma as shown in Figure 4.

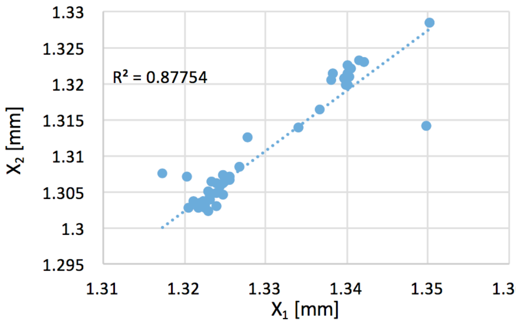

Figure 3: Correlation between the two electromagnetic centres measured by each port in the X plane.

We made several studies and tests in order to understand the different sensitivities found for both planes and the two centres measured at each port, with a difference of around 13 μm, even when exciting the middle cell symmetrically thanks to the taper transitions.

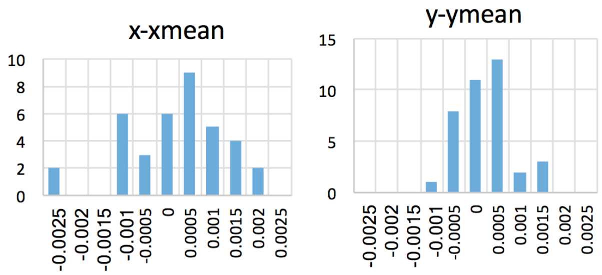

Figure 4: Standard deviation of the electromagnetic centre measurement in the X and Y planes on the left and on the right, respectively.

To address the question on the sensitivity difference, we performed a simulation study using HFSS. A wire scan was done at different offsets from the geometric centre of the AS. The simulation results show that the sensitivity depends on the position in the other axes. However, the same position of the centre is found at each port when the wire is offset in one of the axis.

More simulations were done in order to study the effect of a tilted wire inside the middle cell and in one direction, X in this case, with different angles. Two different centres where obtained at each port, see Figure 5, when the wire moves along the X axis. The simulated tilt configuration doesn't affect to the Y axis.

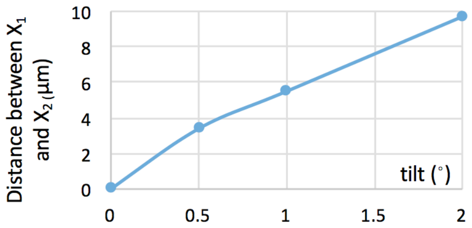

Figure 5: Simulation results of a tilted wire inside the middle cell of the AS with different angles.

As explained in the previous section, the tilt of the wire was calibrated with the CMM. The achieved perpendicularity between the wire and the bench base approach to 0.0025°. Therefore, the estimated tilt cannot solely be explained by the bench error. On the other hand, metrology measurements done with the CMM on the structure also show an inclination of the axis with respect to its base on the order of 0.013° as shown in Figure 6. In the worst case, both angles would add linearly and the expected tilt could rise to 0.0155°. This is far from the value needed to justify a difference of 13 μm between centres which would be according to simulations of around 2.5° as seen in Figure 5.

Errors concerning the accuracy on the positioning of the linear stages are discarded as well as errors on their orthogonality [6].

To understand the difference in precision from both axes, we performed a test with the structure rotated 90°. The results concerning precision in X and Y were the same in both cases and resemble Figure 4. Which means that the eventual random errors do not come from the structure geometry and potential asymmetry but from the acquisition chain including waveguide to SMA adaptors, cables and VNA.

In order to stablish the repeatability of our measurement, we performed 12 measurements in 8 days after zeroing the position of the linear stages. The results can be seen in Figure 7. We proceeded with the installation of a new wire in 4 different days. The influence of temperature can be seen as a fluctuation between the measurements in days 3, 4 and 5. Repeatability is in this case better than 5 µm. Under the same conditions of temperature, tension of the wire and calibration of the VNA, repeatability seems to be better than 0.5 µm. Conditions are lost when we change the wire and, as a consequence, they can't be compared with each other for repeatability studies.

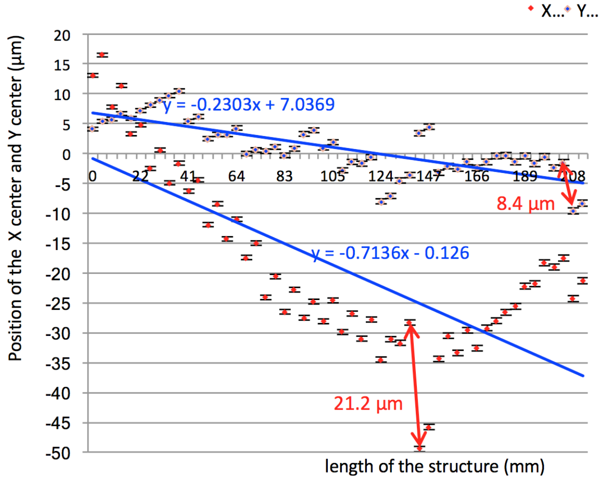

Figure 6: Position of the geometric centre along the length of the AS measured by the CMM on the X and Y axis.

