PACMAN Project:

a study on:

Particle Accelerator Components' Metrology and Alignment to the Nanometre scale

Michele MODENA, CERN

ALERT 2016 Workshop

14-16 September 2016
Trieste, Italy

Outline:

- *Project Structure*
- *PACMAN project objectives*
- *Description of the individual ESR activities*
- *Status and some first results*
- *Conclusions*

Project Structure:

1. *Partners and Network*

PACMAN = a study on **P**article **A**ccelerator **C**omponents' **M**etrology and **A**lignment to the **N**anometre 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 NETWORK

CERN, CH
Cranfield University, UK
Delft University of Technology, NL
ETH Zürich, CH
IFIC, ES
LAPP, FR
SYMME, FR
University of Liberec, CZ
University of Sannio, IT
SYMME, FR
University of Pisa, IT
DMP, ES
ELTOS, IT
ETALON, DE
Hexagon Metrology, DE
METROLAB, CH
National Instruments, HU
SIGMAPHI, FR
TNO, NL

Web site: http://pacman.web.cern.ch/

Project Structure:

2. *Management Organization*

Supervisory Board

CERN,
HEXAGON METROLOGY, ETALON, ELTOS, METROLAB, DMP, SIGMAPHI, 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

Project Structure:

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

			ESR 1.1	ESR 1.2	ESR 1.3	ESR 2.1	ESR 2.2	ESR 3.1	ESR 3.2	ESR 3.3	ESR 4.1	ESR 4.2
ble skills	Personal development and communucation	Communication to the general public		x	x	x	x	x	x	x	x	x
		Personal awareness and impact										
		Making presentations										
		Balancing Performance and Pressure	x									
		Research career										
		Team building										

			ESR 1.1									SR 4.2
Technical skills	Specific technical training	MATLAB										
		Basics of metrology	UNI									
		COFFMET dimploma in metrology	CERN									
		CMM fundamentals QINDOS	IND									
		Advanced course in FSI, CERN										
		C++										
		Indico for beginners-Meeeting organization										
		Optics laboratory										
		Industrial metrology and Machine vision										
		Physical Geodesy and Geodynamics										
		Project parameter estimation										
		ALTIUM										
		Drupal										
		School "Italo Gorno"										
		Precision engineering	UNI									
		ANSYS										
		CATIA smarteam										
		Geometrical dimensioning and tolerancing										
		Engineering optimization										
		Mechatronic system design										
		Microwave measurements										CERN
		Labview developer										CERN
		RF& Communications Algorithm Engineering										IND
		HFSS										CERN
		CST Particle studio										CERN
		Solid works (CADfor indutrial parts)										
		Design technologies for embedded MPSoC										
		LaTeX										UNI

Project Structure:

4. *Outreach & Dissemination*

Organized at CERN

39 contributions.
More than 50 participants

http://indico.cern.ch/event/332431/contributions/

Project Structure:

4. *Outreach & Dissemination*

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

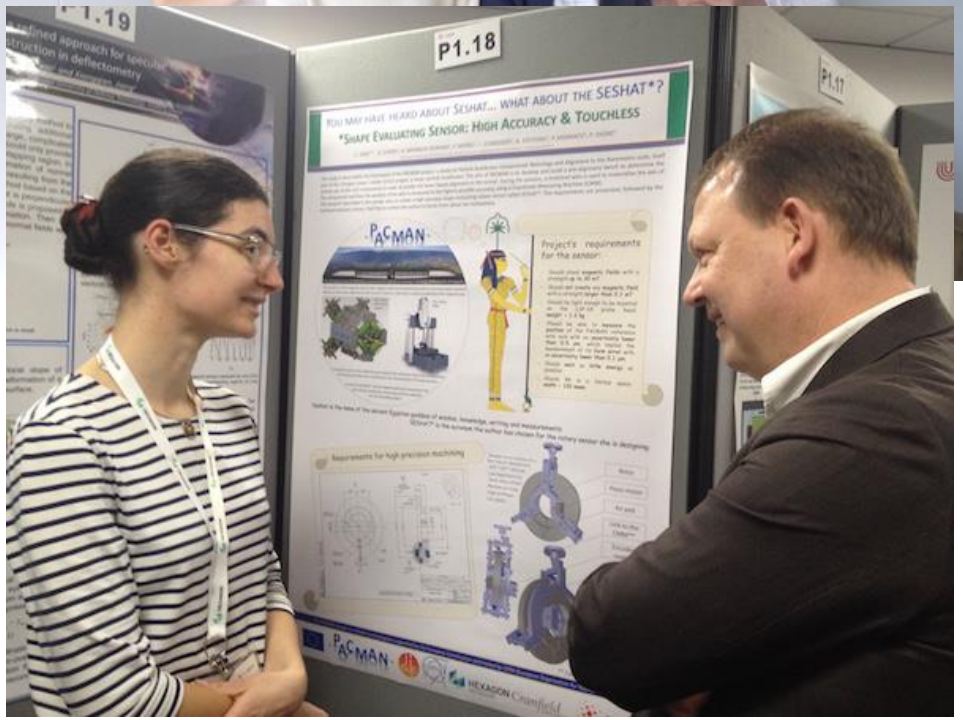
38 contributions.
More than 50 participants

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

Project Structure:

4. *Outreach & Dissemination*

Outreach with Schools of Geneva area ("Promotion of women in Science" is one of the O&D subjects)



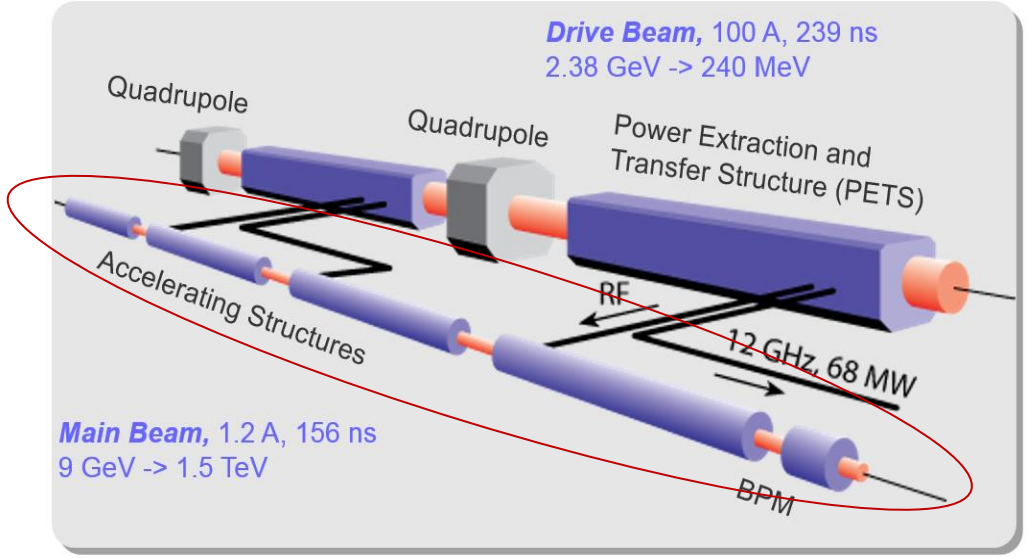
Dissemination at European Society of Precision Engineering (EUSPEN) event in UK

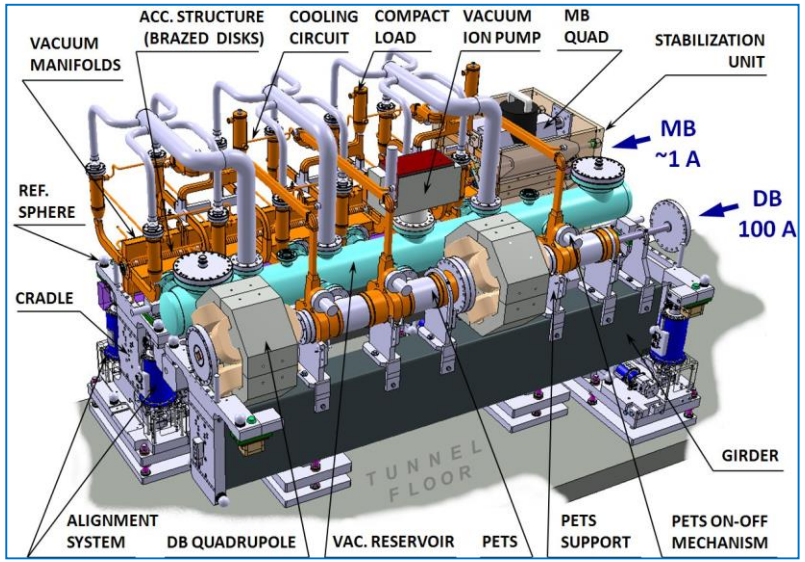
With Italian Prime Minister Matteo Renzi at Fermilab

