PACMAN PROJECT: A NEW SOLUTION FOR THE HIGH-ACCURACY ALIGNMENT OF ACCELERATOR COMPONENTS

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Abstract

The beam alignment requirements for the next generation of lepton colliders have become increasingly challenging. As an example, the alignment requirements for the three major collider components of the CLIC linear collider are as follows. Before the first beam circulates, the Beam Position Monitors (BPM), Accelerating Structures (AS) and quadrupoles will have to be aligned up to 10 µm w.r.t. a straight line over 200-m-long segments, along the 20 km of linacs. PACMAN is a study on Particle Accelerator Components' Metrology and Alignment to the Nanometre scale. It is an Innovative Doctoral Program, funded by the EU and hosted by CERN, providing high quality training to 10 Early Stage Researchers working towards a PhD thesis. The technical aim of the project is to improve the alignment accuracy of the CLIC components by developing new methods and tools addressing several steps of alignment simultaneously, to gain time and accuracy. The tools and methods developed will be validated on a test bench. This paper presents the technical systems to be integrated in the test bench, the results of the compatibility tests performed between these systems, as well as the final design of the PACMAN validation bench.

INTRODUCTION

Fiducialisation is one of the key steps in the alignment of particle accelerators [1]. It consists of determining the position of the reference axis of the following components w.r.t. external targets (fiducials): the magnetic axis of the quadrupole magnets, electrical zero of the BPMs, and the RF axis of the accelerator structures. The fiducials will be used later to align the components at their theoretical position in the tunnel general coordinate system when their reference axes are not accessible anymore. For the CLIC project the pre-alignment requirements of the components are very tight: up to 10 µm along 200-m-long sliding windows [2]. The fiducialisation should be carried out within an accuracy of ± 5 µm at 1σ. The aim of the PACMAN project is to develop methods and tools allowing the fiducialisation of several accelerator components of different types, in the environment of a 3D Coordinate Measuring Machine (CMM), in order to gain efficiency and accuracy in view of the huge number of components needed in the CLIC accelerator [3][4]. The feasibility and performance of the means developed will be tested and validated on the Final PACMAN Alignment Bench (FPAB), using an assembly which consists of two critical CLIC main beam components: a 15 GHz BPM and a quadrupole. The technical systems composing this FPAB as well as the status of preparation of the bench itself are the subject of this paper.

THE FINAL PACMAN ALIGNMENT BENCH (FPAB)

Description of the FPAB

An assembly of two components is part of the FPAB:

- A CLIC RF-BPM, operating at 15 GHz [5]
- A CLIC Main Beam quadrupole, with an overall length of 441 mm, a nominal field gradient of 200 T/m and a bore radius of 5 mm.

The two components are supported on an upgraded nano-positioning system.

The whole assembly will be located on the Leitz Infinity CMM platform, in the air-conditioned room of the CERN metrology laboratory. A seismic sensor, installed on top of the quadrupole will characterize the environment of measurements, as shown in Figure 1 below.

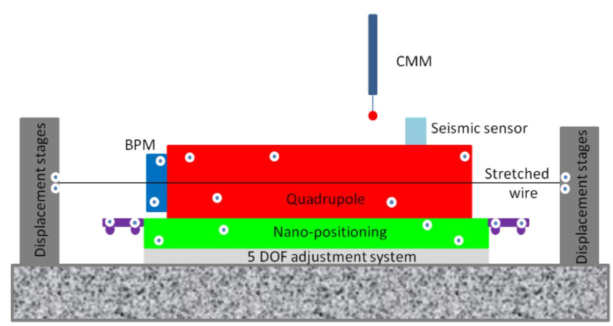

Figure 1: Technical systems of the FPAB.

Objective of the FPAB

The objective of the FPAB is to validate the concepts and tools developed to determine the magnetic and electrical axes by means of a stretched wire. Once the wire has been used to locate the reference axis, three different methods will be validated to determine the position of the reference axis w.r.t. the fiducials:

- Non-contact CMM [6]
- Micro-triangulation [7]
- Frequency Scanning Interferometry (FSI) [7].

A common wire to localize the magnetic axis and electrical zero, and measurable by micro-triangulation and CMM has been chosen. The wire and all the FPAB technical systems are described in the next chapter.

FPAB TECHNICAL SUBSYSTEMS

Common Wire

A study on different available materials and some trials led to the conclusion that the reference wire will be made of Copper/Beryllium (98%/2%), with a diameter of 100 µm. Additional tests and measurements performed on wires from different providers aimed to validate the wire fulfils all requirements of the PACMAN project [8].

