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MEASURING AND ALIGNING ACCELERATOR COMPONENTS TO THE NANOMETRE SCALE*

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Abstract

First tests have shown that the precision and accuracy required for linear colliders and other future accelerators of 10 micrometers is costly and lengthy with a process based on independent fiducializations of single components. Indeed, the systematic and random errors at each step add up during the process with the final accuracy of each component center well above the target. A new EC-funded training network named PACMAN (a study on Particle Accelerator Components Metrology and Alignment to the Nanometer scale) will propose and develop an alternative solution integrating all the alignment steps and a large number of technologies at the same time and location, in order to gain the required precision and accuracy. The network composed of seven industrial partners and nine universities and research centers will be based at CERN where ten doctoral students will explore the technology limitations of metrology. They will develop new techniques to measure magnetic and microwave fields, optical and non-contact sensors and survey methods as well as high accuracy mechanics, nano-positioning and vibration sensors.

INTRODUCTION

CLIC (Compact Linear Collider) is a study for a future electron-positron collider in the multi TeV range that would provide significant fundamental physics information complementary to the Large Hadron Collider (LHC) [1]. It consists of two almost 50 km long accelerators that will accelerate electrons and positrons and collide them at a nominal centre-of-mass energy of 3 TeV. The alignment of passive and active components along such an accelerator shall reach unprecedented small values at the nanometre and micrometre level. Indeed, we observe in future accelerator projects that the tolerance concerning the position of the beam inside an accelerator is becoming increasingly tight. In order to achieve this, the static alignment of fundamental components must be included within a few micrometres with respect to a reference line over several hundreds of meters. For a LINAC-based machine like CLIC these components are quadrupole magnets, accelerating structures and beam position monitors. They are objects weighing less than a ton and measuring more than a meter long. Still, their reference axes must be aligned within a few micrometres.

The current alignment strategy consists of three steps: first to measure for each component the position of its reference axis w.r.t external targets named fiducials (fiducialisation process), then to align the components on a common support, and finally to align this support in the accelerator tunnel using alignment sensors. First tests concerning this strategy have shown that the precision and accuracy required for linear colliders of 10 micrometres can be reached with this serial process, but its implementation is lengthy which makes unpractical to apply to a large number of units. The objective of the PACMAN [2] network is to propose and develop an alternative solution integrating all the alignment steps and a large number of technologies at the same time and location. We plan to build a prototype alignment bench integrating all the metrology and electromagnetic measurements plus active nano-positioning and background monitoring.

The principle of the pre-alignment PACMAN bench is sketched in Fig. 1.

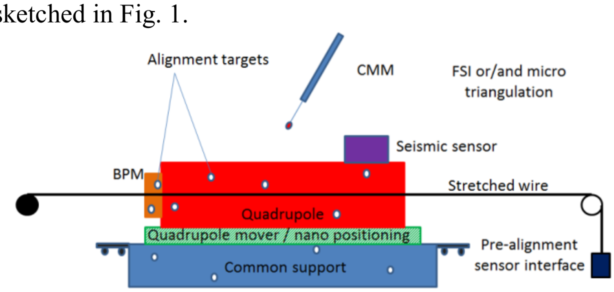

Figure 1: Schematic view of the final PACMAN pre-alignment bench. The bench is based in a stretch wired system that allows measuring the magnetic axis of a quadrupole and offset in a BPM at the same time as the position of the wire is measured by means of a CMM.

During the course of the program a prototype alignment bench will be built in which the final demonstration of the PACMAN systems (methods, alignment sequence and algorithms) will be implemented. The solution developed within the PACMAN network needs to be robust and also work reliably in an industrial environment. The specific issues that need to be tackled to reach this goal will be presented in the following section. They define the PhD research goals of the ten students hired by the network.

INTERNATIONAL NETWORK

This project comprises eight private companies as Associated Partners that will provide training to the young researchers through secondments and tailored training. Besides CERN, seven universities and research laboratories are part of the network and will provide academic supervision to the students and guide them through their PhD programs (see Fig. 2). All partners are part of the PACMAN research project and will

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contribute to the success of the program.