The objectives of PACMAN

(1) introduction to CLIC project

Alignment challenges for CLIC, the Compact Linear Collider project *(R&D)*, chosen as study case for PACMAN





For CLIC 3 TeV layout : would be required more than 20 000 modules ! , 2m length

The objectives of PACMAN

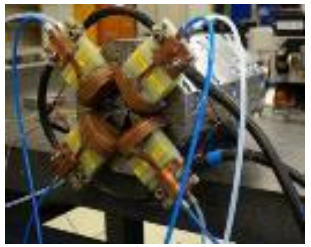
(2) State of the art

Mechanical pre-alignment:

~ 0.2-0.3 mm over 200 m

Active pre-alignment:

14-17 μm over 200 m



	BPM	Quad	AS
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

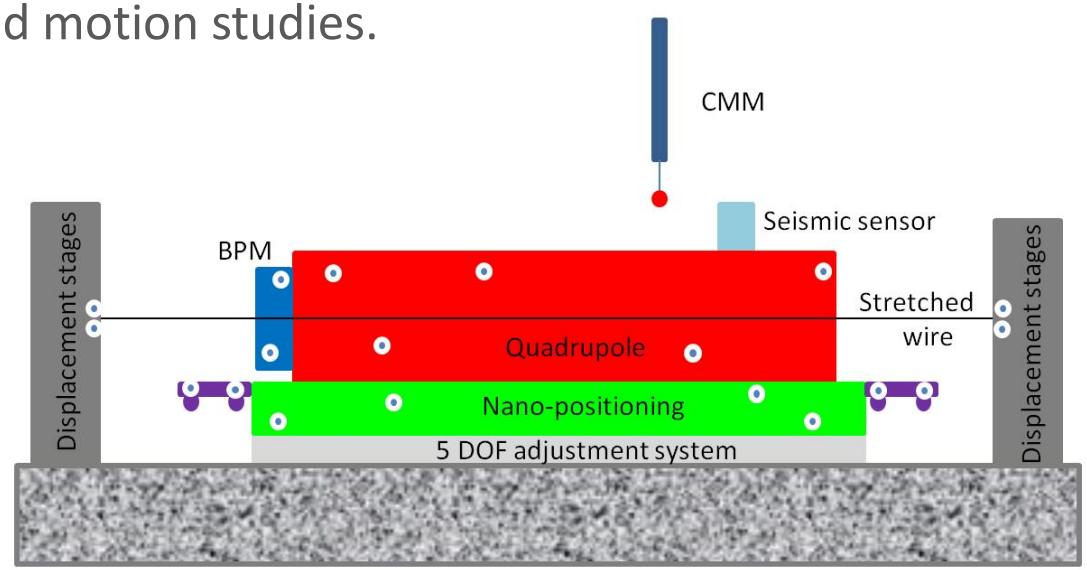
Combine measurements, & fiducialization in the same place to gain time & accuracy

Demostrate the feasibility on a Final PACMAN bench

Possible estrapolation 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



WP1: Metrology

Introduction

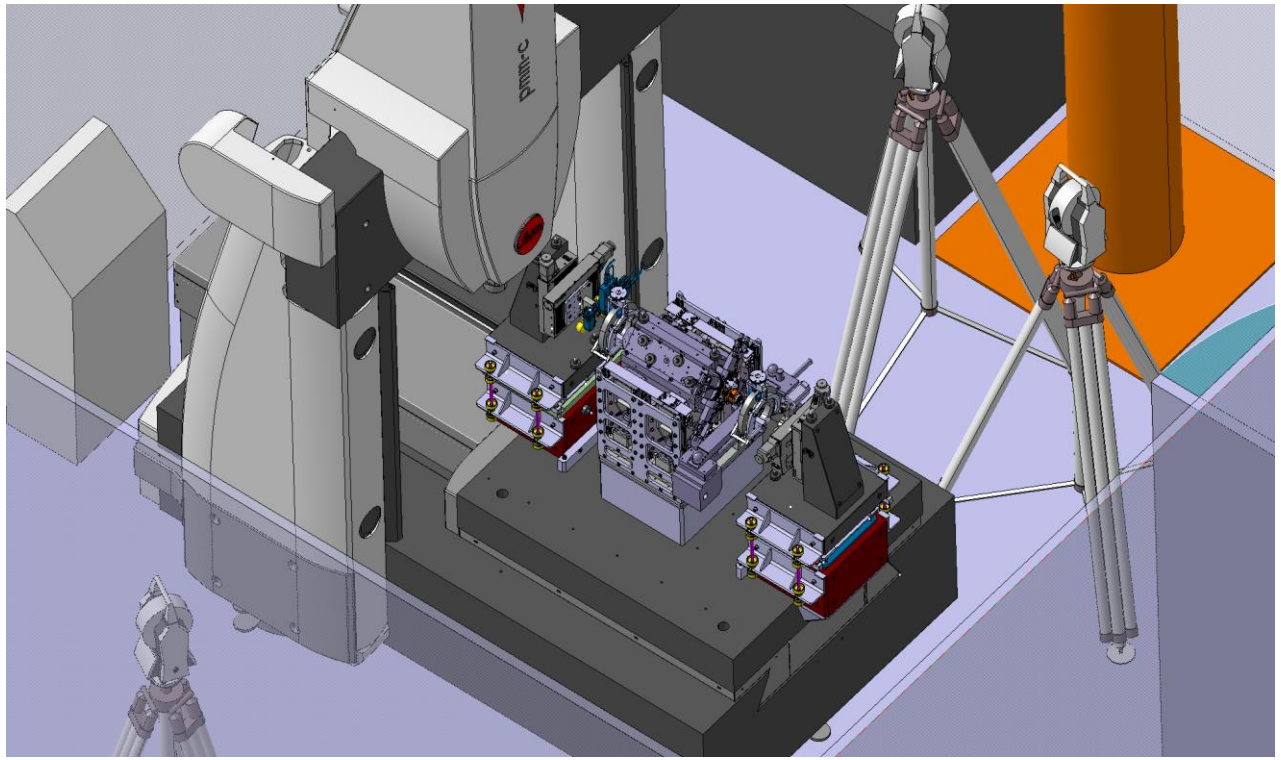
It include the activities of 3 ESR (Early Stage Researcher):

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

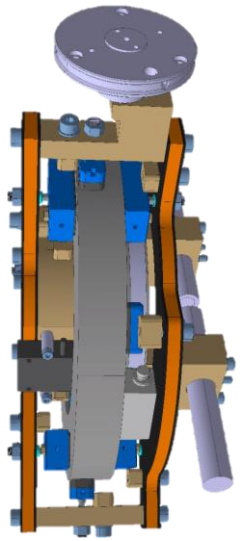


WP1

"Non contact high precision sensor for Leitz Infinity CMM"

ESR1.1 Claude Sanz

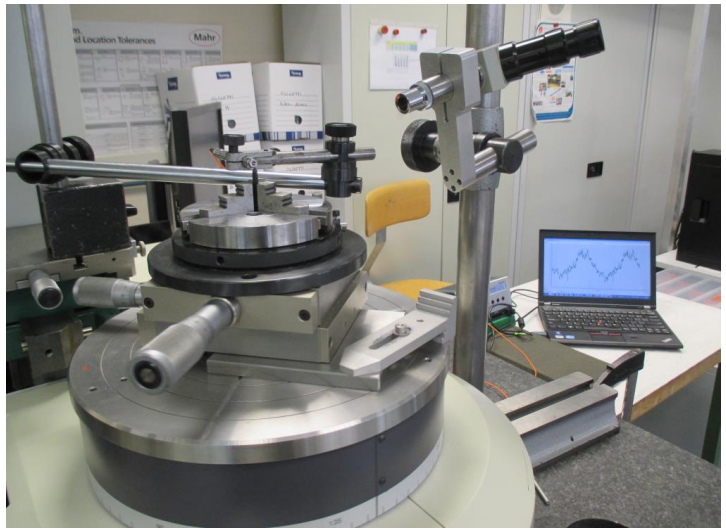
Design of a high precision, touchless and rotary sensor:

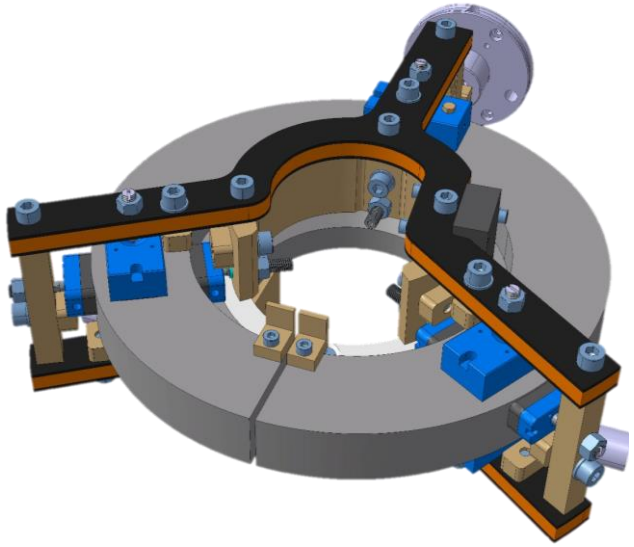


Requirements:

- *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*

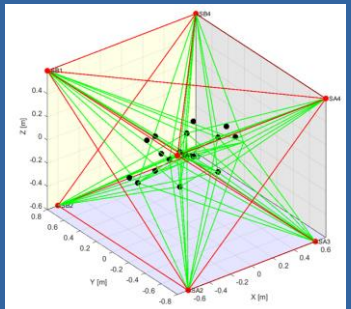
:



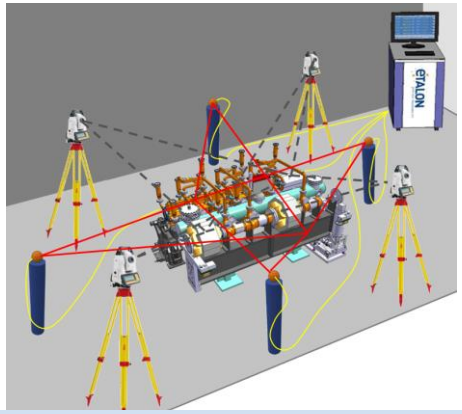


WP1
"Development and validation of an absolute Frequency Scanning Interferometry (FSI) network"

ESR1.2 Solomon Kamugasa



- Development of high refractive index glass retroreflectors
- Development of a reference sphere and its kinematic mount
- Simulations of the best configuration for the FPB (Final PACMAN Bench)



- *8 FSI stations in total*
- *4 FSI stations on each side*
- *17 fiducials in total*
- *3 fiducials can be seen by all 8 stations*
- *7 fiducials per side seen by 4 stations*
- *96 observations in total*

Advantages:

- *Totally free network*
- *5 microns "a priori" standard deviation*
- *Solved with LGC++ (Least Squares method)*
- *1000 simulations*
- *Based on Monte Carlo Method*

WP1

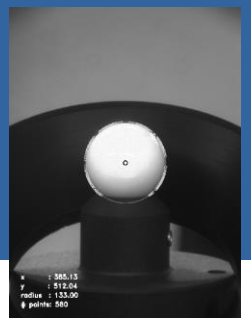
"Micro-triangulation for high accuracy short range measurements of dynamic objects"

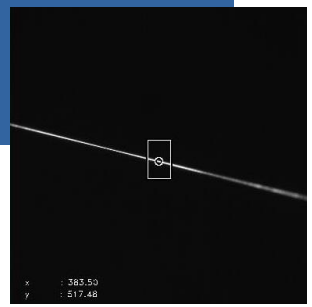
ESR1.3 Vasileios Vlachakis

- 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 alghoritm:
- 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





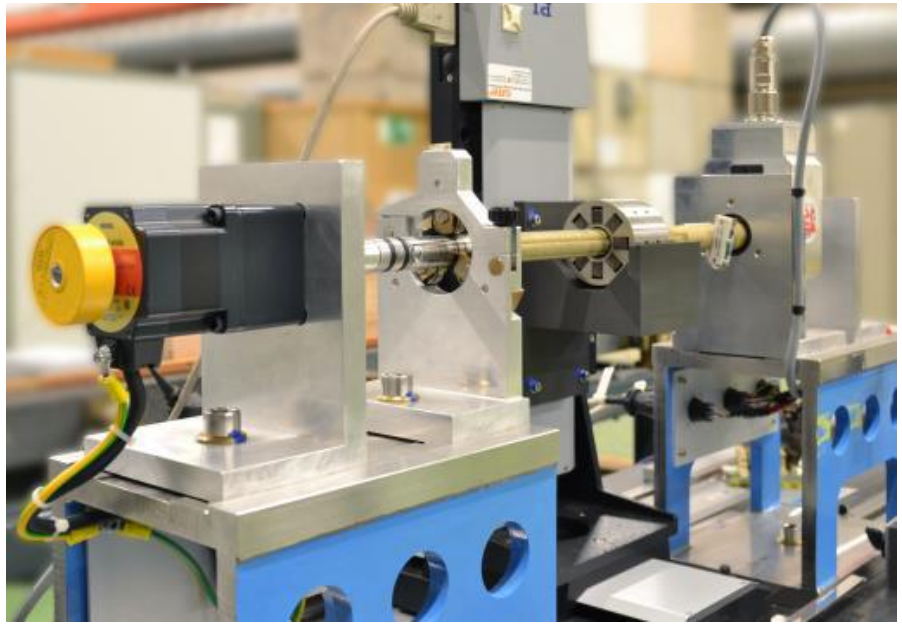
Reconstruction alghoritm:
- Based on least square adjustment analysis
- Main difficulties: targets and wire measured in a unique coordinate system, modeling of the wire, weighting the observations
- Status: algorithms developed in Matlab

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.

WP2

Stretch-wire Magnetic Measurements

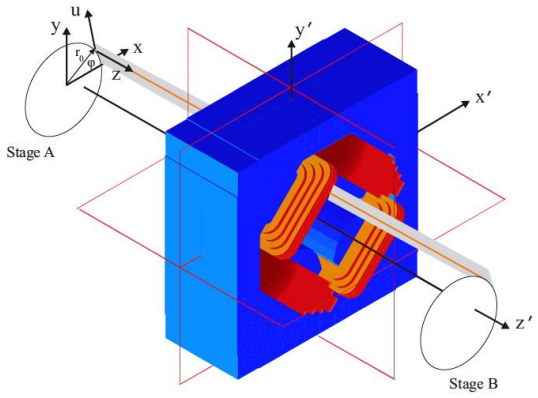
ESR2.1 Domenico Caiazza

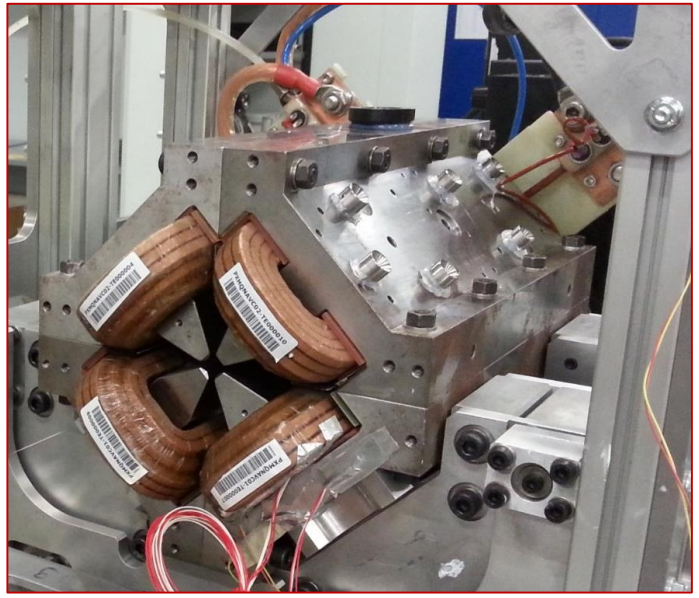
- Analysis of the metrological performance varying the measurement configuration for the vibrating-wire method

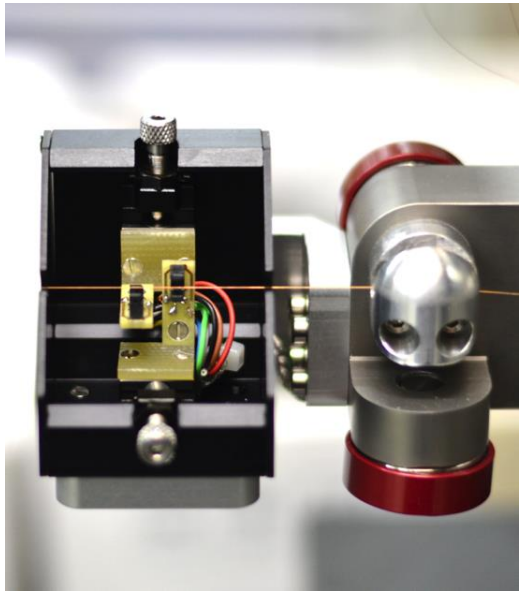
Advances: Metrological characterization of phototransistors, CCD sensors, and optical fiber sensors for measuring the peak-to-peak oscillation amplitude

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

Advances: Correction of background field (Earth magnetic field, tensioning motor etc.)