Wire System to Localize the Magnetic Axis

The CuBe wire stretched through the bore of the quadrupole magnet is excited by an alternating current and therefore starts oscillating in the magnetic field. The amplitude of vibrations is minimum when the wire is located at the magnetic axis [9]. The wire is supported externally of the magnet by two precision alignment stages mounted on granite supports. The wire is pre-tensioned by a stepper motor. The wire lies in between two ceramic spheres of 1 mm in diameter. Two 1.5" supports for fiducials are associated with these ceramic spheres; their position w.r.t these spheres (and consequently the wire) has been measured with a micrometric accuracy. The fiducials are used to reconstruct the position of the wire using laser tracker or FSI measurements. The repeatability in repositioning the wire in such a support was assessed to be ±1.5 µm [10]. At both ends of the wire, a pair of linear displacement stages from PI-miCos are mounted orthogonally to position the wire with a repeatability less than 0.1 µm and an absolute accuracy less than 1 µm, within a travel range of 50 mm. The wire oscillation amplitude is measured by a pair of optical (CCD) micrometres from Keyence, orthogonally mounted on one of the wire stage. These micrometres have a range of 6 mm, a repeatability of ± 0.3 µm, and an accuracy of ± 0.5 µm. They generate a voltage proportional to the wire displacement, which is acquired by a 18-bit acquisition card from National Instruments.

Wire system to Localize the Electrical Zero of the BPM

Two measurement methods have been investigated on a dedicated setup to locate the electrical zero:

- RF signal excitation [11] of the wire and analysis of RF signal transfer through the slot-coupled waveguides of the cavity [12],
- Using the stretched wire as a passive target, while detecting/minimizing the asymmetry using amplitude and phase measurement of the S-parameters between the four BPM ports.

For integration purposes, the latter method has been retained to provide the metrology equipment a free access to the wire. The same setup of wire and displacement stages as for the localization of the magnetic axis will be used.

Upgraded Nano-positioning System

The mechanical design of a 4 degrees of freedom (dof) nano-positioning system for the CLIC quadrupoles has been completed and a first prototype has been manufactured. Furthermore, an active vibration isolation strategy to achieve the stability requirement of 1.5 nm r.m.s at 1 Hz has been proposed and implemented [13].

Parasitic structural eigen modes have been measured on the prototype [14]. A review of the mechanical design and several dynamic simulations on an optimized finite element model of the prototype showed that the base plate is the root cause of the parasitic dynamics [15, 16]. To address this issue, an upgraded base plate was designed and will be manufactured and assembled. In addition, the supporting frame has been lowered to allow visible access to the magnet fiducials by the micro-triangulation and the FSI systems. Finally, the linear encoders, measuring the lateral displacement of the magnet, have been moved to a better location.

Seismic Sensor

The seismic sensor must fulfil the following requirements for the FPAB: a 0.1-200 Hz bandwidth, a resolution better than 0.1 nm r.m.s at 1 Hz and no influence by external magnetic fields. Three types of sub-nanometric displacement transducers are going to be cross-checked: interferometers, optical encoders and capacitive sensors. The transducers will be integrated within one mechanical body, using the same data acquisition and processing. The transducer with the highest resolution will be implemented into a mechanical design developed by LAPP [17] and will be used on the FPAB.

Measurement of the Wire Location using a Sensor Plugged in the CMM Measuring Head

The form error of the wire is a source of uncertainty in the positioning of the wire axis, as it is done using the measurement of a circle on the wire surface. To tackle this issue, a Shape Evaluating Sensor of High Accuracy, Touchless (SESHAT) is being designed. The aim of this sensor is to measure the wire shape with an uncertainty of 100 nm in order to determine if the position of the measurement fits the required accuracy. The SESHAT must fit the requirements of the PACMAN bench [18], e.g., to be as light as possible, to have a low energy emission, to be stiff enough and torsionally rigid, and be able to perform non-contact measurements. The concept proposed consists of a piezo motor, high-precision air bearings, a chromatic confocal sensor, and a high accuracy encoder. It is made of different materials, including carbon sandwich panels.

