The scaled, 1 m long, PETS was installed and operated in beam driven mode with external RF re-circulation in order to compensate for the lack of drive beam current and pulse length. The PETS routinely produced RF power with peak levels well in excess of the CLIC specifications.

The new high RF power variable RF reflector and variable RF short circuit were designed and fabricated. These devices have replaced the external recirculation in the special, 1 m long PETS installed in CTF3. The PETS ON/OFF operational principle and high peak RF power capability were successfully demonstrated in experiments with the CTF3 drive beam.

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2.8 PACMAN (Particle Accelerator Components Metrology and Alignment to the Nanometer scale)

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2.8.1 **Introduction**

The alignment of passive and active components along the CLIC accelerator shall reach unprecedented small values at micrometer level and with nanometer resolution. Indeed, this is a common requirement for the next generation of accelerators. Whether for producing a high number of collisions at the highest energy, or for producing the brightest light from light sources, the tolerance concerning the position of the beam inside an accelerator is becoming increasingly tight. In practice, the static alignment of three fundamental components must be included within a few micrometers with respect to a reference line over several hundreds of meters. These components are quadrupole magnets, accelerating structures, and beam position monitors. They are heavy objects sometimes weighting more than a hundred kilograms and measuring one meter long or more. Still, their reference axis must be aligned within a few micrometers.

Nowadays, the current alignment strategy used in most accelerators 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 and other future accelerators of 10 micrometres cannot be reached with this serial process. Additionally, accelerators are logically built out of modular elements built as mechanical supports on which the components are assembled. These modules constitute the backbone of sometimes several kilometres of accelerator and are industrially produced in large numbers, typically in the order of thousands of units. The requirement of tighter tolerances in the alignment inside these modules shall thus be fulfilled at the manufacturing premises.

A group of scientists at CERN have put together an EC-funded Initial Training Network composed by private companies, universities and research institutions interested in metrology under the name of PACMAN (a study on Particle Accelerator Components Metrology and Alignment to the Nanometer scale). The partners of the network are listed in Table 1. They will supervise a group of ten doctoral students working on electromagnetism, mathematics, precision mechanics, microwave technologies, electronics, mechatronics, nano-positioning, controls engineering and computing.

The main objective of the network is the training of young researchers on a multicultural, multidisciplinary environment. The students will be trained through research, and on the job through secondments in the partner private companies. They will follow academic training and supervision towards the completion of a PhD. The PACMAN network will also embark on outreach activities addressed to the general public, young children and female scientist in particular to increase awareness of the importance of research in society and also of the Marie Curie actions.

Table 1: Partners of the PACMAN network

Coordinating organization	Country
CERN	CH
Universities	
ETH Zurich	CH
Universita' del Sannio	IT
Cranfield University	UK
TU Delft	NL
IFIC (Universidad de Valencia)	ES
Research institutions	
LAPP	FR
SYMME	FR
TNO	NL
Private sector companies	
Hexagone	DE
Etalon AG	DE
Metrolab	CH
SigmaPhi	FR
Eltos	IT
DMP	ES
National Instruments	HU

The scientific objective of the PACMAN 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, in order to gain the required precision and accuracy. The solution proposed by the PACMAN network needs to be robust and also work reliably in an industrial environment. By the end of the program, a prototype alignment bench will be built in which the final demonstration of the PACMAN system (methods, alignment sequence and algorithms) will be implemented.

A number of issues need to be tackled previously. In practice we have to:

- optimize the manufacturing of the mechanical components of magnets and monitors and their assembly by applying ultra-high precision engineering and accurate machining techniques,
- refine methods for magnetic measurements that will deliver the functional axis of magnets with very small aperture and with the required accuracy by using vibrating wire techniques and printed circuit boards rotating search coils,
- refine and propose new measurements for finding the electromagnetic center of microwave cavities to nanometer resolution. Investigate laser and wire excitation and capacitive measurements,
- design new methods of absolute alignment between all the components inside the CLIC modules and their associated fiducials using a stretched wire as reference,
- develop portable methods of absolute alignment based on a combination of new techniques like micro triangulation and Frequency Scanning Interferometry (FSI),
- improve the commercial apparatus and seismic detectors to work in harsh environment and in magnetic fields by reviewing their mechanical and electronic design as well as the integrated feedback,
- study ground motion and other environmental noise to be able to filter it accordingly using seismic sensors,
- position the quadrupole and the attached beam position monitor with the help of actuators to the nanometer level,

• build a prototype alignment bench integrating all the metrology and electromagnetic measurements plus active nano-positioning and background monitoring,

• automatize this test bench,

The network delegates onto four science and research work packages. They will be described in the following sections.

2.8.2 **WP1. Metrology and Alignment**

This work package concentrates mostly on metrology, mechanics, electronics, optics, image analysis and magnetism. Three students will integrate this package together with Hexagon metrology, Cranfield University, ETH-Zürich and Etalon AG.