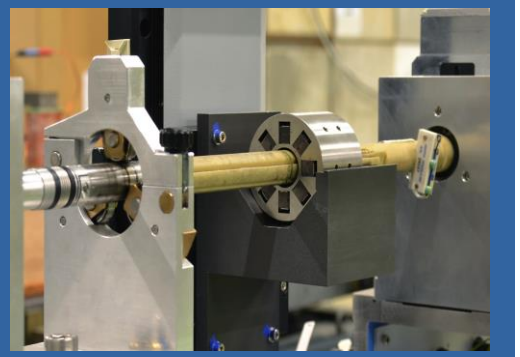


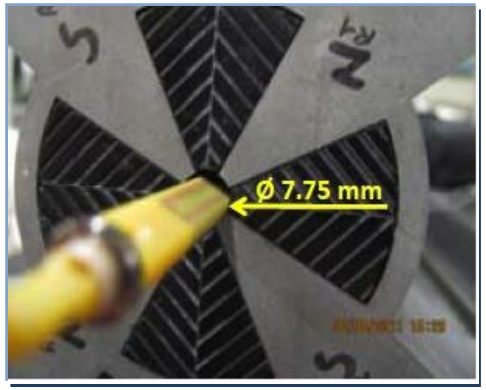
Advancement and innovation in miniature PCB rotating coils for Magnetic Measurements

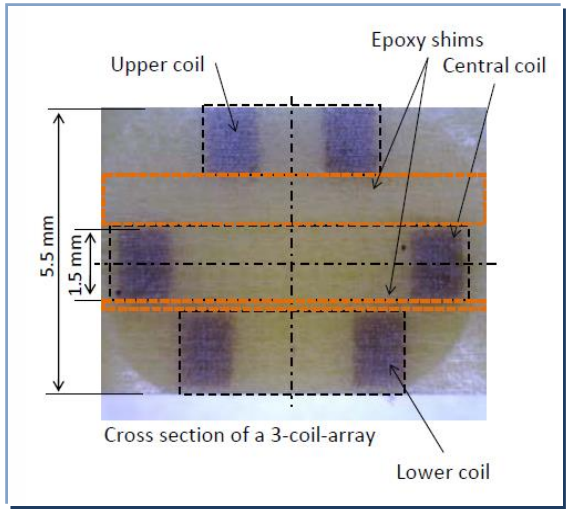
WP2

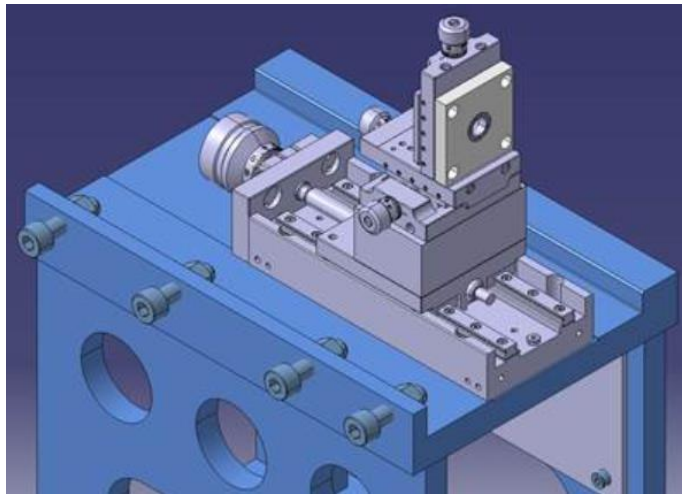
Miniature Rotating Coils for MM

ESR2.2 Giordana Severino









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

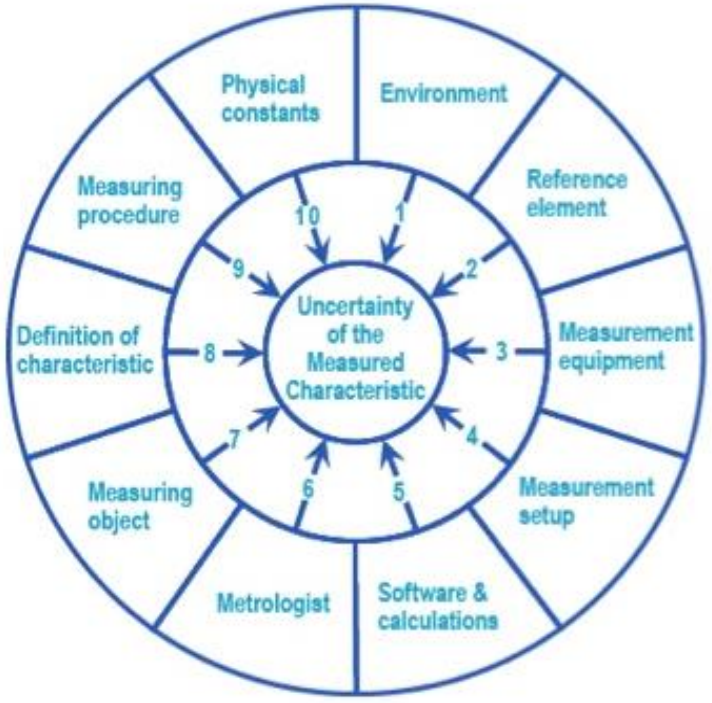
Advances: In situ coil calibration in the presence of sextupole components

WP3: Precision Mechanics

Introduction

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.



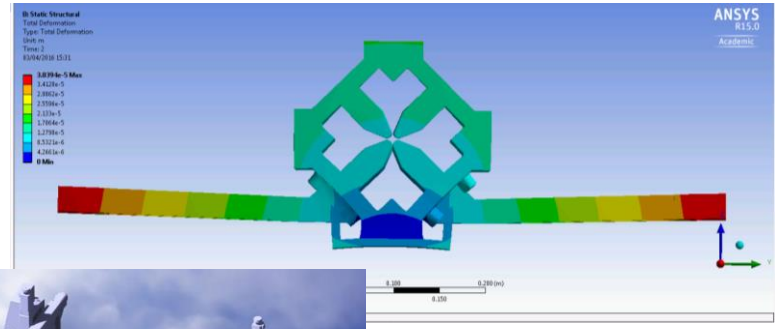
Evaluation and possible mitigation of the uncertainty global budget of the FPB

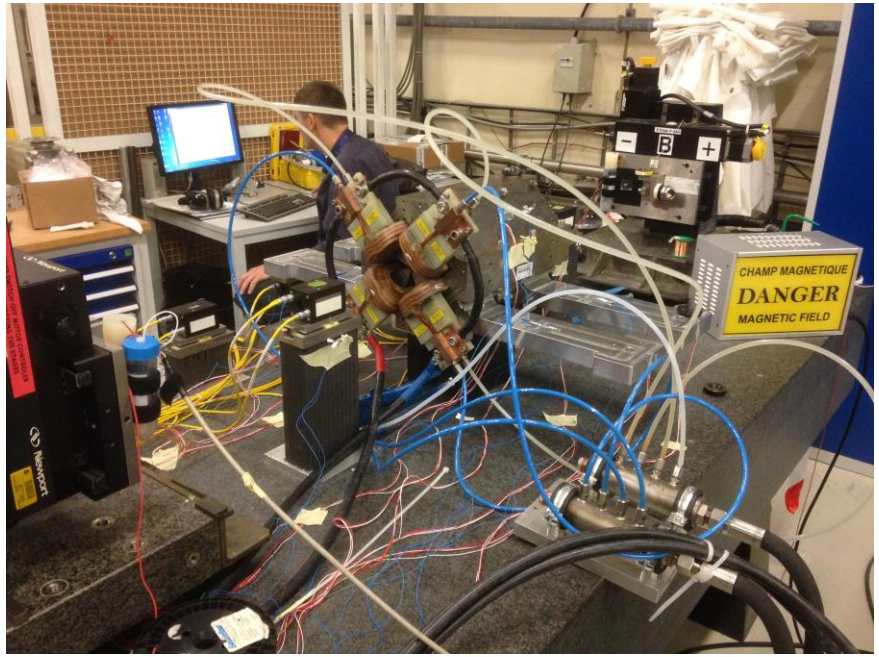
WP3

PACMAN bench Uncertainty Budget and propagation

ESR3.1 Iordan Doytchinov

- The main task is to provide a PACMAN Uncertainty Budget estimation according to **GUM** (**G**uide to the Expression of **U**ncertainty in **M**easurement by **BIPM,** the **B**ureau **I**nternational des **P**oids et **M**esures) 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





WP3

Development of Vibration Sensors

ESR3.2 Peter Novotny

Which vibration sensor for PACMAN?

