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MAIN ACHIEVEMENTS OF THE PACMAN PROJECT FOR THE ALIGNMENT AT MICROMETRIC SCALE OF ACCELERATOR COMPONENTS

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Abstract

The objectives of the PACMAN project are to improve the precision and accuracy of the alignment of accelerator components. Two steps of alignment are concerned: the fiducialisation, i.e. the determination of the reference axis of components w.r.t. alignment targets, and the initial alignment of components on a common support assembly. The main accelerator components considered for the study are quadrupole magnets, 15 GHz Beam Position Monitors (BPM) and Radio Frequency (RF) structures from the Compact LInear Collider (CLIC) project. Different methods have been developed to determine the reference axis of these components with a micrometric accuracy, as well as to determine the position of this reference axis in the coordinate frame of the common support assembly. The tools and methods developed have been validated with success on dedicated test setups using CLIC components. This paper provides a compilation of the main achievements and results obtained.

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Abstract

The objectives of the PACMAN project are to improve the precision and accuracy of the alignment of accelerator components. Two steps of alignment are concerned: the fiducialisation, i.e. the determination of the reference axis of components w.r.t. alignment targets, and the initial alignment of components on a common support assembly. The main accelerator components considered for the study are quadrupole magnets, 15 GHz Beam Position Monitors (BPM) and Radio Frequency (RF) structures from the Compact LInear Collider (CLIC) project. Different methods have been developed to determine the reference axis of these components with a micrometric accuracy, as well as to determine the position of this reference axis in the coordinate frame of the common support assembly. The tools and methods developed have been validated with success on dedicated test setups using CLIC components. This paper provides a compilation of the main achievements and results obtained.

INTRODUCTION

In order to implement beam based alignment and beam based feedback, CLIC components will have to be actively pre-aligned [1]. Before the main beam can go through the different components of the accelerator, the reference axes of the components will have to fit within a cylinder with a radius of a few micrometers over a sliding alignment window of 200 m. Three main types of components are concerned by such requirements: 15 GHz BPMs, RF structures and quadrupoles. In order to ease their pre-alignment, some components will be aligned on the same support: BPM combined with quadrupole, several RF structures installed on the same support [2]. These supports will be equipped with pre-alignment sensors to determine continuously their position w.r.t. a straight reference of alignment installed in the tunnel. Actuators with 5 degrees of freedom will allow adjusting this position. Considering such assemblies, two major steps will be needed to perform a micrometric pre-alignment: the fiducialisation of the components, i.e. the determination of the position of their reference axis w.r.t. external alignment targets (fiducials), and their initial alignment on the common support. The PACMAN project aims at proposing a solution to carry out both steps at the same time, to gain time and accuracy [3]. New methods and tools were developed to determine the magnetic axis of quadrupoles, the electro-magnetic axis of RF structures and electric zero of BPM, using a metallic wire. New measurement means were developed to localize the position of such a reference wire w.r.t. fiducials, based on a 3D Coordinate Measuring Machine (CMM), Frequency Scanning Interferometry (FSI) and micro-triangulation. Complementary studies were undertaken to have a better characterization of the environment using a seismic sensor, to perform nanometric displacements on the quadrupoles, to conclude on the general uncertainty of measurements of such a process, and to develop miniaturized rotating search coil systems for magnetic measurements.

This paper presents the main achievements obtained first on dedicated benches developed for the validation of the methods, and then on the PACMAN Final Alignment Bench (PFAB) consisting of a BPM and a quadrupole.

STRETCHED WIRE AS REFERENCE

The common wire used for metrological, magnetic, electric and electro-magnetic measurements is a key component of the study. A 100 µm diameter wire has been chosen, after being characterized for dimension and magnetic properties. It is composed of copper and beryllium (Cu 98%; Be 2 %) [4]. Only one criterion was not fulfilled during the tests: the form error of the wire is larger than 0.5 µm, partially due to pieces of dust on the wire. To overcome this problem, a sensor named “Shape Evaluating Sensor: High Accuracy and Touchless” (SESHAT) has been designed to measure the form of the wire and thus to increase the accuracy of the overall measurement [5].

REFERENCE AXIS FIDUCIALISATION

Radio Frequency Structures Fiducialisation

A test set-up [6] to measure the electromagnetic center of high-gradient Accelerating Structures (AS) has been developed for alignment purposes. The methods carried out were validated using the TD24 AS for CLIC [7]. In previous simulation studies, it was demonstrated that a resolution of 1 µm is achievable [7]. A conducting wire, stretched and kept fixed along the AS is used to perturb the first dipole mode excited in the AS at 17 GHz using a network analyzer. The AS is moved in X and Y directions with two orthogonal linear stages in steps of 2 µm. Two different measurements were performed with similar results to detect the position where the perturbation is minimized.