The monitoring at micrometric precision of large structures like bridges or buildings or the precise control of machining tools in industry is becoming ever more standard. However, both applications are interested only in relative measurements performed with respect to a given reference time. Only Coordinate Measuring Machines (CMM) have ever achieved micrometric precision and accuracy in absolute measurements. Within this work package, we aim to develop new methods of absolute metrology in the micrometer range and make them portable. We plan to bring the already existing CMM technology to our required accuracy and resolution.

In the field of CMM, a new optical sensor has been developed by Hexagon Metrology for the Leitz PMM-c Infinity LSP4 measurement head, allowing very high precision rugosimetry measurements [1]. To be used for targets as a vibrating stretched wire it would require further upgrading from one axis to 3D measurements. Micrometric portable means exist, e.g. measurement arm, but they do not perform measurements at the required accuracy and precision. Two methods under development are proposed to be tested, validated and implemented as portable means: Frequency Scanning Interferometry (FSI) and Micro-Triangulation. The SME Etalon AG has introduced FSI to the market recently: thanks to optical fibers and corner cubes, very precise measurements of distances are already performed. This is a relative measurement system, planned to be used for monitoring applications as the control of systematic deviations of CMM machines. The next step, going beyond the state-of-the-art, is to develop an absolute measurement method, based on FSI. Finally, alignment using micro-triangulation performs angle measurements on illuminated targets, by automatic image recognition. This system is currently under development by the university of ETH Zürich [1].

We intend to develop an optical sensor to be plugged in the Leitz CMM measurement head 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.

In parallel, we will develop an absolute portable metrology method based on Frequency Scanning Interferometry. In collaboration with Etalon AG, we intend to develop the fiducials allowing the centering of optical fiber in order to perform absolute measurements of distance.

We intend to adapt Micro-triangulation for high accuracy on short range measurements of dynamic objects. In other to do this, it is necessary to increase the frequency of acquisition up to 50 Hz, synchronize the CCD camera and develop the detection algorithm for a vibrating stretched wire and targets. Prior simulation of the different configurations and verification on the experimental model will be part of the required research.

2.8.3 **WP2. Magnetism**

Disciplines directly related to this work package are magnetism, mechatronics, signal processing, numerical analysis and optimization, and partial differential equations. Two doctoral students will join this work package together with Eltos, Metrolab, Sigmaphi and the University of Sannio

The standard technique to measure the field quality in accelerator magnets is the rotating search coil. The magnetic axes of a quadrupole can be determined to a precision of micrometres which is indeed the required accuracy for new accelerators. However, for small-aperture accelerator magnets like the ones used in the future linear colliders, the sensitivity of search coils is difficult to maintain as for smaller coils, the coil cross section is not point like with respect to the surface spanned by the probe. Recently, the oscillating wire technique has been extended to field quality measurements by exciting the wire with a sinusoidal excitation current. The vibrations of the wire can be used to reconstitute the integrated transversal field components. The aim of this work package is to develop very accurate magnetic measurement techniques capable of measuring integral fields and magnetic axes of small aperture magnets at the micrometre scale. As a single method may not fulfil all the requirements of precision and portability, both the rotating coil and the stretched wire will be investigated, cross-checked and brought to their intrinsic limitations.

Rotating search coils wound on an epoxy-glass spacer have been used for magnetic measurements of normal and superconducting magnets of large aperture. They have routinely been used at CERN and in industry and reach a precision of 2 micrometres for the magnetic axes measurement [3]. Smaller coils have been produced recently with the printed circuit board technology and used at CERN for the measurement of magnets for the CLIC study. However, the accuracy of the coil positioning is not of the same order compared to the classical coils. In parallel, oscillating wire measurements of magnetic fields have been developed in recent years by the University of Sannio in collaboration with CERN [4]. The achieved accuracy of the alignment between the wire and the magnetic axis is of 10 micrometres. This work package aims for an alignment accuracy of 1-2 micrometres when using an oscillating wire which will be common to all the other work packages.

We will develop a magnetic measurement system based on the oscillating wire field-measuring technique for small aperture magnets integrating 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.

In parallel PACMAN will also build a magnetic measurement system based on rotating search coil 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.

A cross check of the results of both instruments is essential as only the oscillating wired method can be integrated in the prototype alignment bench whereas the rotating search coil is potentially more accurate.

