

STATUS OF THE PACMAN PROJECT

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Abstract

PACMAN*, a study on Particle Accelerator Components' Metrology and Alignment to the Nanometre scale, is an Innovative Doctoral Programme, funded by the European Commission, hosted by CERN, providing a high quality training to 10 Early Stage Researchers (ESR) working towards a PhD. It is a multi-disciplinary project covering diverse fields such as beam instrumentation, magnetic measurements, metrology, high accuracy alignment and high precision mechanics. The objective of the PACMAN project is to propose new methods allowing the determination of the reference axis of accelerator components w.r.t. external alignment targets (fiducialisation process). A test bench, using components of the Compact Linear Collider (CLIC) study, will demonstrate the feasibility of the solutions developed and that a micrometric accuracy of their fiducialisation process can be reached. The results of this study, which has started in September 2013, are detailed. They concern the methods developed using a stretched wire to determine: the magnetic axis of small aperture magnets, the electrical centre of a 15 GHz Radio Frequency-Beam Position Monitor (RF-BPM) and the electro-magnetic axis of an accelerating cavity. They integrate also the solutions carried out to measure the position of the wire w.r.t. the external alignment targets. Other systems developed in the frame of the project are also taken into account: a nano-positioning system to validate the nanometric resolution of the BPM and a dedicated seismic sensor to characterize the environment during the measurements.

INTRODUCTION

The preservation of the emittance is a key issue for the next generation of linear colliders, and more particularly for CLIC [1], that will have nanometric beams size at the collision point. To reach such objectives, a strategy of alignment was proposed in the Conceptual Design Report of the CLIC study edited 3 years ago, consisting among others of a high accuracy and active pre-alignment of the components [2]. The aim of the PACMAN project [3] is to improve the pre-alignment accuracy of the major components of the CLIC main linac: 15 GHz RF-BPM, Accelerating Structures (AS) and quadrupole magnets along the main beam. This will be achieved by developing new methods and tools addressing several steps of pre-alignment simultaneously, using a stretched wire acting as

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a reference to fiducialise the components in the accurate environment of a 3D Coordinate Measuring Machine (CMM) [4].

The tools and methods developed will be then validated on a final bench to demonstrate their feasibility, before being extrapolated on other projects.

This paper reviews first the requirements concerning the pre-alignment of the CLIC study and the improvements in term of accuracy targeted by the PACMAN project. It then presents the objectives and first results obtained, concerning the determination of the reference axis of components using a stretched wire, the means to determine the position of this wire acting as a reference of alignment, and the alternative studies undertaken to achieve such a goal.

CLIC PRE-ALIGNMENT REQUIREMENTS AND PACMAN

The requirements concerning the pre-alignment of the three types of main component: BPM, AS and quadrupoles, are beyond the actual state-of-the-art. For a sliding window of 200 m, the standard deviations of the transverse position of the reference axis of each component (magnetic axis for a quadrupole, electric axis for a BPM and electro-magnetic axis for an AS) w.r.t. a straight line fit must be less than 14 μm for AS and BPM and less than 17 μm for quadrupoles [2].

Taking into account the number of components to be pre-aligned (more than 4000 BPM and quadrupoles, more than 60000 AS) and the very tight tolerances required, an active pre-alignment will be implemented. The position of the components, more precisely the position of their supports, will be determined continuously by alignment sensors, and re-adjusted by actuators. To ease the process, several components will be assembled on the same support: 4 AS per girder support, 1 BPM coupled with 1 quadrupole. This assembly step will occur after the determination of the reference axis of the components w.r.t. external alignment targets (fiducialisation). Then, the position of the pre-alignment sensors interface will be determined in the referential frame of the assembly support. Once the assembly support is installed in the tunnel, the pre-alignment sensors are plugged on their interface; measurements w.r.t. a straight reference line are carried out. Combining all the above-cited measurements, the position of the reference axis of each component can finally be deduced in the global coordinate system of the tunnel

The PACMAN project aims at combining at the same time the fiducialisation and the assembly steps, in the

environment of one of the most accurate 3D CMM of the world, in use at CERN: the Leitz Infinity CMM, with a Maximum Permissible Error (MPE) of $0.3 \mu\text{m} + 1 \mu\text{m}/\text{m}$. The 10 researchers (ESR) working towards a PhD will collaborate to propose and validate different methods and tools related to metrology.

The first objective of the project was to choose a common wire compatible with all the different types of measurements to be performed. A Copper Beryllium wire with a diameter of 0.1 mm has been retained and its characterization has been performed successfully by ESR1.1 concerning the following parameters: electrical resistivity, micro hardness, linear mass, diameter, variation of the roughness fulfil the initial requirements, with only one criteria which is not fulfilled: the form error [5]. The form error will be determined in-situ during the process of measurement of the wire.

The methods developed to determine the reference axis of components using this wire as well as the first results obtained are detailed in the next chapter.