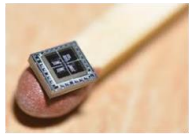
Bandwidth = 0.1 ~ 200 Hz
Resolution ≤ 0.1nm (RMS@1Hz)
Magnetic fields resistance

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

Seismometers
× Bandwidth
✓ Resolution

PZT Accelerometers
✓ Bandwidth
× Resolution

Geophones
× Bandwidth
× Resolution

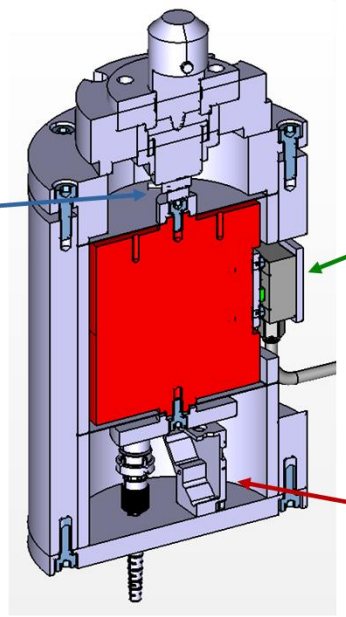


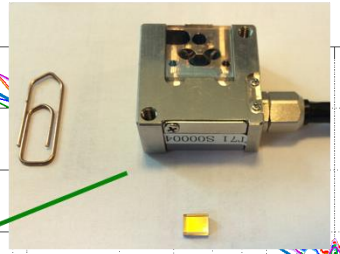
MEMS accelerometers
✓ Bandwidth
× Resolution

Force Balanced optical accelerometers
✓ Bandwidth
≈ Resolution

→ Proposed a NEW trasducer (3in1); the direct comparison should avoid data ambiguity

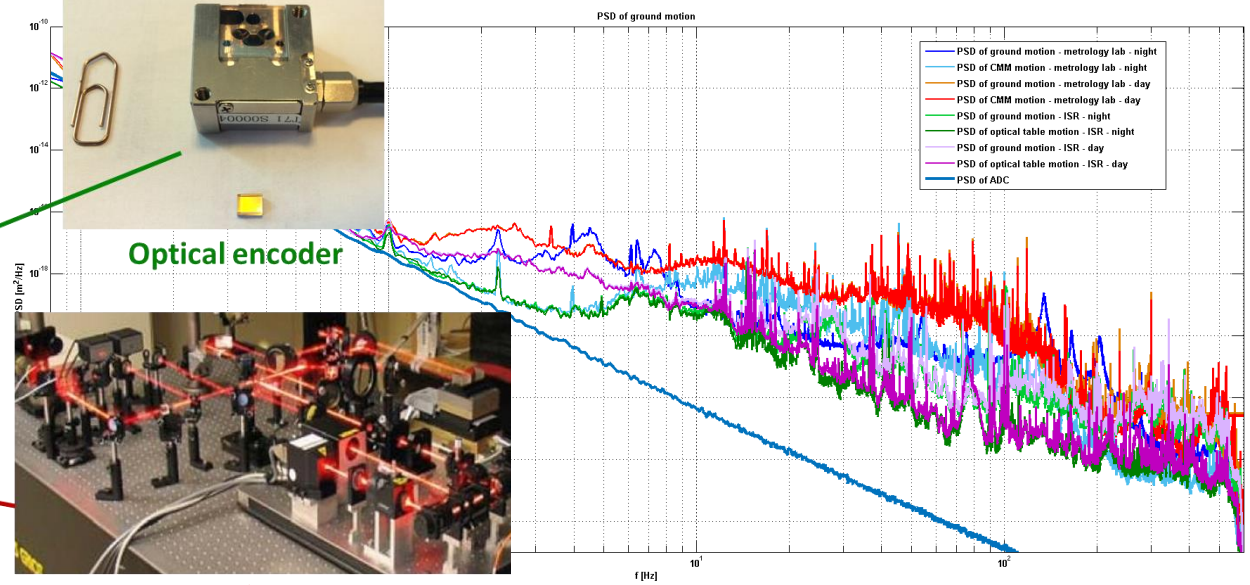
Capacitive sensor





Optical encoder

Interferometer



WP3

Development of nano-positioning system for components alignment

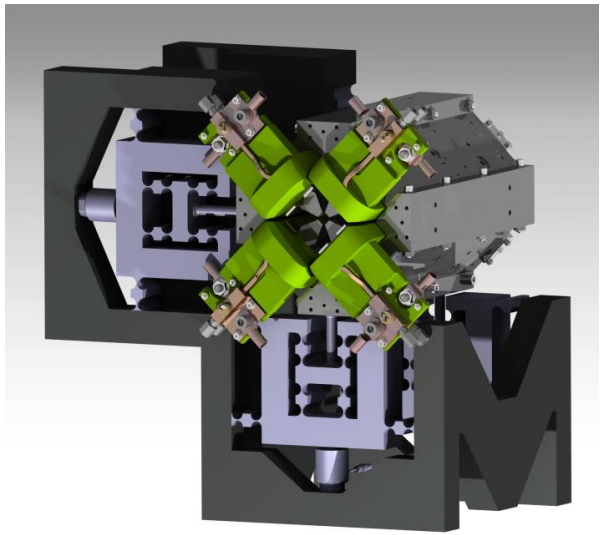
ESR3.3 David Tshilumba

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)*

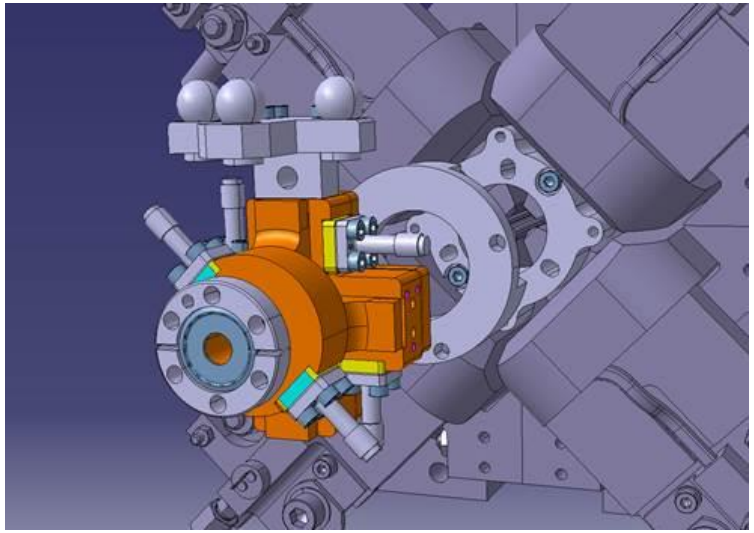


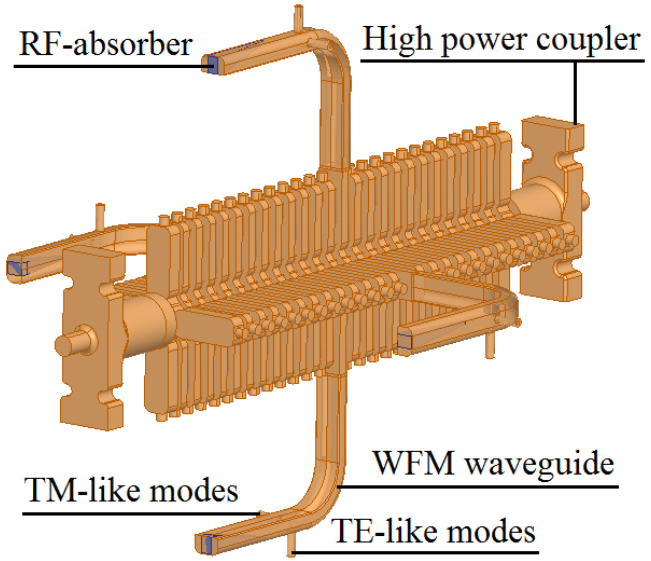
WP4: RF Instrumentation and Technologies