2.8.4 WP3. Precision Mechanics and Nano-Positioning

The work package 3 exploits and develops the disciplines of mechanical and manufacturing engineering; nanotechnology; metrology and measurement; mechatronics; material science; seismology; control engineering; numerical analysis, simulation and optimization; and signal processing. Three students will join the research with the support of DMP, TNO, SYMME, LAPP, Cranfield University and TU Delft

The initial position of the magnetic centre and its relative alignment to the beam position monitor is guaranteed by ultra-high precision engineering of the quadrupole magnet itself. Active mechanical stabilization is required to limit the vibrations of the magnetic axis to the sub-nanometre level in a frequency range from 1 to 100 Hz. A stabilization system isolates the quadrupole from ground motion for up to six degrees of freedom using seismic sensors and actuators performing nano-positioning. The aim of this work package is to reach and maintain statically and dynamically the position of the main beam quadrupole axis at nanometre level.

Ultra high precision engineering is responsible for many of the latest technology developments in medical diagnostics, aerospace, optoelectronics, etc. The integration of the manufacturing procedures with metrology is however a new field with rare examples as the Cranfield BoX [5]. The stabilization of structures at the nanometre scale is a concern in various fields of precision engineering like integrated circuit lithography, interferometers, microscopes, or in manufacturing [6]. CLIC stabilization has proven to reduce the integrated displacements of ground motion by a factor of the order of 10 above 1 Hz with a reduction of transmissibility going up to a factor 500. Displacements are reduced to the sub-nanometre level in a laboratory environment. This was done with stiff actuating supports to be robust against external forces that otherwise would upset the alignment. The solution needs to be adapted to the component chosen for the project and confronted with other technical systems involved as micrometric alignment. Seismic sensors currently available in industry can measure in the sub-nanometre range and at low frequency [7]; however, they have not been designed to work in an accelerator environment where radiation and magnetic fields play a determinant role.

As part of the PACMAN research, we will re-engineer the quadrupole magnets assembly from the point of view of ultra-high precision engineering including the yokes quadrant mating surfaces, Beam Position Monitor support and the assembly procedure to guarantee an initial co-alignment at the micrometre level. The same attention will be paid to the mechanical integration of the prototype alignment bench

We 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 in the presence of radiation and stray magnetic fields. 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.

At last, we will upgrade the first prototype of nano-positioning to be used for the test setup. We 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.

2.8.5 **WP4. Microwave Technology**

This last work package focuses on microwave technology. It exploits metrology, ground motion, automation and general electromagnetism. Two doctoral students will form the core team of the work package with National Instruments and IFIC (University of Valencia) as partners.

There are two main Radio Frequency components being produced for CLIC. Besides the 12GHz accelerating cavities, the CLIC beam position monitor has been designed like a resonant device operating at microwave frequencies (15 GHz) [8] to achieve the very high spatial (50 nm) and temporal (50 ns) resolution required. For the absolute alignment of both components we rely on ultra-high precision mechanics both for the accelerating cavity as for the BPM cavity rigidly attached to the quadrupole. Still, the spatial resolution limit of the BPM system, is expected to be 1 nm or below for longer integration times. This work package aims to use RF excitation in a microwave cavity to measure accuracy to the micrometre level and resolution to the nanometre level. Qualifying the cavities at these extreme limits requires the monitoring and correlation of environmental data, e.g. ground motion, temperature, etc.

State of the art: The use of a stretched wire for determining the alignment between a beam position monitor and a quadrupole has been previously exploited in DESY for the Tesla Test Facility (now FLASH) [9]. However, the use of the system at smaller resolution and higher frequencies necessitates understanding of environmental noise and multiple corrections. Similar experimental set-ups have been studied recently for monitoring the displacement of test cryo-modules during cool-down with a precision of a few micrometres [10]. Concerning the accelerating cavities, alignment is done up to now by ultra-high precision machining and bonding of the disks that form the structure [11]. The only means to verify the alignment is from the outside diameter of the structure using classical metrology methods. This provides only an indirect measurement of the internal manufacturing precision and disregards any internal deformation due to the bonding process. Other alignment techniques based on the excitation of an RF signal by the beam itself when passing through the structure are being currently studied [12].

We aim to demonstrate the nanometre resolution of the beam position monitor by using a RF excitation on the stretched wire. 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.

In parallel, we will investigate an independent measure of the axis of RF accelerating cavities to cross check against the mechanical alignment and provide laboratory, non-destructive tests. We will investigate the limits of the classical techniques and compare them to lasers excitation and stretched wire. We shall consider the use of the RF input ports and/or the damping waveguides as transmission lines.

2.8.6 **Conclusion**

PACMAN project (EC-funded Initial Training Network) has started on the 1st of September 2013, for a duration of 4 years. The “kick-off” Meeting with participation of all Partners has just taken place (20 November 2013). The recruitment of the 10 PhD students is under way and the work on the project will really start beginning of next year with a first period of intensive training of the students, followed by a period of secondment in industry, combined with study at CERN and trainings at universities, towards a common goal: the validation of the developed methods on the prototype alignment bench. More details about the program and the Partners involved in the project can be found at the PACMAN web site: http://pacman.web.cern.ch

2.8.7 **References**

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