PACMAN project:
a new solution for the high-accuracy alignment of accelerator components

Hélène MAINAUD DURAND

IPAC 16
09-13 May 2016

PACMAN project

Outline:

- The objectives of PACMAN
- PACMAN test bench
- First results

PACMAN = a study on Particle Accelerator Components' Metrology and Alignment to the Nanometre scale
It is an Innovative Doctoral Program, hosted by CERN, providing training to 10 Early Stage Researchers.

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

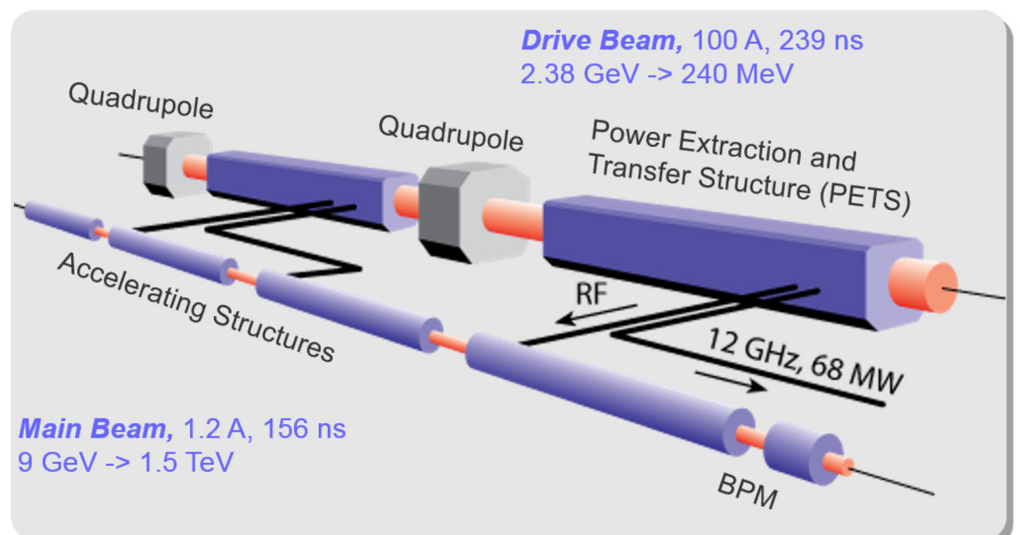
8 academic partners
8 industrial partners
Duration : 4 years
Start date: 1/09/2013

PACMAN NETWORK

CERN, CH
Cranfield University, UK
Delft University of Technology, NL
ETH Zürich, CH
IFIC,ES
LAPP, FR
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