Introduction

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

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)

WP4

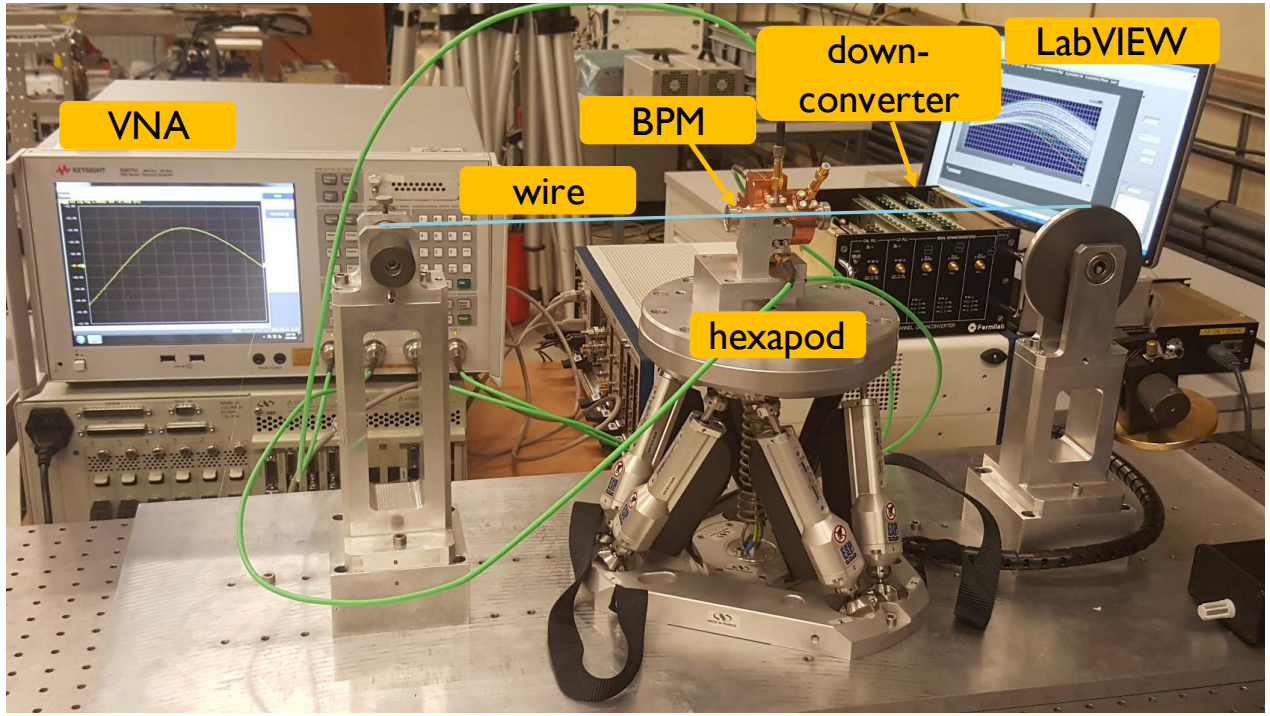
"Alignment and resolution of the Beam Position Monitor operating at microwave frequencies in the nanometre regime"

ESR 4.1 Silvia Zorzetti

***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

Pertubation 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.



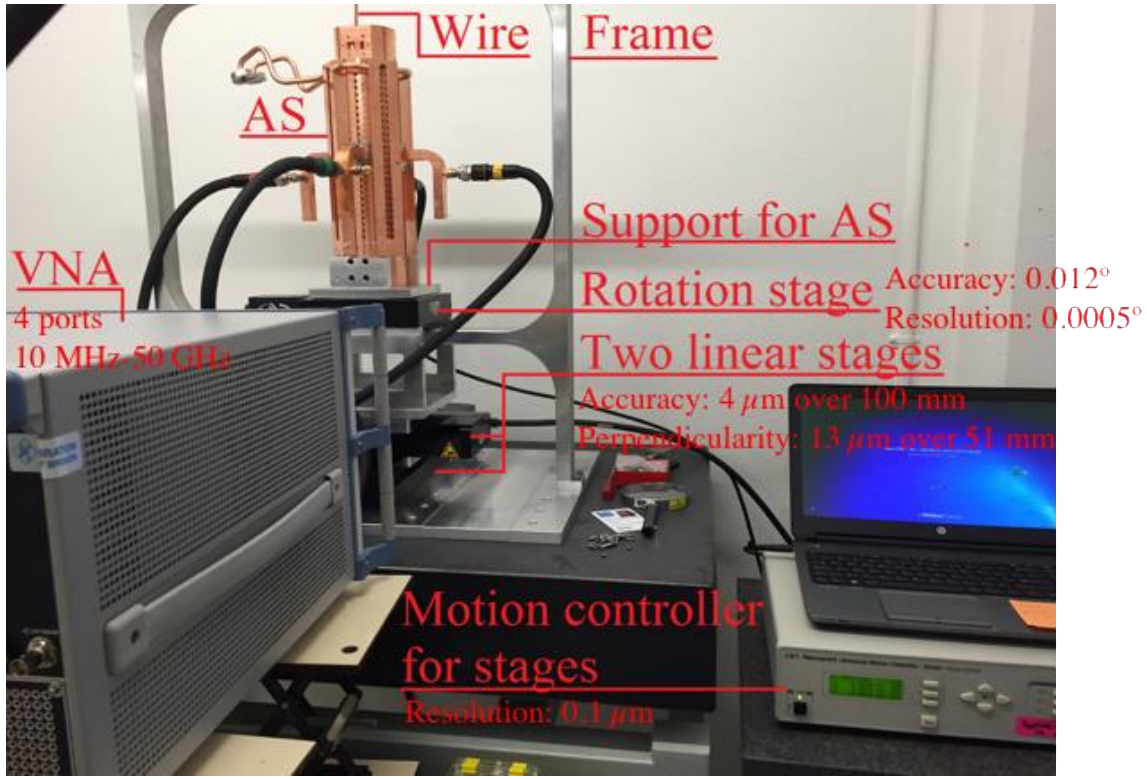
WP4

"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



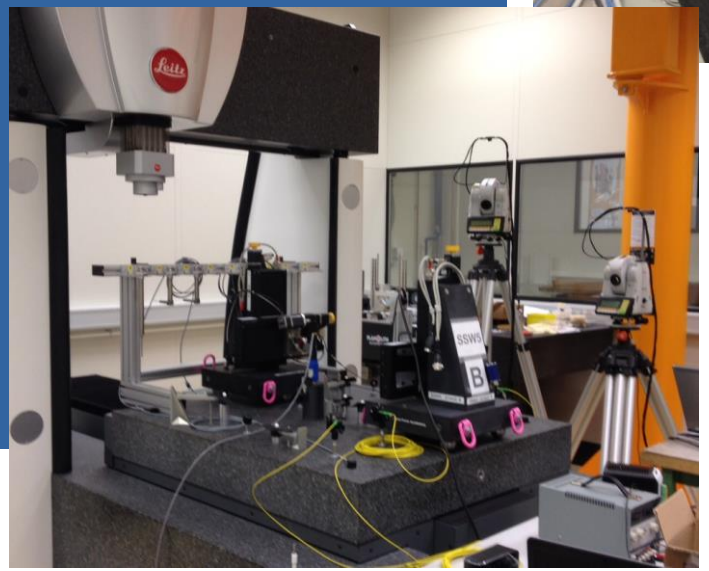
Status of the systems development, integration and first results

- 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).

