PACMAN Project:
a study on:
Particle Accelerator Components’ Metrology and Alignment to the Nanometre scale

Michele MODENA, CERN
PACMAN = a study on Particle Accelerator Components’ Metrology and Alignment to the Nanometre scale, is an Innovative Doctoral Program network founded by the European Commission FP7 Marie Curie Actions, hosted by CERN, providing training to 10 Early Stage Researchers (ESR) all enrolled to PhD studentship programs.

Project Structure:

- 10 ESR engaged in their PhD studies
- 9 Academic partners
- 8 Industrial partners
- Duration: 4 years
- Start date: 1/09/2013

- Total EC contribution: 2,6 MEuro
- Wealthy budget for student training/formation
- Secondment in Industry mandatory.
PACMAN

Particle Accelerator Components’ Metrology and Alignment to the Nanometre scale. Main aim: improve the accuracy of alignment for the components to be installed in the next generation of particle accelerators.

PACMAN is an Innovative Doctoral Program Network, offering training to 10 Early Stage Researchers hosted by CERN thanks to The European Commission’s FP7 Marie Curie Actions. The human objective of the Marie Curie program is to create a new generation of scientists equipped with a wide-ranging expertise in advanced engineering and instrumentation. The technical objective of the PACMAN project is to develop highly accurate metrology and alignment techniques. Early stage researchers have the opportunity to work in close collaboration with all of

Web site: http://pacman.web.cern.ch/
Supervisory Board
CERN,
HEXAGON METROLOGY, ETALON, ELTOS, METROLAB, DMP, SIGMA PHI, NI
PISA univ., CRANFIELD, SANNIO univ., LAPP, ETHZ, IFIC, SYMME, Tech. Univ. of Liberec

Management team

WP0 Management
H. Mainaud Durand
(Network Coordinator)

WP5 Training
N. Catalan Lasheras

WP6 Diss & Outreach
M. Modena

(Communication & admin. Tasks: T. Portaluri)

WP1 Metrology & Alignment
H. Mainaud Durand

WP2 Magnetic Measurements
S. Russenschuck

WP3 Precision mech. & nano-positioning
M. Modena

WP4 Microwave Technology
M. Wendt

2. Management Organization

Project Structure:

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Project Structure:

3. Training & Industrial secondement for the ESR/PhD students

Michele Modena - CERN, ALERT2016 Workshop, Trieste 14-16/9/2016
Project Structure:

4. Outreach & Dissemination

Organized at CERN

39 contributions.
More than 50 participants

http://indico.cern.ch/event/332431/contributions/
4. Outreach & Dissemination

Organized in Debrecen, HU (with the contribution of National Instruments)

38 contributions.
More than 50 participants

http://indico.cern.ch/event/458671/contributions/
Outreach with Schools of Geneva area ("Promotion of women in Science" is one of the O&D subjects)

With Italian Prime Minister Matteo Renzi at Fermilab

Dissemination at European Society of Precision Engineering (EUSPEN) event in UK
Alignment challenges for CLIC, the Compact Linear Collider project \((R&D)\), chosen as study case for PACMAN

The objectives of PACMAN

(1) introduction to CLIC project

For CLIC 3 TeV layout: would be required more than 20,000 modules! , 2m length
Mechanical pre-alignment:
~ 0.2-0.3 mm over 200 m
Active pre-alignment:
14-17 µm over 200 m

CLIC 3 TeV N. of Comp. to be aligned:
~ 4000 ~ 4000 ~ 140000

Error budget:
14 µm 17 µm 17 µm

Fidu/alignment strategy:
- Alignment of the components on their support/module
- Module transport in the tunnel, checks and final module alignment “in-situ”
The objectives of PACMAN

Combine measurements, & fiducialization in the same place to gain time & accuracy

Demonstrate the feasibility on a Final PACMAN bench

Possible extrapolation of methods & tool to other projects

Some key issues (describing the main research lines):

• Magnetic measurements with a **vibrating stretch-wire** (developing also MM miniature systems based on printed circuit board minute rotating search coils)

• Determination of the **electromagnetic center** of BPM and AS using a **stretch-wire**

• Absolute measurement methods: development of a new “no-touching” measuring head for CMM to measure the **stretch-wire**, development & combination of FSI and micro-triangulation measurements methods for cross-check and as long-term practical alternative for real applications

• Improve **seismic sensors** and ground motion studies.