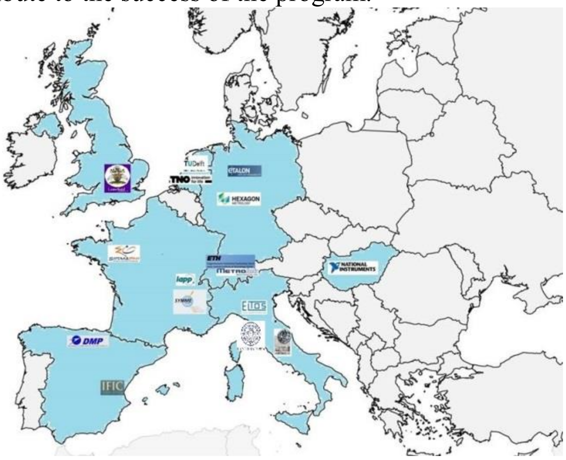

Figure 2: The list of associated partners forming the PACMAN network including private companies (DMP ES; ELTOS, IT; ETALON, DE; Hexagon Metrology, DE; Metrolab, CH; National Instruments Europe, HU; SIGMAPHI, FR and TNO, NL) and universities and research laboratories (Cranfield U., UK; ETH Zurich, CH; LAPP, FR; SIMME, FR; Sannio U., IT; IFIC-UV, ES; TU Delft, NL and Pisa U., IT)

SCIENTIFIC PROGRAM

We have divided the research into four main work packages, each one making use of a different scientific area. The Work Package teams pursue the same scientific goal: develop new or upgrade existing measuring techniques to their ultimate precision and resolution; and their integration into the prototype alignment bench. Within each work package two or three Early Stage Researchers (ESR) will follow a line of investigation and prepare at the same time their PhD work.

WP1 Metrology and Alignment

ESR1.1 will develop an optical sensor to be plugged in the measurement head of the Leitz CMM [3] currently used by the metrology lab at CERN for high precision positioning of objects such as ceramic balls and vibrating stretched wires. The sensor must provide absolute measurements in the local coordinate system of the CMM and provide the most accurate and repeatable measurements without relying on a similar external reference in order to establish a proportional relationship. Different sensors types (cWPS, oWPS, opto coupler) must be studied including their mechanical, electronic and optical parts. Furthermore, the measurement head must be upgraded to work in an environment with magnetic fields. The ESR will work in close collaboration with Hexagon metrology.

ESR1.2 will develop an absolute portable metrology method based on Frequency Scanning Interferometry. In collaboration with Etalon AG. The ESR will develop the fiducials allowing the centring of optical fibre in order to perform absolute measurements of distance. Different configurations of FSI network should be studied through simulations in order to choose the best one for the measurements sequences.

ESR1.3 will adapt Micro-triangulation [4] for high accuracy short range measurements of dynamic objects. After an initial training provided by ETHZ and in collaboration with this institution, the ESR will apply this technology to the project. Tasks include raising the acquisition frequency up to 50 Hz, synchronizing the CCD camera and developing the detection algorithm for a vibrating stretched wire and targets. Prior simulation of the different configurations and verification on the experimental model are part of the required research.

WP2 Magnetism

ESR2.1 will be in charge of the development of a magnetic measurement system based on the oscillating wire field-measuring technique for small aperture magnets [5]. Research will integrate and combine metrological techniques: measurement of vibrations, tension, opto-couplers, data acquisition, digital integrators with methods of potential theory and the solution of the wave equation on vibrating strings. The work will be done in close collaboration with the University of Sannio for the implementation of the method and for the theoretical aspects of the work. The ESR will be trained in magnet manufacturing and measurement techniques in SIGMAPHI and Metrolab.