DETERMINATION OF A REFERENCE AXIS USING A STRETCHED WIRE

Determination of the Magnetic Axis of a Small Aperture Quadrupole Using a Stretched Wire (ESR 2.1)

Two methods can be considered to determine the magnetic axis of a quadrupole using a stretched wire:

- The single stretched wire method. Based on magnetic flux variation, it consists of displacing the wire by moving its extremities and measuring the voltage induced across the wire loop,
- The vibrating-wire method. The wire is fed by an alternating current and placed in magnetic fields. The measurement of its vibration amplitudes and phases will lead to the determination of the magnetic axis, knowing that this one is located at the minimum amplitude [6].

A comparative study has been carried out between both methods, demonstrating their compatibility and a higher accuracy for the vibrating-wire method. Also a repeatability 30 times better (3-4 μm) was observed, combined with a good sensitivity at low integrated strength. One of the major issues of the vibrating wire method is that background magnetic fields such as the Earth's magnetic field must be compensated. A correction procedure has been developed, suitable for strength adjustable magnets and for non-homogeneous field distribution [7].

An uncertainty analysis of the vibrating wire method is under way in order to identify the parameters with the biggest contribution and to optimize the performance from the repeatability and sensitivity point of view.

Determination of the Electrical Centre of a BPM Using a Stretched Wire (ESR 4.1)

Two methods have been studied to determine the electrical axis of a BPM using a stretched wire, first by simulations, then on a dedicated bench:

- The signal excitation method. A 15 GHz signal is fed on a conductive stretched wire, creating an excitation in a similar way to the beam. A scan of the cavity is carried out to find the electrical centre by small transverse displacements of the wire inside the BPM.
- The perturbation analysis method. The stretched wire is used in that case as a perturbation target. The cavity BPM is excited via one of the lateral waveguides and the output signal is analysed on one of the other later waveguides (opposite or adjacent). The minimum perturbations are observed when the wire is located at the centre of the cavity.

Simulations showed a higher sensitivity around the electrical centre for the signal excitation method but an easier integration for the perturbation analysis method: no RF impedance matching is needed, which means no coaxial line consisting of the wire and its beam pipe. A beam pipe would hide the wire and prevent the measurement of its location using a 3D CMM [8].

A dedicated bench has been put in place, for which the 5 Degrees of Freedom (DOF) displacements performed by a hexapod are taken as reference. The hexapod has been validated using Leitz Infinity CMM, confirming a bi-direction repeatability below 4 μm , as claimed by the manufacturer, for a load capacity of 5 kg. The measurements performed with the bench fit with the simulated ones and show a repeatability of the order of 1 μm in the determination of the centre using the perturbation analysis method [9].

Determination of the Electromagnetic Axis of AS (ESR 4.2)

Similarly to the BPM case, the perturbation analysis method has been chosen: the wire is displaced while the transmission of power is measured between ports. Extensive simulations using the HFSS software and measurements on a vertical test bench using a vector network analyser showed that a resolution of 1 μm could be reached with an error of 0.01 dB in the determination of the electromagnetic axis [10]. It still needs to be proven that this accuracy is maintained when connecting the actual wake field monitor and acquisition electronics to the accelerating structure instead of the optimised tapers designed for fiducialisation purposes.

This method can be extended to the measurement of the position of the wire from all the cells inserting special feed-throughs and thus verify the cell-to-cell misalignment

achieved during manufacturing of the structure (tolerance of $\pm 5 \mu\text{m}$).

Once the wire is located at the reference axis of each component, its position will have to be measured w.r.t. the alignment targets and pre-alignment sensors interfaces. Three methods are considered in the next chapter for such an objective.

DETERMINATION OF THE POSITION OF THE STRETCHED WIRE USED AS REFERENCE

With the Leitz Infinity CMM (ESR 1.1)

Two challenges must be overcome to use the Leitz Infinity CMM to measure the position of the stretched wire w.r.t. the alignment sensor interfaces. First, such a CMM is not able currently to perform non-contact measurements of the wire. “Off the shelf” sensors able to perform such a performance have been identified and will be tested on a dedicated bench, before being integrated on the CMM measurement head and calibrated. Second, the measurement head will have to be compatible with magnetic fields. First tests performed at Hexagon Metrology have shown that the impact of magnetic fields was not negligible at the level of the measurement head [11] when contact measurements were performed. However, when the measurement head is blocked, e.g. in case of non-contact measurements to the wire, the impact of magnetic fields was proven negligible.

With an Alternative Based on FSI Measurements and Micro-Triangulation (ESR 1.2, ESR 1.3)

The use of a combination of high accuracy angular measurements provided by the micro-triangulation system and absolute distances provided by a Frequency Scanning Interferometry (FSI) system represents an alternative to CMM measurements to measure the position of a stretched wire, with the advantage of being portable solutions, able to be used in the accelerator tunnel, during the installation of the equipment [12].