• Developing **long range nano-positioning system** for alignment & magnet steering capability

• Evaluation of **global uncertainty** of the systems

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WP1 objective: develop 3 methods to determine with the highest precision the position of the stretched wire w.r.t. fiducials:

ESR 1.1: A high accuracy & touchless sensor on the CMM measuring head
ESR 1.2: Frequency Scanning Interferometry (FSI)
ESR 1.3: Micro-triangulation

It include the activities of 3 ESR (Early Stage Researcher):
Design of a high precision, touchless and rotary sensor:

Requirements:
• non-contact measurements
• compatible with strong magnetic fields
• accurate to measure form errors with 100 nm repeatability
• maximum admissible weight of 1.2 kg
• to have an opening
• based on chromatic confocal technology
Advantages:
• Totally free network
• 5 microns “a priori” standard deviation
• Solved with LGC++ (Least Squares method)
• 1000 simulations
• Based on Monte Carlo Method

WP1
"Development and validation of an absolute Frequency Scanning Interferometry (FSI) network"

ESR1.2 Solomon Kamugasa

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• Study, preparation, validation of two algorithms for: wire detection and wire reconstruction
• Validation via cross-check measurements with CMM on the FPB
• Simulation of the measurement configurations

Recognition algorithms:
- center of mass,
- template least-square matching,
- circle matching,
- ellipse matching

Detection algorithm:
• Edge detection (calculation of the axis after fitting in the two edges of the wire)
• Main difficulties: filtering, edge extraction, line fitting, wire center extraction
• Status: algorithms developed in Matlab

Reconstruction algorithm:
• Based on least square adjustment analysis
• Main difficulties: targets and wire measured in a unique coordinate system, modeling of the wire, weighting the observations
• Status: algorithms developed in Matlab

Advantages:
- Remotely operated
- Touchless
- Transportable
- Non destructive
- 3D accuracy better than 10 µm
WP2: Magnetic Measurements development

Introduction

It include the activities of 2 ESR (Early Stage Researcher):

**ESR 2.1**
Stretch-wire systems for magnetic measurement of small-aperture magnets

**ESR 2.2**
Printed circuit board technology for small-diameter field probes.

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- Analysis of the metrological performance varying the measurement configuration for the vibrating-wire method

**Advances**: Metrological characterization of phototransistors, CCD sensors, and optical fiber sensors for measuring the peak-to-peak oscillation amplitude

**Advances**: Correction of the quadrupole strength when higher order multipole errors are present

**Advances**: Correction of background field (Earth magnetic field, tensioning motor etc.)
Advancement and innovation in miniature PCB rotating coils for Magnetic Measurements

**Advances:**
- New positioning system, olive shape sapphire bearings (less vibrations)
- PCB technology radial coils with quadrupole compensation
- Miniature shafts in sapphire (less sag)

**Advances:** In situ coil calibration in the presence of sextupole components
It include the activities of 3 ESR (Early Stage Researcher):

- **ESR 3.1** study of the uncertainty budget, uncertainty propagation and possible uncertainty mitigation for the PACMAN assembly.

- **ESR 3.2** improvement of existing vibration sensors and development of new one dedicated to the PACMAN requirements.

- **ESR 3.3** development of a new nano-positioning system to be utilized for PACMAN/CLIC quadrupoles alignment.
Evaluation and possible mitigation of the uncertainty global budget of the FPB

- The main task is to provide a PACMAN Uncertainty Budget estimation according to **GUM (Guide to the Expression of Uncertainty in Measurement by BIPM, the Bureau International des Poids et Mesures) [http://www.bipm.org/en/publications/guides/gum.html]**.

- **GUM Supplement 1: “Propagation of distributions using a Monte Carlo method”** indicates on how evaluate the measurement uncertainty based on propagation of probability distributions through a mathematical model (Monte Carlo method) and measurements.

- Study of the compensation of thermal effects and the associated uncertainty: simulations versus experiments results.
Which vibration sensor for PACMAN?

Bandwidth = 0.1 ~ 200 Hz
Resolution ≤ 0.1 nm (RMS@1Hz)
Magnetic fields resistance

(State-of-the-art is deeply analysed) →

→ Proposed a NEW trasducer (3in1); the direct comparison should avoid data ambiguity
Upgrade of existing Type1 CLIC module nano-positioning + controller

Fine stage (piezo stacks)
- Resolution: 0.15nm
- Stiffness: 480N/µm
- Useful Stroke: 10 µm

Alternative concept (notch hinges) or long range actuator under study for an integrated positioning system with high stiffness (>100N/µm) capable of moving heavy loads (>50 kg) with high resolution (<1nm) over a large range (≥1mm)
Characterization and alignment of the electromagnetic axes for the critical RF accelerator components:

**ESR 4.1:** 15 GHz cavity beam position monitor (BPM)

**ESR 4.2:** 12 GHz travelling wave accelerating structure (AS)
Two methods are tested:

Signal excitation:
A 15 GHz signal is fed on a conductive stretch-wire, causing an excitation in a similar way as the beam. By scanning the BPM, it is possible to find the signal minimum, i.e. the electrical center.