ESR2.2 will be in charge of the development of a magnetic measurement system based on rotating search coil [6] with printed circuit board technology. This method will be used for direct comparison with the oscillating wire technique and for acceptance of the quadrupole magnets coming from industry. Tasks include the development of control algorithms and software in order to create an industrial-standard measurement device. Again, the work will be done in close collaboration with the University of Sannio. The researcher will work inside ELTOS to learn the basics of the manufacturing of PCBs as well as their inherent limitations. The ESR will also work closely with SIGMAPHI and learn in their premises the basics of magnetic measurements from an industrial point of view.

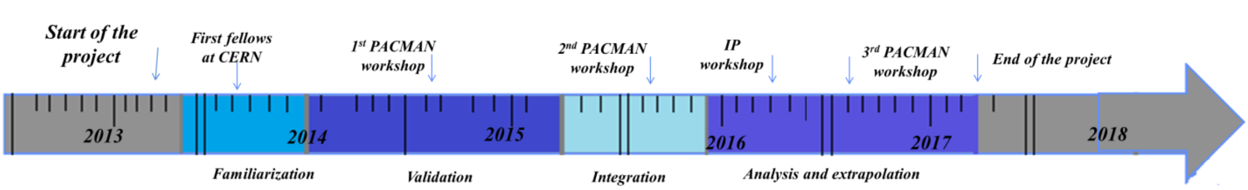

Figure 3: Schematic schedule of the PACMAN project.

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Precision Mechanics and Nano-Positioning

ESR3.1 will re-engineer the quadrupole magnets assembly from the point of view of ultra-high precision engineering. The ESR will re-engineer the yokes quadrant mating surfaces, Beam Position Monitor support and the assembly procedure to guarantee an initial co-alignment at the micrometre level. This researcher will also be responsible of the full mechanical integration of the prototype alignment bench paying special attention to the total error budget. The researcher will collaborate with Cranfield University and will join DMP, an ultrahigh precision mechanical manufacturer for industrial training.

ESR3.2 will determine the technological barriers of seismic sensors against radiation (could reach kGy) and to stray magnetic fields. The ESR will upgrade or develop sensors with a large bandwidth covering the whole frequency region of interest (0.1-100Hz) and presenting sufficiently low noise to measure quiet Ground Motion [7]. The sensors also need to be compact to fit in the crowded space of the prototype alignment bench and light-weight (typically less than a few kg) to avoid disturbing the measured structures. The work will be done in close collaboration with LAPP and the researcher will also join DMP as part of his training.

ESR3.3 will upgrade the first prototype of nano-positioning system [8] to be used for the test setup. The researcher will also study the possibility of using long range actuators in flexural guides for the combination of alignment and stabilization with sub nanometre resolution in a millimetre range. The ESR will closely collaborate with TU Delft and TNO.

Microwave Technology

ESR4.1 will demonstrate the nanometre resolution of the beam position monitor by using a RF excitation on the stretched wire [9]. The measurement should prove sub-micrometre spatial resolution as well as calibration, absolute alignment and long-term stability of a few micrometre or better, as well as high temporal resolution Essential parts of the read-out and control system are based on National Instruments hard- and software and the researcher will work in close collaboration with National Instruments (NI).

ESR4.2 will investigate how to measure the axis of RF accelerating cavities in laboratory, non-destructive tests. The ESR will investigate the limits of the classical techniques [10] and compare them to lasers excitation and stretched wire. The use of the RF input ports and/or the damping waveguides [11] as transmission lines shall be considered. The researcher should use extensive simulation work, low power measurements using a vector network analyser or direct electronics as well as experimental validation on prototype CLIC accelerating structures. Equally to the previous case, the ESR will collaborate with NI.

CONCLUSION

The PACMAN network and program started to run on September 2013. To this day, all ten researchers have been hired by CERN and have started their work by reviewing the literature and joining the activities of their respective activity groups in what we call familiarization phase (see Fig. 3). During the next three years, we expect to see big advancements in the way we characterise mechanical and electromagnetic features of quadrupoles, beam position monitors and accelerating structures. The project is meant to finish by 2017 with a first prototype bench and a thorough understanding on the limitations of alignment for accelerator components.

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