The objectives of PACMAN

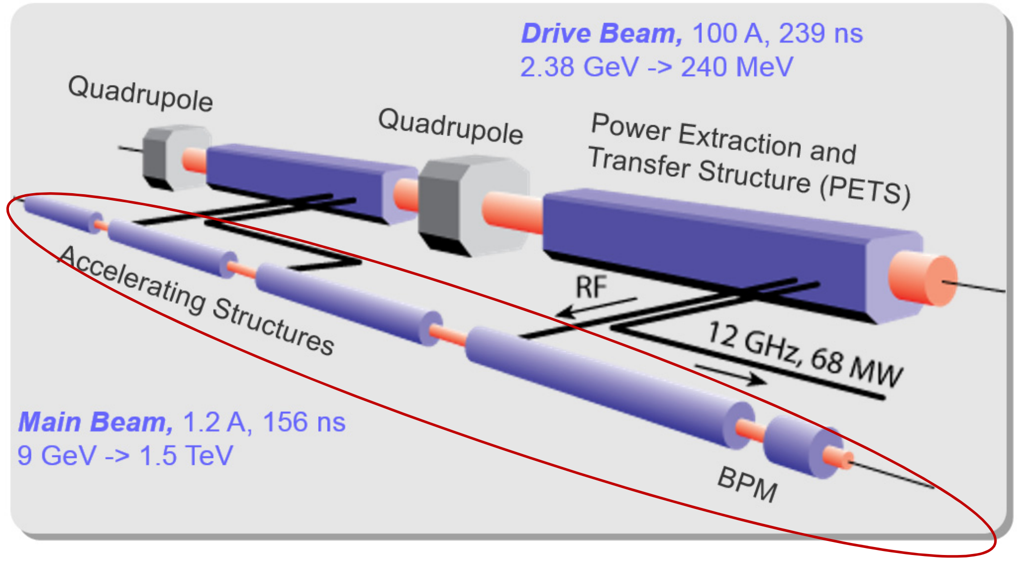
(1) introduction to CLIC project

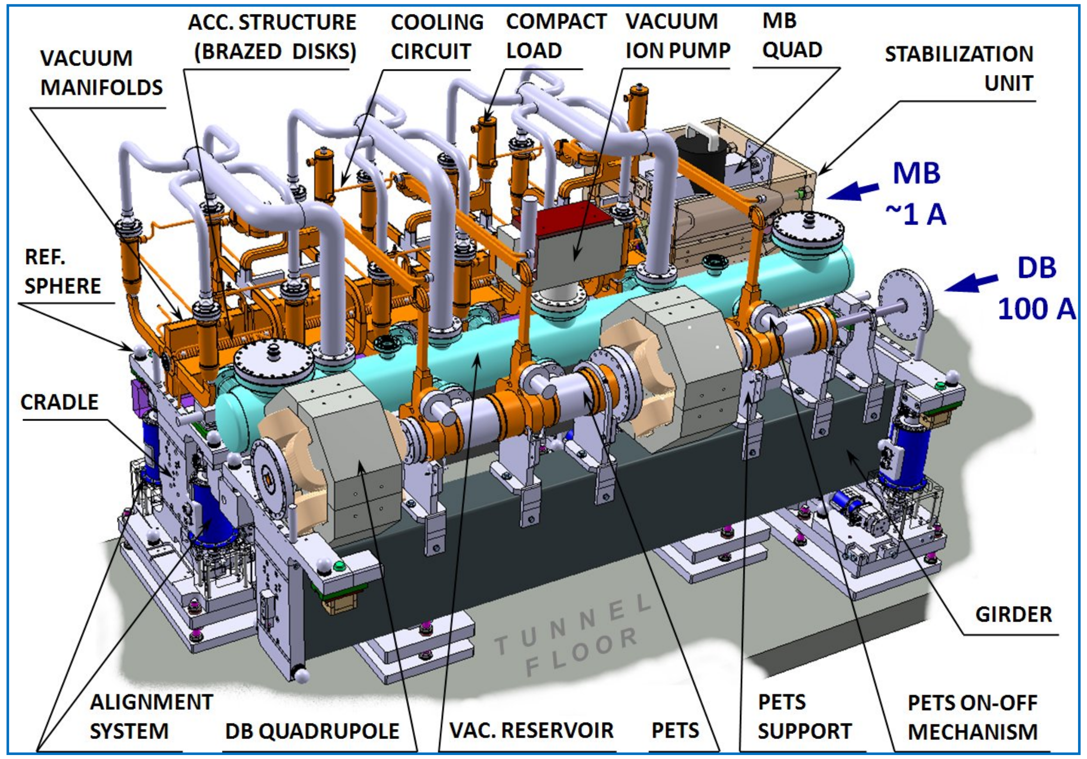


At 3 TeV: 20 000 modules, 2m length

The objectives of PACMAN

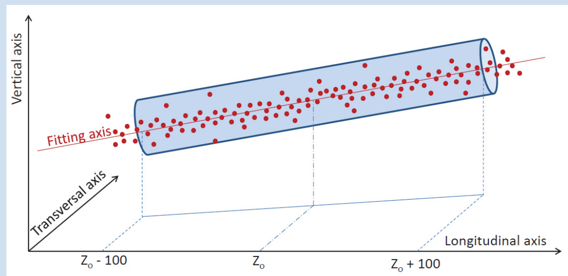
(1) introduction to CLIC project





At 3 TeV: 20 000 modules, 2m length

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

(2) State of the art

Components to be aligned:

	BPM	Quad	AS
Number of components	~ 4000	~ 4000	~ 140 000
Budget of error	14 µm	17 µm	17 µm

Strategy:

BPM Quad

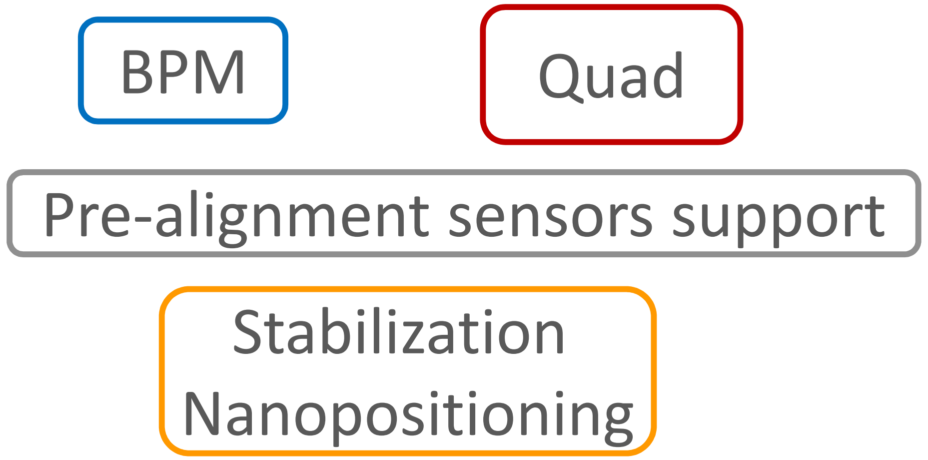
AS AS AS AS

3 steps:

- Fiducialisation of the components and their support
- Initial alignment of the components on their support
- Transfer in tunnel and alignment in tunnel