Perturbation analysis:
The stretch-wire is used as a passive target, while detecting/minimizing the asymmetry using amplitude and phase measurement between the 4 BPM ports.
**WP4**

"Development of direct measurement techniques for the in-situ internal alignment of accelerating structures"

ESR 4.2 Natalia Galindo Munoz

- The 26 cell AS is used for beam acceleration
  - 12 GHz fundamental accelerating mode
  - Unwanted higher order modes (HOM) are excited if the beam is off center or mechanical asymmetries
  - HOM analysis using waveguide couplers
  - A **stretch-wire** is used as perturbation target

- Center of the middle cell of an AS measured with a resolution of 5 µm and accuracy of 20 µm
• One of the global delivery will be the measurement of the “Final PACMAN bench” (FPB) at the most precise CMM of CERN Metrology Lab (Leitz- Infinity).

• Several steps are planned towards this target:

a) Individual systems development and test on dedicated stands
b) Tests of the metrology measurements systems coherence
c) Fiducialization at the CMM of the MM stretch-wire system
d) 1st measurements of PACMAN bench at the CMM (July16)
e) 2nd measurements of PACMAN bench at the CMM (Nov16)  

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Status of the systems development, integration and first results

Phases A,B,C): Top: First results show a very good coherence between hexapod displacements & micro-triangulation measurements.
Left: Comparison between MM stretch-wire mechanics and CMM

Phase D): 1st measurements of PACMAN bench at the CMM (July16): Results under analysis. Detailed plan for next measuring phase under preparation.
FSI + micro-triangulation measurements = alternative to CMM measurements.

Portable & accurate solution
These micrometric measurements could be performed after the transport of components in the tunnel.

The 3rd FINAL PACMAN WORKSHOP that will be hold in March 2017 at CERN, will be the occasion were results from all the PACMAN research domains and potential future applications will be presented and discussed.
PACMAN is an ambitious project to improve the precision & accuracy of the fiducialisation and initial alignment of the CLIC components.

The solutions developed have been validated on individual test setups, and we are now in the phase of integration in the final PACMAN validation bench.

We aim the extrapolation to other projects of developed tools & methods.

Beside technical aspects, there is another dimension of the project: a high quality training program, with the aim to:

- Train young researchers in topics of interest for European Industry
- Improve the career prospects & employability of young researchers
- Enhance public-private research collaboration
- Promote science
- Promote women in science
- Disseminate the results in the private & public sector
REFERENCES:

1. For the 10 individual ESR status and advancements: see the individual contribution at the 2nd PACMAN WORKSHOP (Debrecen – HU, June 2016)

http://indico.cern.ch/event/458671/contributions/

Students has already started to publish paper in Journals and Conf. Proceedings. Some ref. here below:


4. C. Sanz et al., “A rotary mount for positioning a stretched wire axis within a coordinate measurement machine”, IWAA 2016, Grenoble, France, October 2016 (to be published)


7. S. W. Kamugasa, “Frequency Scanning Interferometry for CLIC components fiducialisation”, IWAA 2016, Grenoble, France, October 2016 (to be published)

8. V. Vlachakis, “Upgrade and adaptation of micro-triangulation method & Qdaedalus measurement system for the pre-alignment of CLIC components”, European Portable Metrology Conference, EPMC 2015, Manchester, UK, November 2015

9. V. Vlachakis, “Recent development of micro-triangulation for magnet fiducialisation”, IWAA 2016, Grenoble, France, October 2016 (to be published)


11. D. Caiazza et al., “Performance of the stretched and vibrating wire techniques and correction of background fields in locating quadrupole magnetic axes”, 21st IMEKO World Congress, Prague, Czech Republic, September 2015

12. D. Caiazza et al., “Measuring the longitudinal field profile in quadrupole magnets by vibrating wires, IOP-Journal of instrumentation


18. P. Arpaia et al., “Sensors applications within the research framework of the PACMAN project on metrology for particle accelerators at CERN”, IEEE 2016 Sensors Application Symposium, Catania, Italy, April 2016

19. I. Doytchinov et al., “Uncertainty budgeting for large scale and micron precision accelerators pre-alignment as applied to CLIC”, IWAA 2016, Grenoble, France, October 2016 (to be published)


25. N. Galindo Munoz et al., “Pre-alignment of accelerating structures for compact acceleration and high gradient using in-situ radiofrequency methods”, 7th IPAC, Busan, Korea, May 2016