Micro-triangulation to Locate the Wire

Four Leica TDA 5005 theodolites equipped with QDaedalus systems are used for micro-triangulation measurements. The final configuration of these systems is under study, taking into consideration the lines of sight

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between the theodolites and the targets, as well as the influence of the geometry on the uncertainties. To conduct this study, a simulation software developed for that purpose is used integrating the CAD model of the FPAB [19].

To measure directly the distance between the stretched wire and the fiducials, two algorithms have been developed for the wire detection and the wire reconstruction [20, 21].

FSI to Locate the Wire w.r.t. Fiducials

A multilateration network will be built around the FPAB to determine the distance between the wire and the fiducials. In order to perform measurements in different directions from the same point, the optical fibre end of the Absolute Multiline system has been integrated into a high quality, 38.1-mm-diameter ceramic sphere [22]. Once calibrated, this system will allow 3D coordinate determination of the different fibre tips and targets within the measurement network. A customised support for the ceramic sphere has been designed [22]. It will equip eight stable pillars, located on each side of the measurement volume.

As the uncertainty of coordinates determined by multilateration largely depends on the arrangement of the measurement station w.r.t the targets, a target with an almost unobstructed viewing angle has been developed. It consists of a high-index glass sphere with a sphericity of 63 nm attached to a steel disc [23].

Initial simulation results based on 8 stations and 17 targets with some interstation observations indicate that coordinates can be determined to within the precision of the instruments [26]. The Absolute Multiline has a measurement uncertainty of 0.5 µm per metre. The uncertainty of the final setup including calibrations will need to be taken into account in order to give a more complete picture of the expected final results.

PREPARATION OF THE FPAB

Preliminary Tests of Preparation

The magnetic axis localization system has been tested in the magnetic measurement laboratory at CERN in order to locate the magnetic axis at two current values of the quadrupole: 4 A and 126 A (nominal current). The 4A current value has been chosen for the FPAB as no cooling system is required, thus eliminating the vibrations from the water cooling. During the test, the wire length was 1300 mm and the wire tension 842 g. The magnet was mechanically positioned at the longitudinal middle point along the wire. The magnetic axis was first located with the magnet current set to 126 A and then to 4 A. The measurements at 4A required a correction due to the effect of the background fields [9]. The measured offset between the locations of the two axes (in the local frame of the wire stages) are given in Table 1. The repeatability of a vibrating wire measurement for a fixed current was assessed to be ±0.1 µm for the magnetic centre's horizontal and vertical coordinates and ±1.0 µrad for the pitch and yaw angles [24].

Table 1: Offset Between the Magnetic Axis at 4 A and 126 A Excitation Current

Horiz. centre	Vert. centre	Yaw	Pitch
2.9 µm	3.1 µm	-2.3 µrad	-5.1 µrad

Compatibility Tests in the CMM Environment

Additional tests have been performed to validate the compatibility of the systems in the environment of the CMM. The following conclusions were drawn:

- The Leitz Infinity CMM is not affected by magnetic fields when a non-contact probe is used for the measurements [6]
- FSI measurements performed in the environment of the Leitz Infinity CMM have shown that there is a drift inferior to 1 µm for distances of up to 1 m over a 16 h period [25]. Distances measurements from outside the CMM towards targets mounted on the CMM varied by up to 1 mm whilst the CMM bridge was in motion. However, once the bridge movement was stopped, the distance measurements stabilised with variations of less than 4 µm over a 2 h period [26]. This suggests that measurements from outside the CMM volume to targets on the CMM should not be undertaken whilst the CMM is moved for measurements. Further tests should be conducted to determine the time required for the CMM to stabilise after its motion.
- The compatibility of the stretched-wire system with the CMM environment was also validated [27]. Both the wire static position and vibrations were monitored under different operating conditions. No significant deviation from the normal operation of the system was found.

CONCLUSION

The PACMAN project is progressing well and promising results have already been obtained, e.g., a repeatability of the determination of the magnetic axis within 1 µm and a determination of the electrical zero within a few micrometres. All components for the bench have been ordered. Once pre-assembled, they will be transferred to the metrology laboratory where the validation will start. The simulations performed on the configuration of FSI and micro-triangulation systems show that the determination of the wire position w.r.t the fiducials could be carried out within 10 µm.

In parallel, promising results are being obtained concerning the fiducialisation of accelerating structures within a micrometric resolution [28]. Combined with a 5 dof adjustment system, these new methods of fiducialisation could allow a micrometric pre-assembly of components of different types on the same support and considerably improve the pre-alignment accuracy of the components for the next generation of colliders.

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