The accurate assembly of the set-up in the metrology laboratory at CERN with the CMM, the calibration of the equipment instrumentation and the good linearity of the

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measurements, allow the measurement of the electromagnetic center with a final precision of 1.09 µm in the horizontal plane and 0.58 µm in the vertical plane [8].

Beam Position Monitor Characterization

A dedicated test bench was used to characterize the cavity BPM using a hexapod to displace the BPM in 6 degrees of freedom w.r.t. a stretched wire fixed at both ends [9]. The position of the wire inside the BPM has an impact on the electro-magnetic fields of the excited dipole mode of the cavity [10]. The interference on the dipole eigen-mode takes its minimum when the wire is positioned along the symmetry z-axis of the BPM. Measurements to determine the electrical centre were repeated several times, demonstrating a sub-micrometric repeatability [11]. A piezo actuator was installed between the BPM and hexapod, providing a controlled vertical displacement within a nanometric accuracy. With such a test setup, a resolution of the BPM below 12 nm was demonstrated [12].

Main Beam Quadrupole Alignment

The alignment of the main-beam quadrupole according to its magnetic field axis was performed by means of the reference stretched wire. In particular the vibrating-wire method [13] was employed, because of its high sensitivity. To avoid the impact of the magnet cooling water system in the highly stabilized environment of the CMM, the magnet was powered well below its nominal working conditions (4 A excitation current against 126 A nominal). This required a previous characterization of the magnetic axis behaviour at varying the magnet excitation current [14]. A systematic difference between the nominal and low power magnetic axes was found within 3 µm and taken into account. An innovative technique for correcting the systematic error arising from the background fields was developed [14]. The systematic error from the wire sagitta was corrected by repeating measurements for different values of the wire stretching tension and extrapolating the axis location for an "infinite" tension without sag. The correction amount resulted in 10 µm on the wire vertical position. In a separate study [15], system parameters such as the wire mechanical tension, and wire current frequency amplitude were analysed to optimize the measurement sensitivity and repeatability. This allowed the magnetic axis to be located with submicron repeatability in the same measurement conditions. The repeatability at disassembling and assembling the PFAB is under study.

WIRE POSITION DETERMINATION

Coordinate Measuring Machine

The best identified solution to determine the position of the stretched wire w.r.t. fiducials is the use of the previously mentioned SESHAT sensor. The stator of the sensor will be plugged on the measurement head of the CMM and the rotor, hosting the confocal sensor to measure the form of the wire, will turn around the wire moved on air bearings. All the components were designed and procured, and are under qualification and assembly.

Frequency Scanning Interferometry Solution

An alternative coordinate measurement solution consists of Frequency Scanning Interferometry (FSI) and multilateration. The goal is to achieve the uncertainty required for CLIC component fiducialisation with a portable measurement solution also capable of handling larger volumes than high-accuracy CMMs. The solution is based on reference spheres and kinematic mounts. We have localized the FSI fibre tip and are now able to perform distance measurements in different directions from the same point with micrometric repeatability. Using our developments, we built a multilateration network consisting of 10 measurement stations making observations to targets on the quadrupole assembly and to fiducials on the wire support stage. The fiducials on the wire support stage were previously calibrated to provide information on the position of the reference wire and therefore the magnetic axis [16].

For the first tests we obtained an empirical standard deviation of less than 5 µm for all coordinates. When compared with a Leitz CMM, the coordinates of points on the magnet agree to about 2 µm. The comparison of coordinates on the stages highlighted fixation problems that will be addressed before the next measurements campaign.

Micro-triangulation

A third developed solution to determine the position of the wire w.r.t. fiducials is based on micro-triangulation, i.e. on horizontal and vertical angle measurements from theodolites to targets. The requirement for accurate, automatic and contactless angle measurements is fulfilled with the use of the QDaedalus measuring system [17, 18].

Within the PACMAN project, we have developed a computer vision algorithm, based on edge detection, to enable the contactless measurement of the stretched wire.

Given the fact that the standard triangulation can handle only observations to targets and not to the wire, we have developed an expanded mathematical model which describes both the observations to the targets and to the wire. Moreover, we have created a software to implement the expanded mathematical model, which enables us to perform the micro-triangulation network analysis and to simulate various configurations before the installation of the system.

To validate the method, we performed a micro-triangulation test measurement, cross-checked with a CMM measurement. The comparison concerns the position of the fiducials, and the position and orientation of the wire in space. The preliminary results show an accuracy always better than 20 µm for the wire position, and of about 40 µm/m for the wire orientation, compared to CMM [19].