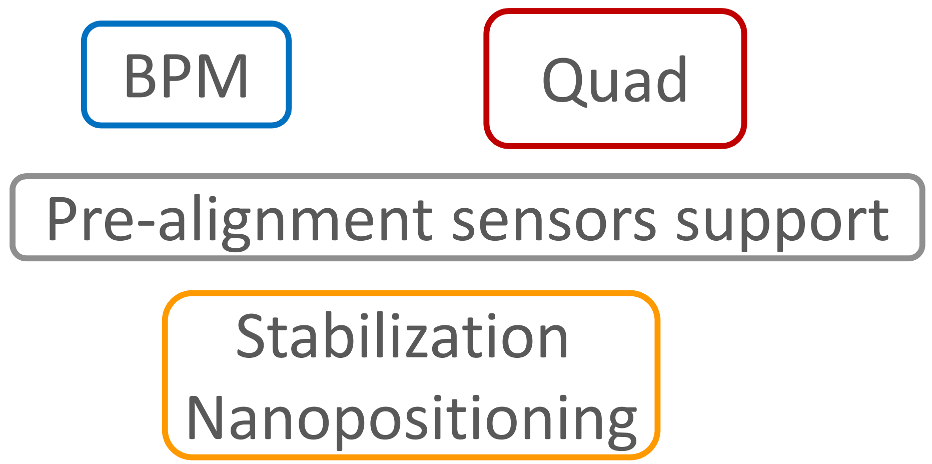
The objectives of PACMAN

(3) Example: case of MB quad + BPM

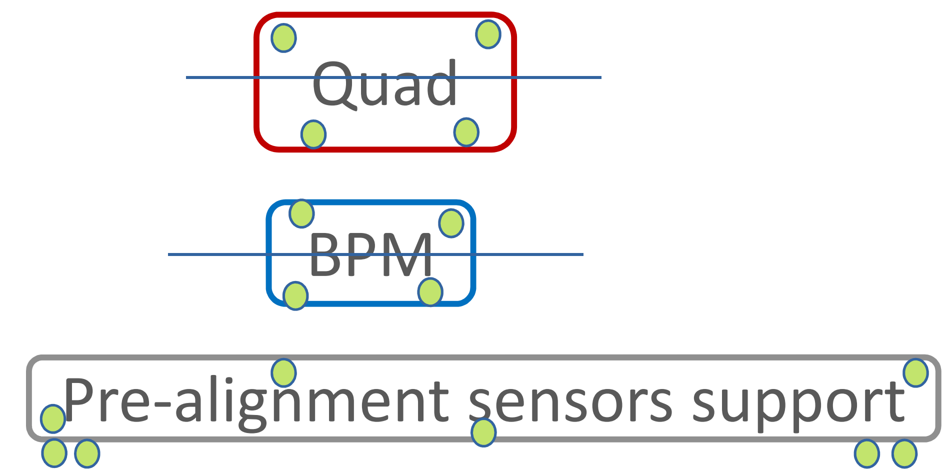


The objectives of PACMAN

(3) Example: case of MB quad + BPM

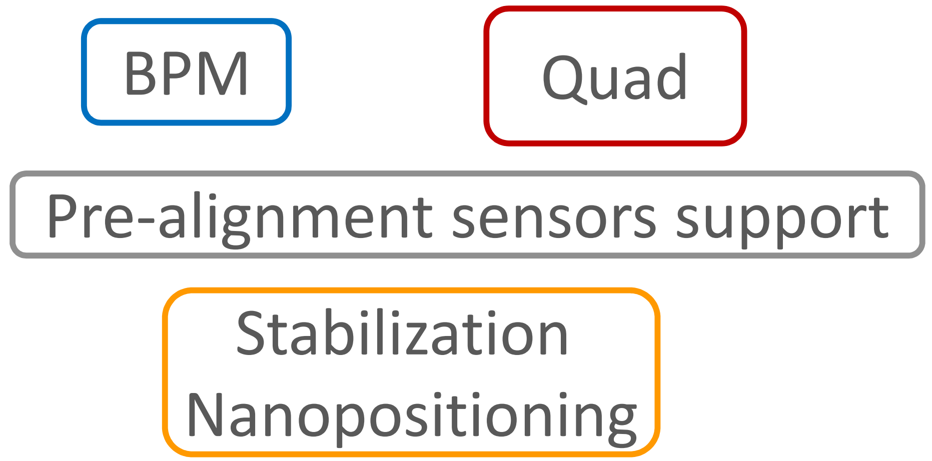


Fiducialisation:

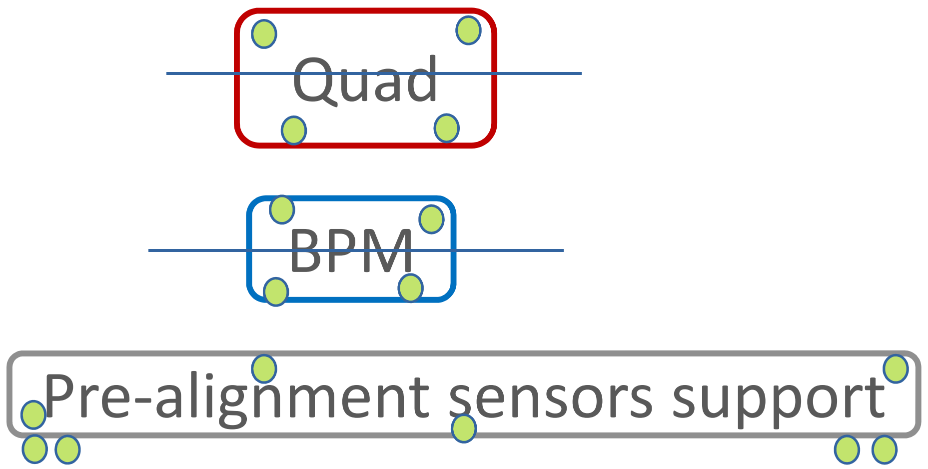


The objectives of PACMAN

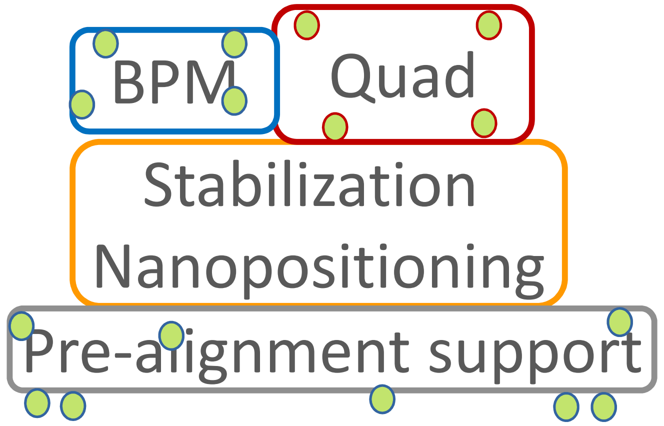
(3) Example: case of MB quad + BPM



Fiducialisation:

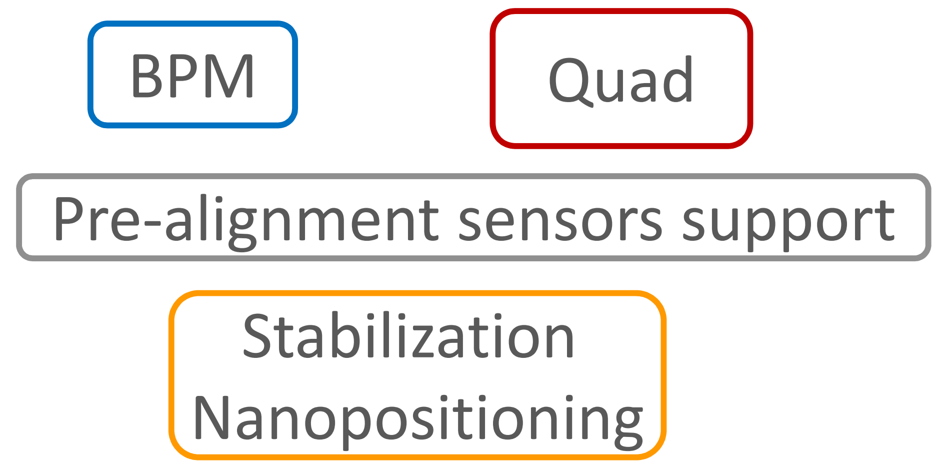


Initial alignment:

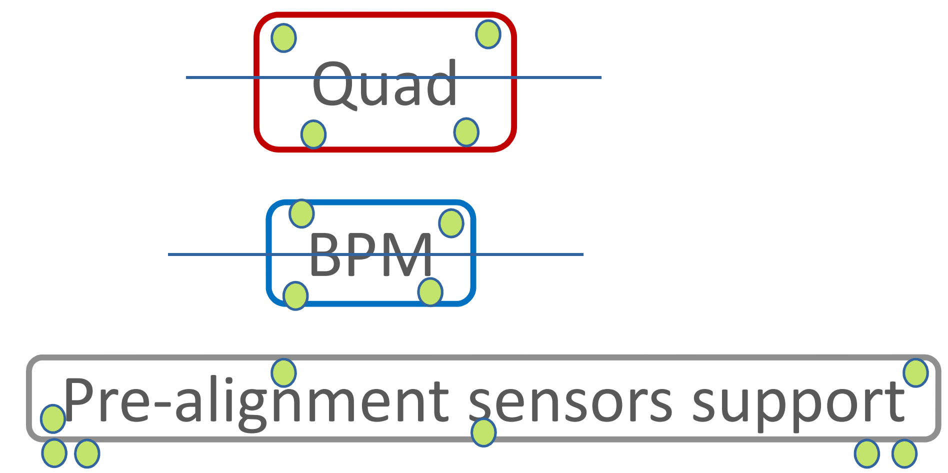


The objectives of PACMAN

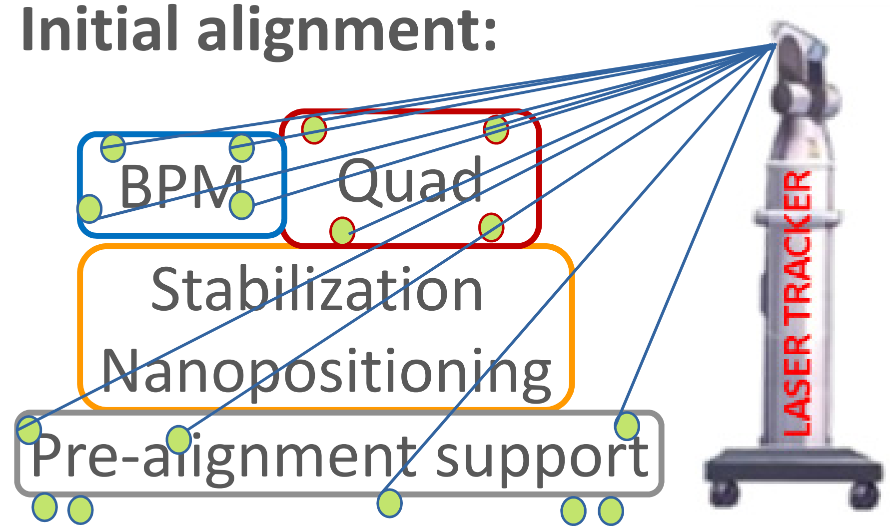
(3) Example: case of MB quad + BPM



Fiducialisation:

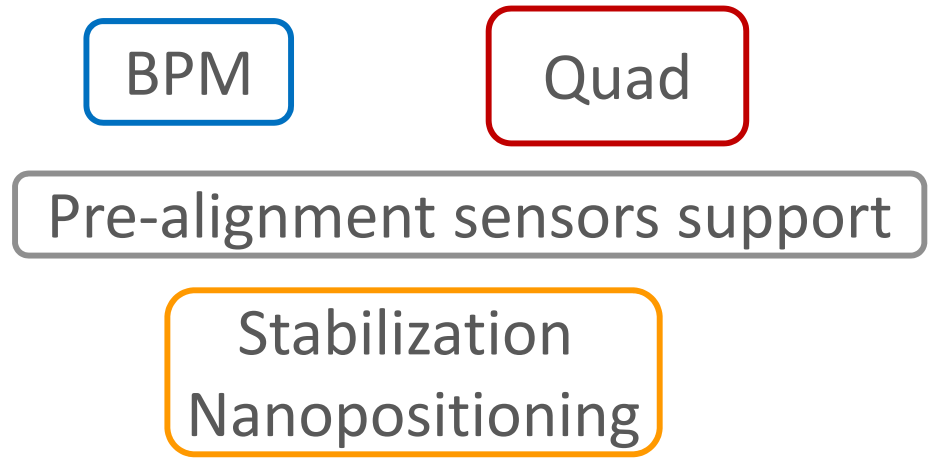


Initial alignment:

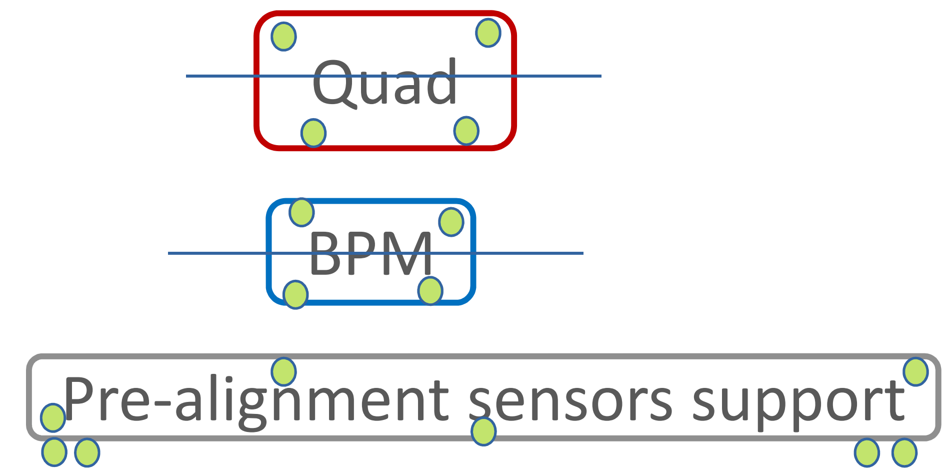


The objectives of PACMAN

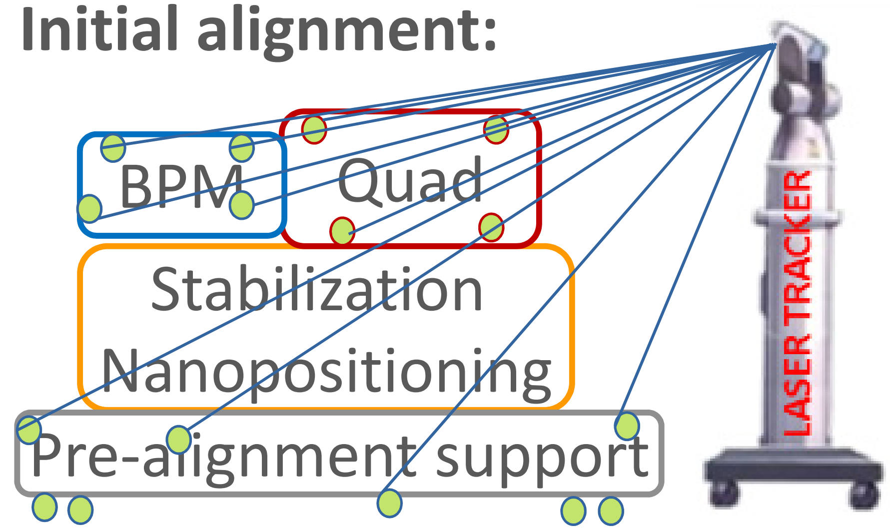
(3) Example: case of MB quad + BPM



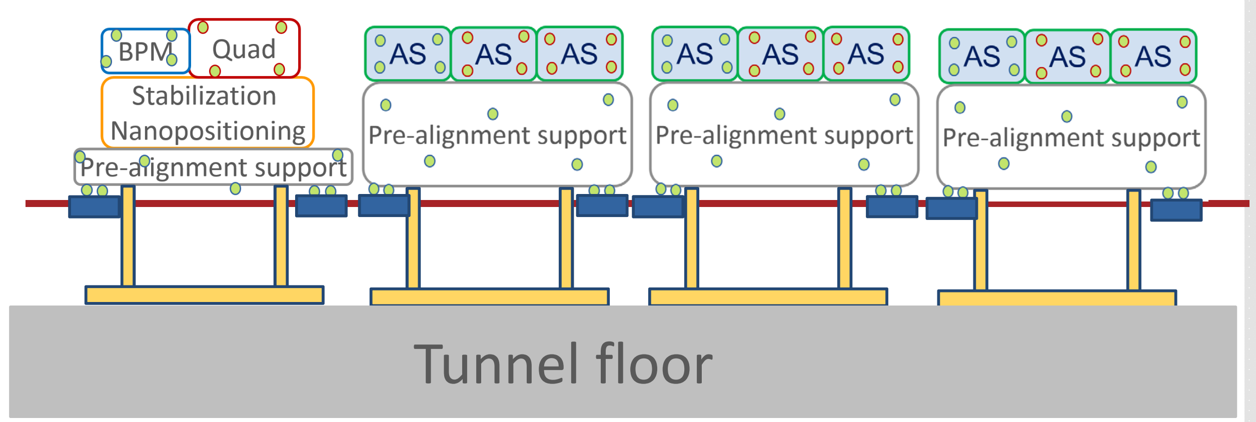
Fiducialisation:



Initial alignment:



Transfer in tunnel & alignment



The objectives of PACMAN

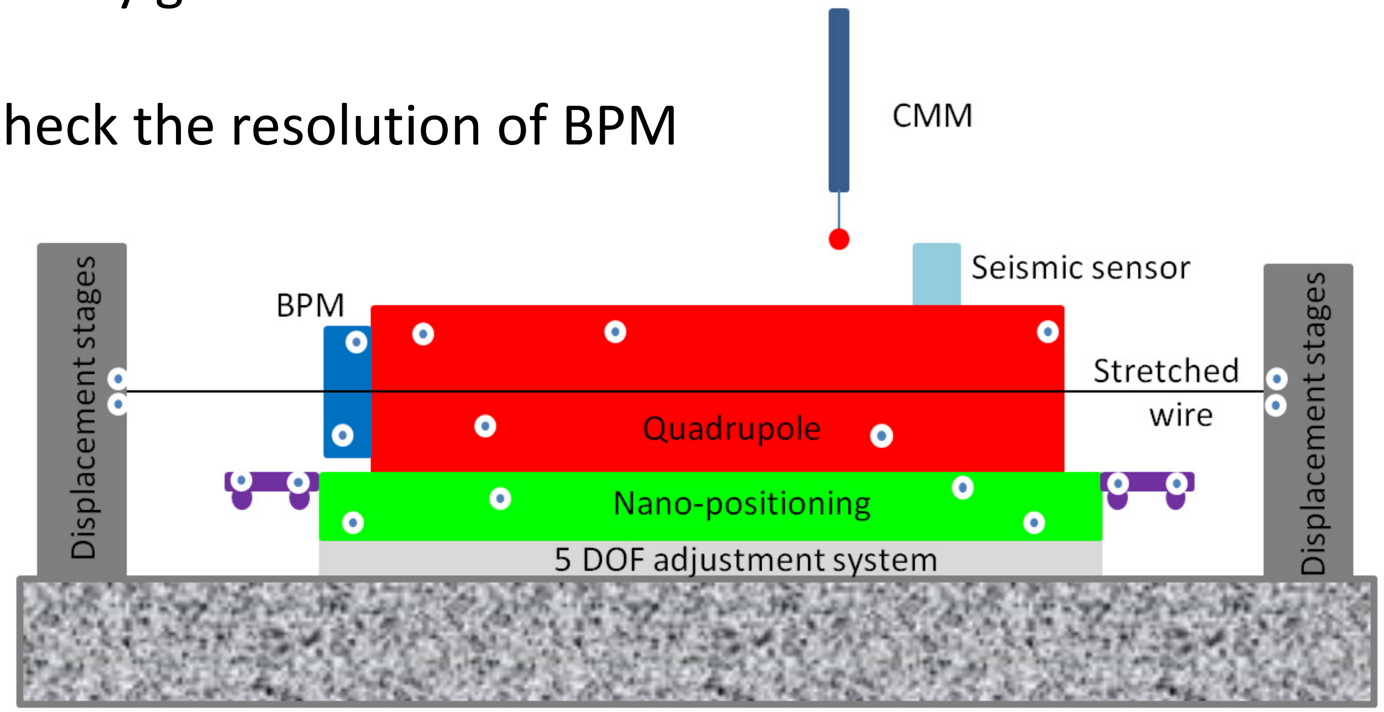
Combine references & methods of measurements in the same place to gain time and accuracy