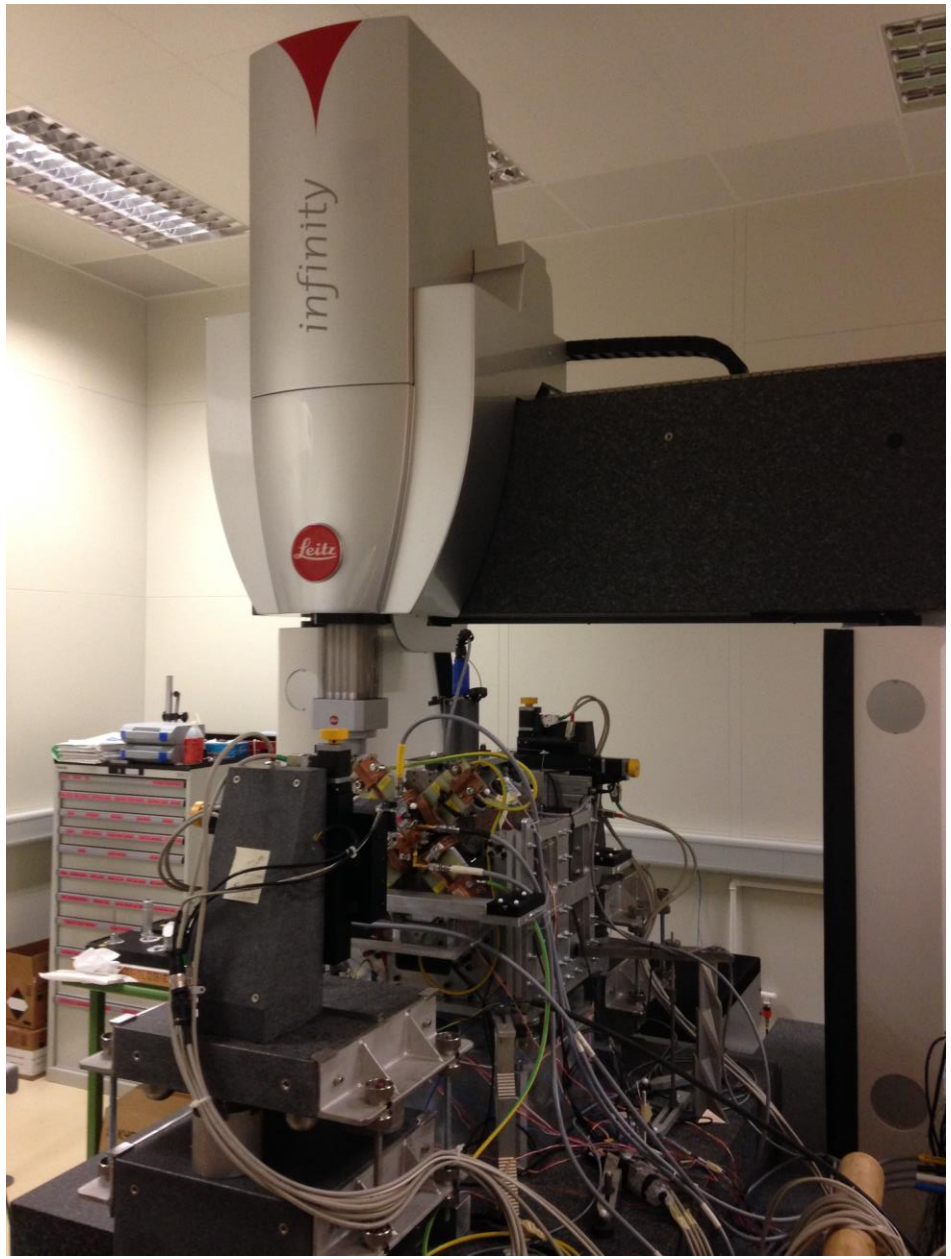
- Several steps are planned towards this target:

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)* ***t.b.d***

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

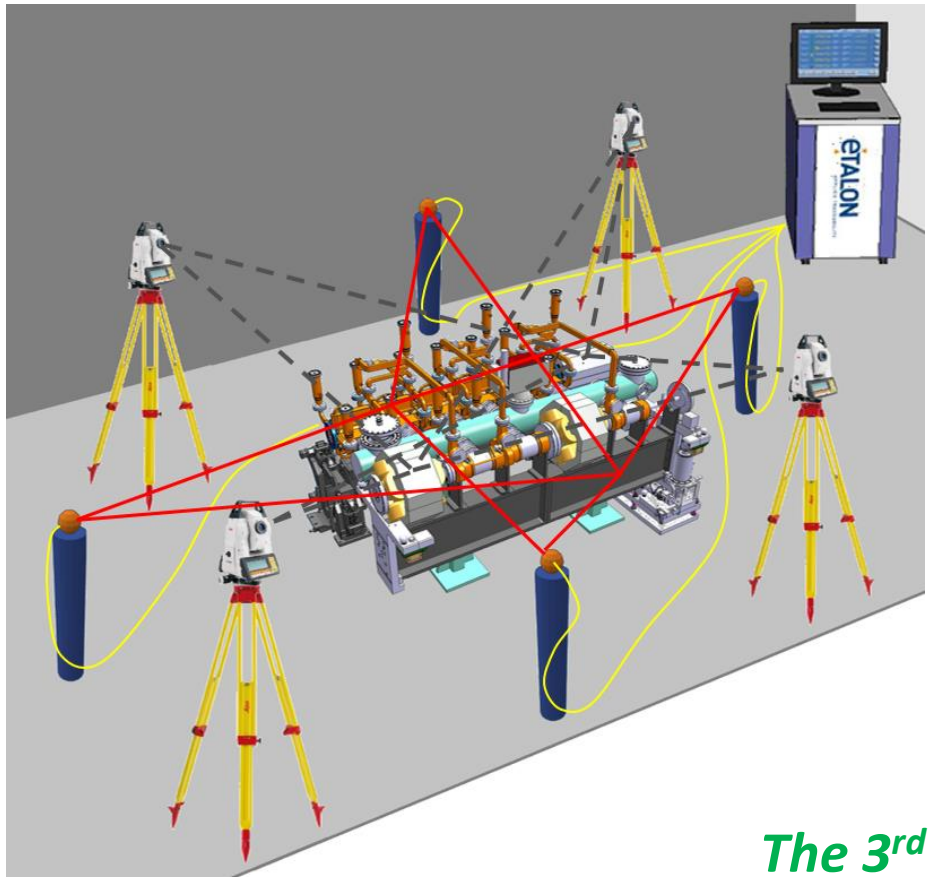


Phase D): 1st measurements of PACMAN bench at the CMM (July16): Results under analysis. Detailed plan for next measuring phase under preparation.

Another final objective of PACMAN :

Potential application to other cases & projects

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 March2017 at CERN, will be the occasion were results from all the PACMAN research domains and potential future applications will be presented and discussed.*

Summary

- 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:

1. *C. Sanz et al., "New potential for the Leitz Infinity coordinate Measuring Machine", EUSPEN 15th International conference and Exhibition, Leuven, Belgium, June 2015*
2. *C. Sanz et al., "Characterization and measurement to the sub-micron scale of a reference wire position", 17ème Congrès International de Métrologie (CIM 2015), Paris, September 2015.*
3. *C. Sanz et al., "Rotating sensor for new possibilities on Leitz Infinity Coordinate Measuring Machine", EUSPEN 2016, Nottingham, UK, May 2016*
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)*
5. *S.W. Kamugasa, V. Vlachakis, "PACMAN study of FSI and micro-triangulation for the pre-alignment of CLIC", International Workshop on Accelerator Alignment 2014, Beijing, China, October 2014.*

6. S.W. Kamugasa, "Development of an absolute FSI network for CLIC component micrometric pre-alignment", European Portable Metrology Conference, EPMC 2015, Manchester, UK, November 2015

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)

10. D. Caiazza et al., "Challenges in measuring the longitudinal field profile of a magnet by a vibrating wire", 20th IMEKO TC4 International Symposium, Benevento, Italy, September 2014

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

13. D. Caiazza et al., "Uncertainty analysis of a vibrating-wire system for magnetic axes localization", 9th International Conference on Sensing Technology, Auckland, New-Zealand, December 2015

14. G. Severino et al., "Calibrating the sensing-coil radius feed/down from a harmonic reference", IMEKO 2014, Benevento, Italy, September 2014

15. S. Sanfilippo et al., "Small-diameter rotating coils for field quality measurements in quadrupole magnets", IMEKO 2014, Benevento, Italy, September 2014

16. G. Severino et al., "Rotating-coil calibration in a reference quadrupole considering roll-angle misalignment and higher-order harmonics", Measurement Journal, vol. 87, 74-82, March 2016

17. G. Severino et al., "Performance analysis of miniaturized PCB coils for small-aperture magnet qualification", IEEE Sensors conference 2015, Busan, South Corea, November 2015

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)

20. S. Zorzetti et al., "CLIC BPM quadrupole pre-alignment in the frame of the PACMAN Marie Curie action", 20th IMEKO TC4 International Symposium, Benevento, Italy, September 2014.