COMPLEMENTARY STUDIES

Seismic Sensor

A study of a seismic sensor was performed. It is a custom-made sensor in which 3 different types of sub-nanometre displacement transducers have been integrated: a Fabry-Perot interferometer, an optical encoder and a capacitive transducer. This sensor has allowed us to compare the resolution of all the transducers under the same conditions, thus enabling us to verify the most suitable transducer for a seismic sensor. The resolution of all the transducers was measured while the reference mass was locked and thus there was no relative motion between the mass and the sensor casing. Results of this measurement are shown in Table 1. However, to reach the requirements of the PACMAN project, a further increase in resolution was needed. This was achieved by implementing a forth transducer into the seismic sensor: a multi-pass Michelson interferometer. With this interferometer a resolution of 6.5 pm was achieved in a configuration with 8 reflections which is more than 4 times better than the best of commercial transducers, i.e. the optical encoder [20].

Table 1: Resolution RMS Values Measured for Individual Transducers with Mass-locking Technique

Transducer	**Resolution RMS @ 1 Hz (pm)**
Fabry-Perot interferometer	69.3
Optical encoder	28.8
Capacitive sensor	39.8
Multi-pass Michelson interferometer N=8x	6.5

Uncertainty Budget

CLIC alignment requirements have targeted pre-alignment measurements uncertainty of 14 µm (1σ). Studies identified two gaps of knowledge [21]. First stochastic model of the CMM was calibrated [22] with standard ISO 10360 tests and used to propagate the task specific measurement uncertainty. It was found that Maximum Permissible Error for length measurement (MPEE) qualification of a CMM used for alignment does not provide accurate task specific reference. Uncertainty can vary from 3 times the MPEE (for 0.6 m long magnets) to below the MPEE (for 2 m long magnets). The task uncertainty to know the location of a fiducial in a dimensional reference frame of 3 spheres was found to be between 4-8 µm at 1σ (excluding thermal effects), depending on the magnet size and the quality of the spheres surface used.

The second gap was the lack of understanding and quantification of the thermal errors. Studies have found that for the PFAB, the magnetic axis can drift by 2 µm/°C. The reference fiducial markers can drift with more than 4 µm/°C. Both empirical and numerical models were created to compensate these errors and study their uncertainty. Probabilistic robustness analysis showed that empirical models can compensate thermal errors with an uncertainty of 3 µm (1σ). Probabilistic Finite Element Model (FEM) models showed that they could predict/compensate the drift with an uncertainty of the order of 4-7 µm (1σ)

Nano-positioning System

Nano-positioning system, part of the CLIC stabilization system [23] was optimized after investigation to find the origin of the parasitic Eigen modes below 100 Hz. A new reinforced base plate was put in place combined with the bolting and gluing of the components in the base region. To control the lateral motion of the magnet from a direct measurement, new supports for optical encoders were installed. To improve the line of sights to the fiducials, side plates were lowered.

Nanometric experiments could take place thanks to these improvements. The response time to position the magnet laterally (most challenging degree of freedom to control) with 50 nm steps can be reduced by a factor five by applying advanced controllers in comparison to classical Proportional Integral (PI) feedback control. The strategy proposed is a combination of PI feedback (for the tracking) and positive position feedback for active damping of targeted modes.

Miniaturized Rotating Search Coils

A miniaturized Printed Circuit Board (PCB) rotating coil was designed with a compensation winding for the main fields to measure the higher-order harmonics of field error, while reducing the spurious harmonics due to the imperfect motion (shaft vibration and torsion). The PCB sensor was produced at CERN with a custom process to guarantee a high precision of the tracks and layer alignment and a reduced thickness. The shaft is made of synthetic sapphire of optical quality which provides a high stiffness to the PCB. Successful tests of sensor performances were carried out at Fermilab. The compensation ratio of reference sensor was 10 [24]; the new sensor has a better performance with about 420 dipole compensation and 176 quadrupole compensation. The repeatability on the measured harmonics is of about 0.2 units. The calibration of sensor position [25] shows that the sensor is shifted w.r.t the design position of 22 µm in radial and 62µm in vertical direction. The sensor is indeed precisely assembled and has a negligible sagitta thanks to the shaft rigidity.

CONCLUSION

A lot of "premières" were already achieved in the PACMAN project and have to be underlined: the resolution of BPM below 12 nm using a wire instead of a beam, the smallest search coil of 26 layers ever manufactured, the most accurate portable system of measurement for large scale measurements (below 5 µm accuracy for a 1 m3 volume), the 1st seismic sensor integrating 3 different transducers, and the most accurate absolute fiducialisation process of quadrupole, BPM and AS ever achieved.

All the methods and tools developed provide very interesting perspectives for the initial alignment and fiducialisation of the CLIC components. Furthermore, they can be extrapolated to other projects as FCC-ee [26].

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