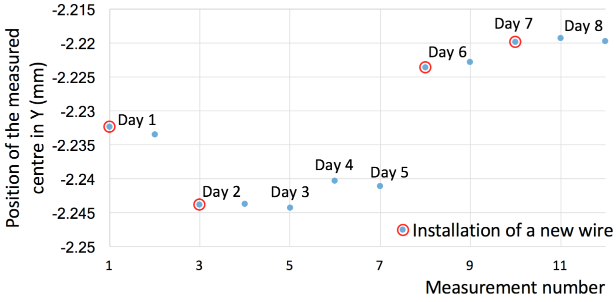

Figure 7: Position of the linear stage in the vertical plane where the electromagnetic centre is measured 11 times under different conditions.

ABSOLUTE MEASUREMENTS ON THE ACCELERATING STRUCTURE

Recent measurements have been done in the context of the CMM to first evaluate a possible existing correlation between the RF measurements and the geometric measurements. Second, we want to answer the question about repeatability and reproducibility of the RF measurements. And third, we want to reference the position of the AS with respect to the absolute position of the wire, or fiducialisation.

In order to perform these measurements, we have distributed 18 fixed spheres or targets around the test bench, as shown in Figure 1, whose positions are measured by the CMM. The absolute position of the wire is determined by 3 fiducials located in each wire positioning system. This reference is supported by a plane formed by 4 spheres placed on the frame of the test-bench. These 10 spheres form a reference system. The AS is moved several times to the position where the electric centre has been measured using the RF method and, at each position, the CMM measures up to 8 fiducials glued on the structure. The 8 targets on the structure forms a second reference system that can be related to the reference system formed by the wire and the frame. The results are currently being analysed.

CONCLUSION

We have developed a method to locate the centre of the electromagnetic field inside the middle cell of the TD24 AS at 17 GHz with a stretched wire, a VNA and two orthogonal linear stages that move the AS in the horizontal and in the vertical planes. Two measurements are done from two different ports with similar results. The measurements converge rapidly and have a precision of 1.09 µm in the horizontal plane and 0.58 µm in the vertical plane.

We have also investigated the sources of errors. Tilted structure is detected after CMM calibration that can be minimised supported with the RF measurements using two micrometres installed in the test bench. Using the same method, we combine the two measurements similarly to virtual ports with similar results. Constant temperature is mandatory in order to avoid another source of error.

Finally, absolute measurements have been done in the CMM for fiducialisation purposes and the results concerning repeatability and reproducibility are being analysed.

ACKNOWLEDGEMENTS

It is fair thanking all the colleagues at CERN involved in the development, implementation and construction of the test set-up, the metrology measurements and the PACMAN supervision support. We present our gratitude and respect for the collaboration with IFIC-LAL and the PhD supervision together with the Polytechnic University of Valencia, Spain. And finally, we honour the European Union's 7th Framework Program Marie Curie Actions for founding the PACMAN project.

REFERENCES

[1] PACMAN website: http://pacman.web.cern.ch

[2] H. Minaud Durand, K. Artoos, M. Buzio, D. Caiazza, N. Catalan Lasheras, A. Cherif, I. Doytchinov, A. Faus-Golfe, J-F Fuchs, A. Gaddi, N. Galindo Munoz, J-C Gayde, S. W. Kamugasa, M. Modena, P. Novotny, S. Russenschuck, C. Sanz, G. Severino, D. Tshilumba, V. Vlachakis and S. Zorzetti, 'Main achievements of the PACMAN project for the alignment at micrometric scale of accelerator components", IPAC'17, Copenhagen, Denmark, May 2017, paper TUPIK077, this conference.

[3] N. Galindo Munoz, N. Catalan Lasheras, A. Faus Golfe, V. Boria, M. Wendt and S. Zorzetti, "Electromagnetic field pre-alignment of the compact linear collider (CLIC) accelerating structure with help of wakefield monitor signals", *IBIC'15*, Melbourne, Australia, September 2015, paper TUPB054, pp. 446-450.

[4] CLIC CDR, "A multi-TeV linear collider based on CLIC technology: CLIC Conceptual Design Report", edited by M. Aicheler, P. Burrows, M. Draper, T. Garvey, P. Lebrun, K. Peach, N. Phinney, H. Schmickler, D. Shulte and N. Toge, CERN-2012-007

[5] A. Grudiev and W. Wuensch, "Design of an X-band accelerating structure for the CLIC main linac", *LINAC'08*, Victoria, Canada, September 2008, paper THP062, pp.933-935.

[6] N. Galindo Munoz, N. Catalan Lasheras, A. Faus-Golfe, V. Boria and A. Grudiev, "Pre-alignment of accelerating structures for compact acceleration and high gradient using in-situ radiofrequency methods", *IPAC'16*, Busan, Korea, paper WEPOR016, pp. 2696-2699.

[7] F. Peauger W. Farabolini, P. Girardot, A. Andersson, G. Riddone, A. Samoshkin, A. Solodko, R. Zennaro and R. Ruber, "Wakefield monitor development for CLIC accelerating structure", *LINAC'10*, Tsukuba, Japan, paper TUPB098, pp. 641-643.