21. S. Zorzetti et al., "Design of the 15 GHz BPM test bench for the CLIC test facility to perform precise stretched-wire RF measurements", July 2015, IOP Science, Measurement science & technology, Volume 26, number 9

22. S. Zorzetti et al., "Stretched-wire techniques and measurements for the alignment of a 15 GHz RF-BPM for CLIC", International Beam Instrumentation Conference IBIC 2015, Melbourne, Australia, September 2015.

23. S. Zorzetti et al., "An innovative methodology to directly analyze the nanometric resolution of an RF cavity BPM", IBIC 2016, Barcelona, Spain, September 2016.

24. N. Galindo Munoz et al., "Electromagnetic field alignment of the Compact Linear Collider (CLIC) accelerating structure with help of wakefield monitor signals", International Beam Instrumentation Conference IBIC 2015, Melbourne, Australia, September 2015.

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
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- Paul Morantz (Cranfield Univ.)
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- Pasquale Arpaia (Univ. of Sannio
- Laurent Brunetti (LAPP)
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- Marie-Julie Leray (Sigmaphi)
- Pascal Lequerre (Eltos)
- Alicia Gomez (DMP)
- Teun van den Dool (TNO)
- Joe Woodford (NI)
- Jacques Tinembart (Metrolab)

The CERN supervisors:

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CERN support:

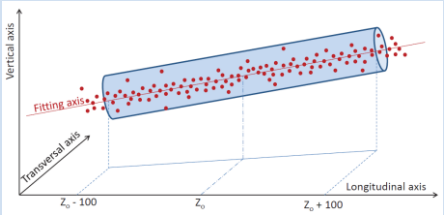
- Seamus Hegarty, Charlyne Rabe, Karen Ernst, Gregory Cavallo, Nicolas Friedli, François Nicolas Morel

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

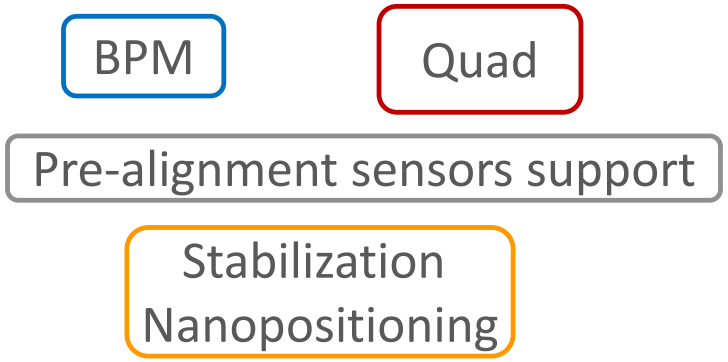
Beam based Alignment & Beam based feedbacks

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

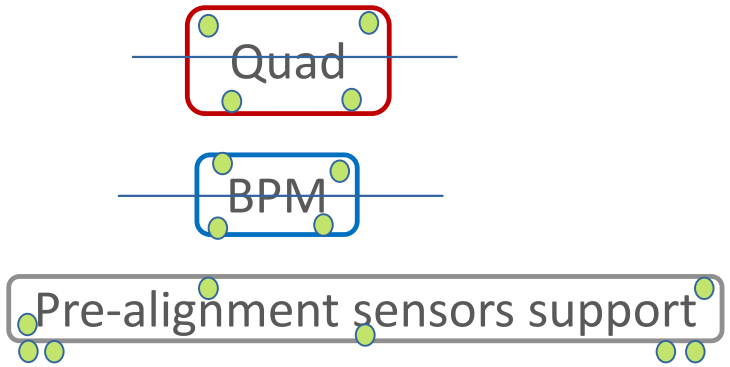
→ **Minimization of the emittance growth**

The objectives of PACMAN

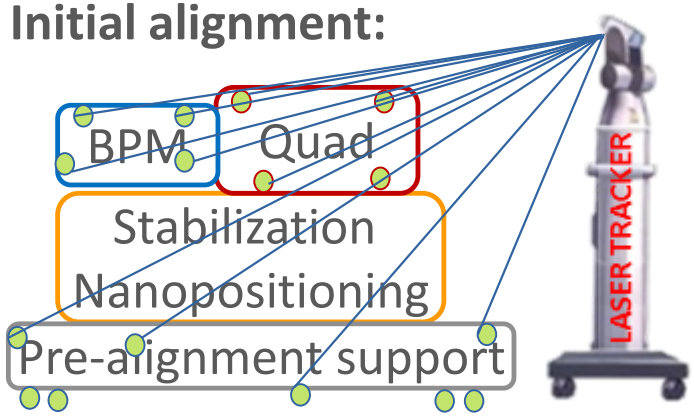
(3) Example: case of MB quad + BPM



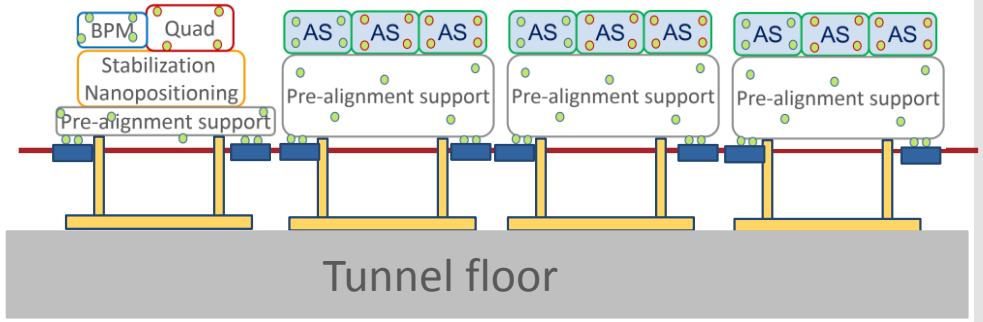
Fiducialisation:



Initial alignment:



Transfer in tunnel & alignment



WP1: Metrology

Introduction

It include the activities of 3 ESR (Early Stage Researcher):

Objective of WP1: develop 3 methods to <u>determine with the highest precision the position of the stretched wire w.r.t. fiducials</u>:

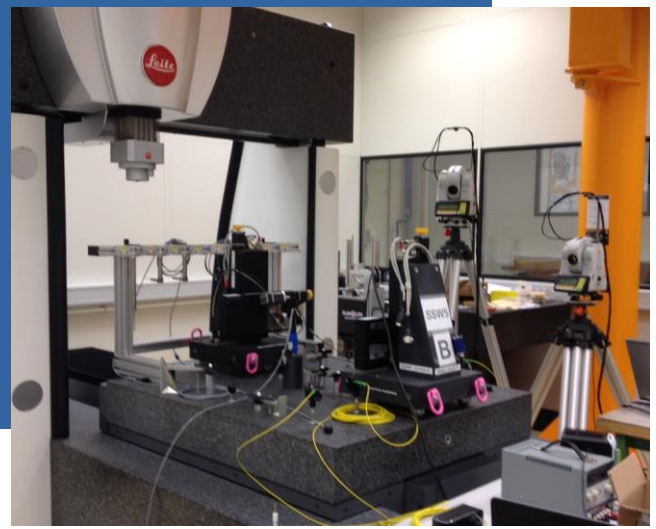
ESR 1.1: A high accuracy & touchless sensor on the CMM measuring head

ESR 1.2: Frequency Scanning Interferometry (FSI)

ESR 1.3: Micro-triangulation

CuBe wire characteristics	Nominal values
Electrical resistivity [μΩ/cm²/cm]	5.4 – 11.5
Limit tension [Kg]	0.5 – 1.3
Micro-hardness [Vickers]	100-362
Linear mass [mg/m]	64.80
Diameter [μm]	100
Form error circularity [μm]	> 0.5
Roughness [nm]	10-20

Status of the systems development, integration and first results



Magnetic axis determination for different magnet currents

Current (A)	X_c (µm)	Y_c (µm)	ϕ_c (µrad)	θ_c (µrad)
126	0	0	0	0
4	2.9	3.1	-2.3	-5.1

After correction of background effects

Repeatability of the determination

Current (A)	σ_x (µm)	σ_y (µm)	σ_ϕ (µrad)	σ_θ (µrad)
140	± 0.07	± 0.09	± 0.3	± 0.5
4	± 0.03	± 0.17	± 0.5	± 0.3

Repeatability

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

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