The Absolute Multiline system, manufactured by Etalon AG, is the only commercialised FSI system in the world. The first objective is to establish the 3D position of the FSI optical fibre tip from the exterior. A prototype of station consisting of an aluminium sphere with a diameter of 38.1 mm has been manufactured, in which the FSI collimator is centred. A modus operandi close to the Electronic Distance Measurement calibrations has been put in place in order to determine the centring offset of the collimator, within a few micrometres. Second objective is to adapt such a system for multilateration measurements, e.g. to measure distances to several points from a single point. Concerning the alignment targets, several types of spheres are under study, particularly glass spheres with a refraction index close to 2, able to be measured from different stations. The theoretical trajectory of the beam inside the glass sphere is under study with the help of the University of Liberec, the key point being the intensity of

the return signal that must be strong enough to be analysed. To measure several targets from one station, one option under study is to install the station on displacement stages; the design and calibration of such solution is under study.

Concerning micro-triangulation, an inventory of all the hardware and software upgrades to be performed on the QDaedalus system has been carried out. The challenge concerns the detection of the wire, using image processing techniques, and the reconstruction of its catenary shape, using angles from several theodolites to arbitrary, non-identical and non-materialized points of the wire. The first tests performed at ETH Zürich show that it is possible to detect the common Copper Beryllium wire from a distance of 2 m, to extract the edges with 0.1 pixels precision, and to estimate the local axis within a few micrometres. The method and associated algorithms to reconstruct the wire over its all length remain to be implemented.

Once the position of the wire is determined, additional studies are foreseen to determine the resolution of the BPM developed, using a nano-positioning system foreseen for CLIC to displace the BPM w.r.t. the wire, and seismic sensors to characterize the environment of measurements. These two additional studies are detailed in the next chapter, as well as the development of an alternative method to determine the magnetic axis of small aperture magnets.

ADDITIONAL STUDIES

Characterization of the Environment (ESR3.2)

One of the goals of the PACMAN project is to demonstrate the nanometric resolution of the 15 GHz RF-BPM, in the final PACMAN test setup. Such tight measurements will imply a very good knowledge and characterization of the vibration sources of the environment of measurement. This will be performed by a seismic sensor installed on the quadrupole, fulfilling the following requirements: a bandwidth comprised between 0.1 Hz and 200 Hz, a resolution below 0.1 nm at 1 Hz, a dynamic range above 80 dB, a compact size to be hosted on top of the quadrupole, not sensitive to stray magnetic fields. An inventory of “off the shelf” sensors was carried out. The behaviour of accelerometers, force balanced optical accelerometers, seismometers, geophones, has been simulated with Matlab and Simulink software; the seismic sensors have been compared according to different parameters: sensitivity, bandwidth and noise level. Dedicated procedures of acquisition and control have been put in place to start the sensors characterization.

A Long Range Nano-positioning System (ESR3.3)

A full mechanical system has been designed, manufactured and assembled for vibration isolation and nanometric positioning purposes for the quadrupole [13] but presented low eigen modes, below 50 Hz while the objective is to have frequency modes above 100 Hz. The low modes have been identified by a Finite Element Analysis showing that gluing rather than bolting the components of the assembly leads to a maximum reduction

of eigen frequencies of 8.5% (compared to 40% for the bolting). A re-design of the bedplates of the system is under way, and the current nano-positioning will be upgraded to be used for the final PACMAN bench.

In parallel, the study and development of long range actuators are under way, cumulating two functions: nanometric displacements over a long stroke, in order to allow nanometric positioning (nanometric displacements over a few micrometres) and pre-alignment adjustment (micrometric displacements over a few millimetres) of the quadrupole. Different options are under study to realize high stiffness load/long range actuators: the use of linear piezo-motors or a hybrid actuator, e.g. a combination of stepper motors with piezo stacks.

An Alternative to Determine the Magnetic Axis of Small Aperture Magnets (ESR 2.2)

An alternative to the stretched wire method based on Printed Circuit Board (PCB) rotating coil is proposed to determine the magnetic axis of small aperture quadrupoles and measure some key parameters as magnet field harmonics, main field direction and integral field gradient [13-14]. The development of small rotating coils raises several issues: the dimensions must be reduced without losing sensitivity, a compromise must be found concerning the design of the shaft between its stiffness and its radius, new technology and materials are needed for small shafts and PCB coil process needs to be improved. A new design of PCB and shaft is under way, taking into account all these parameters. A bench to perform such measurements is also under study. It will integrate better bearings around the shaft to achieve smaller vibration amplitudes and torsion. The location of encoders and motors will be optimized as well as the bearing assembly setup. Two calibration procedures have been studied: the classical calibration and the in-situ calibration [15].

Measurement Using Budget for Future Particle Accelerators Alignment Bench (ESR3.1)

A measurement uncertainty of the final PACMAN bench of 7 μm is targeted. The identification of the sources of errors is nearly completed. This will allow the determination of a complete budget of errors for the final bench.

CONCLUSION

The 10 PACMAN PhD students started working on their subject more than one year ago. After a familiarization phase, consisting of intensive training, discussions with experts and reading to prepare their literature review, as well as simulations and tests to determine the best methods and tools, the students have started validating their solutions on dedicated benches. A common 0.1 mm diameter Copper Beryllium wire, considered as reference of alignment, has been chosen for the whole project and characterized successfully. The first results presented in that paper are more than promising, confirming that a new way of pre-aligning components such as BPM, AS and

quadrupoles, more accurate and less time-consuming than the current methods in use, will soon be demonstrated.

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