Thank you for the attention
The students:
- Claude Sanz
- Vasileios Vlachakis
- Solomon Kamugasa
- Domenico Caiazza
- Giordana Severino
- Iordan Doytchinov
- Peter Novotny
- David Tshilumba
- Silvia Zorzetti
- Natalia Galindo Munoz

The academic supervisors:
- Paul Shore (Cranfield Univ.)
- Paul Morantz (Cranfield Univ.)
- Paul Comley (Cranfield Univ.)
- Markus Rothacher (ETH Zürich)
- Pasquale Arpaia (Univ. of Sannio)
- Laurent Brunetti (LAPP)
- Bernard Caron (SYMME)
- Jo Spronck (TU Delft)
- Luca Fanucci (Univ. of Pisa)
- Angeles Faus Golfe (Univ. of Valencia)

The CERN supervisors:
- Ahmed Cherif, Jean-Christophe Gayde, Jean-Frédéric Fuchs, Stefan Russenschuck, Marco Buzio, Michele Modena, Andrea Gaddi, Kurt Artoos, Manfred Wendt, Nuria Catalan Lasheras

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The industrial supervisors:
- Jürgen Schneider (Hexagon Metrology)
- Norbert Steffens (Hexagon Metrology)
- Heinrich Schwenke (Etalon)
- Marie-Julie Leray (Sigmaphi)
- Pascal Lequerre (Eltos)
- Alicia Gomez (DMP)
- Marie-Julie Leray (Sigmaphi)
- Teun van den Dool (TNO)
- Joe Woodford (NI)
- Jacques Tinembart (Metrolab)
Spare slides
The objectives of PACMAN

(1) introduction to CLIC project: alignment tolerances

Beam off
- Mechanical pre-alignment: ~ 0.2-0.3 mm over 200 m
- Active pre-alignment: 14-17 µm over 200 m

Beam on
- Beam based Alignment & Beam based feedbacks
  - One-to-one steering
  - Dispersion Free Steering
  - Minimization of AS offsets
    - Make the beam pass through
    - Optimize the position of BPM & quads by varying the beam energy
    - Using wakefield monitors & girders actuators

Minimization of the emittance growth
The objectives of PACMAN

(3) Example: case of MB quad + BPM

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ESR 1.2: Frequency Scanning Interferometry (FSI)

ESR 1.3: Micro-triangulation

<table>
<thead>
<tr>
<th>CuBe wire characteristics</th>
<th>Nominal values</th>
</tr>
</thead>
<tbody>
<tr>
<td>Electrical resistivity [µΩ/cm²/cm]</td>
<td>5.4 – 11.5</td>
</tr>
<tr>
<td>Limit tension [Kg]</td>
<td>0.5 – 1.3</td>
</tr>
<tr>
<td>Micro-hardness [Vickers]</td>
<td>100-362</td>
</tr>
<tr>
<td>Linear mass [mg/m]</td>
<td>64.80</td>
</tr>
<tr>
<td>Diameter [µm]</td>
<td>100</td>
</tr>
<tr>
<td>Form error circularity [µm]</td>
<td>&gt; 0.5</td>
</tr>
<tr>
<td>Roughness [nm]</td>
<td>10-20</td>
</tr>
</tbody>
</table>
Status of the systems development, integration and first results

Magnetic axis determination for different magnet currents

<table>
<thead>
<tr>
<th>Current (A)</th>
<th>$X_c$ (µm)</th>
<th>$Y_c$ (µm)</th>
<th>$\phi_c$ (µrad)</th>
<th>$\theta_c$ (µrad)</th>
</tr>
</thead>
<tbody>
<tr>
<td>126</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>4</td>
<td>2.9</td>
<td>3.1</td>
<td>-2.3</td>
<td>-5.1</td>
</tr>
</tbody>
</table>

Repeatability of the determination

<table>
<thead>
<tr>
<th>Current (A)</th>
<th>$\sigma_x$ (µm)</th>
<th>$\sigma_y$ (µm)</th>
<th>$\sigma_\phi$ (µrad)</th>
<th>$\sigma_\theta$ (µrad)</th>
</tr>
</thead>
<tbody>
<tr>
<td>140</td>
<td>± 0.07</td>
<td>± 0.09</td>
<td>± 0.3</td>
<td>± 0.5</td>
</tr>
<tr>
<td>4</td>
<td>± 0.03</td>
<td>± 0.17</td>
<td>± 0.5</td>
<td>± 0.3</td>
</tr>
</tbody>
</table>

Phase C: Compatibility of the stretched-wire system with the CMM environment validated.

After correction of background effects

Repeatability
- Repeating a scan for 10 times
- Standard deviation of the residuals

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