Prove their feasibility on a final bench

Extrapolate the tools & methods developed to other projects

Some key issues

- Magnetic measurements with a vibrating stretched wire (and alternative based on printed circuit boards rotating search coils)
- Determination of the electromagnetic center of BPM and AS using a stretched wire
- Absolute methods of measurements: new non contact sensor for Coordinate Measuring Machine (CMM), combination of Frequency Scanning Interferometry (FSI) and micro-triangulation measurements as an alternative
- Improve seismic sensors and study ground motion
- Nano-positioning system to check the resolution of BPM

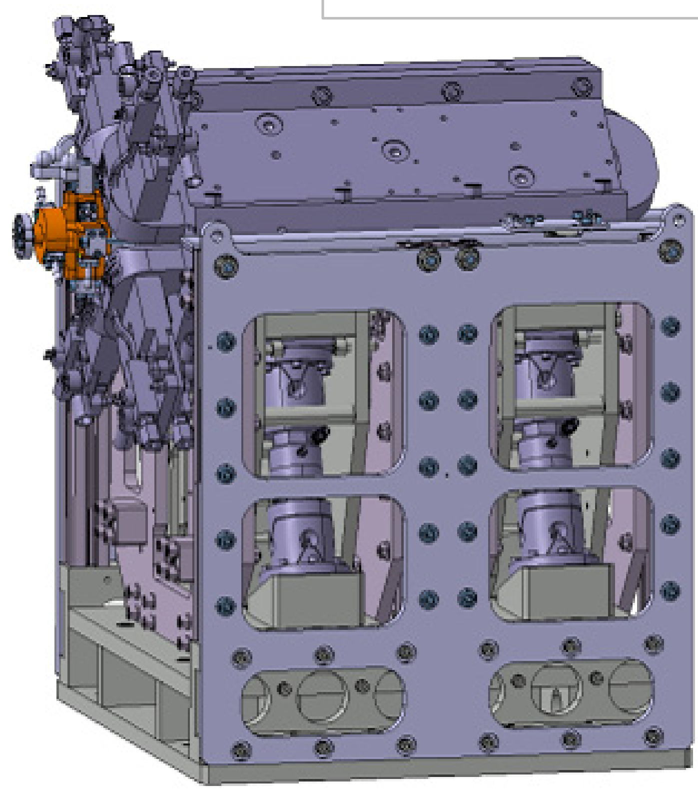


Technical systems

Components to be aligned

MB quadrupole
Nominal field gradient: 200 T/m
Bore Ø: 100 mm
Length: 441 mm

RF-BPM
Operating @ 15 GHz

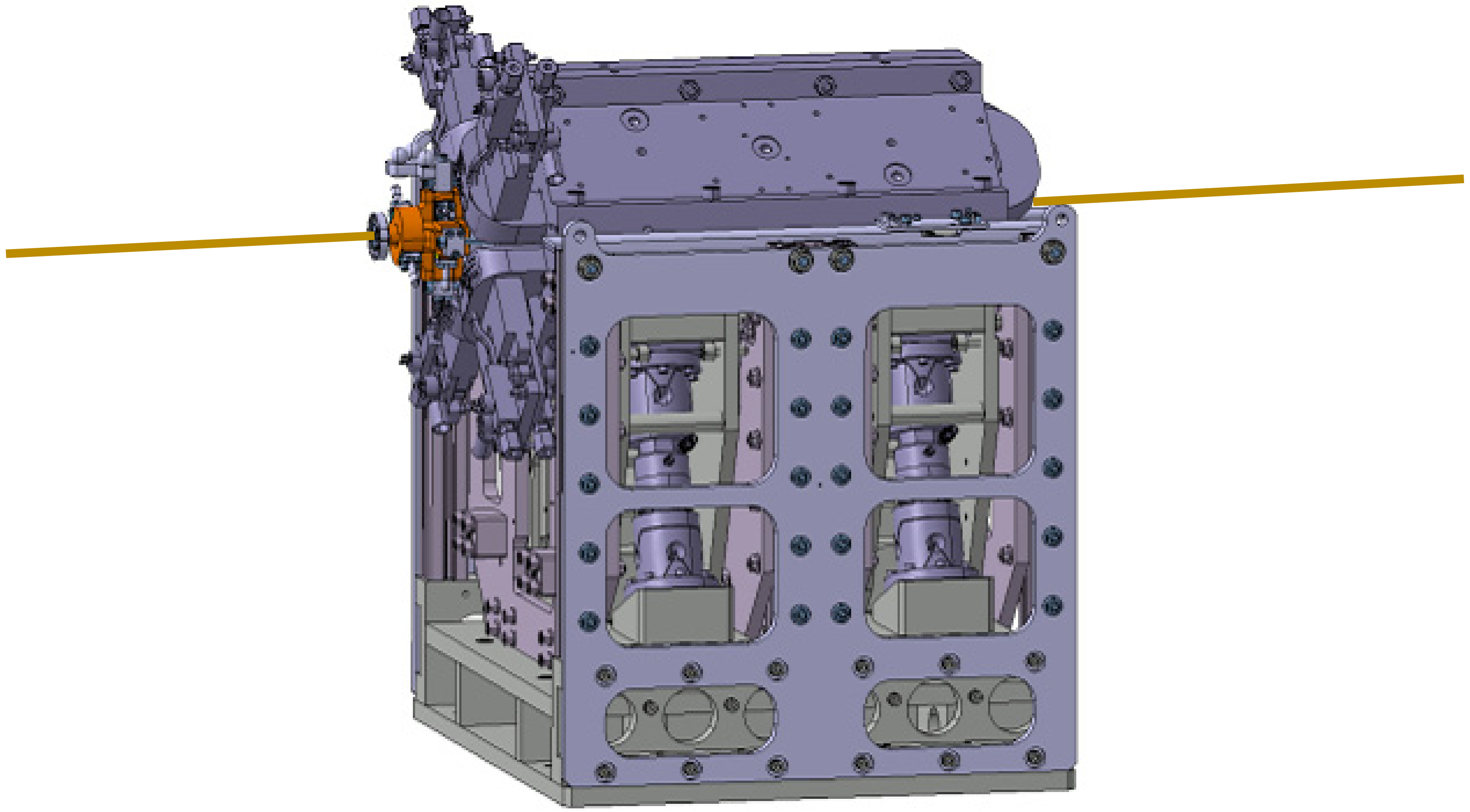


Nano-positioning
4 dofs (radial & vert. translations, pitch & yaw)
Piezo stack actuator:
- Stiffness: 480 N/µm
- Stroke: 15 µm
- Resolution: 0.15 nm

Flexural joints (high axial & rotational stiffness)

Technical systems

Reference wire

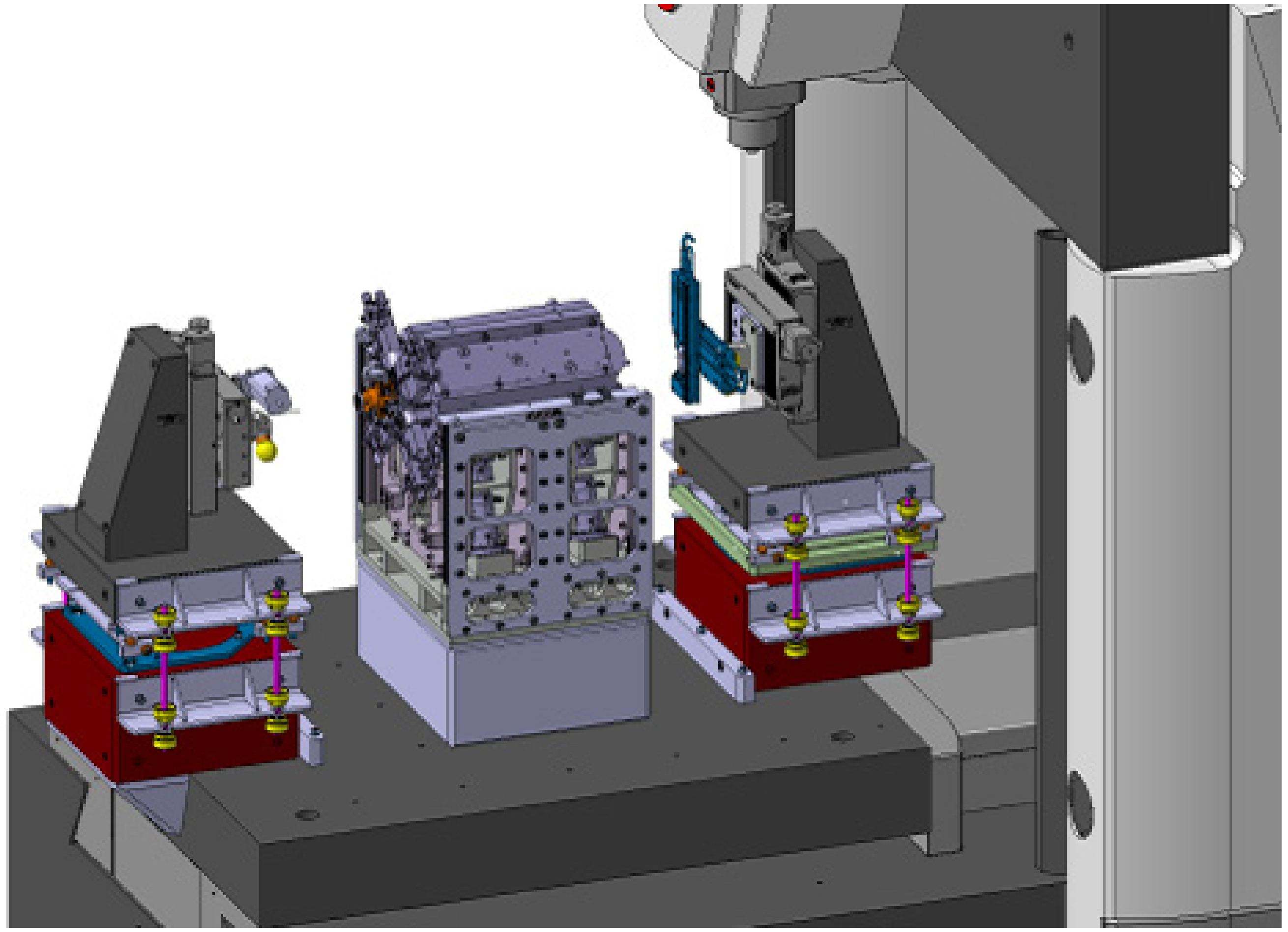


Reference wire
Copper/Beryllium (98%/2%)
Wire Ø : 100 µm

Technical systems

Wire displacement system

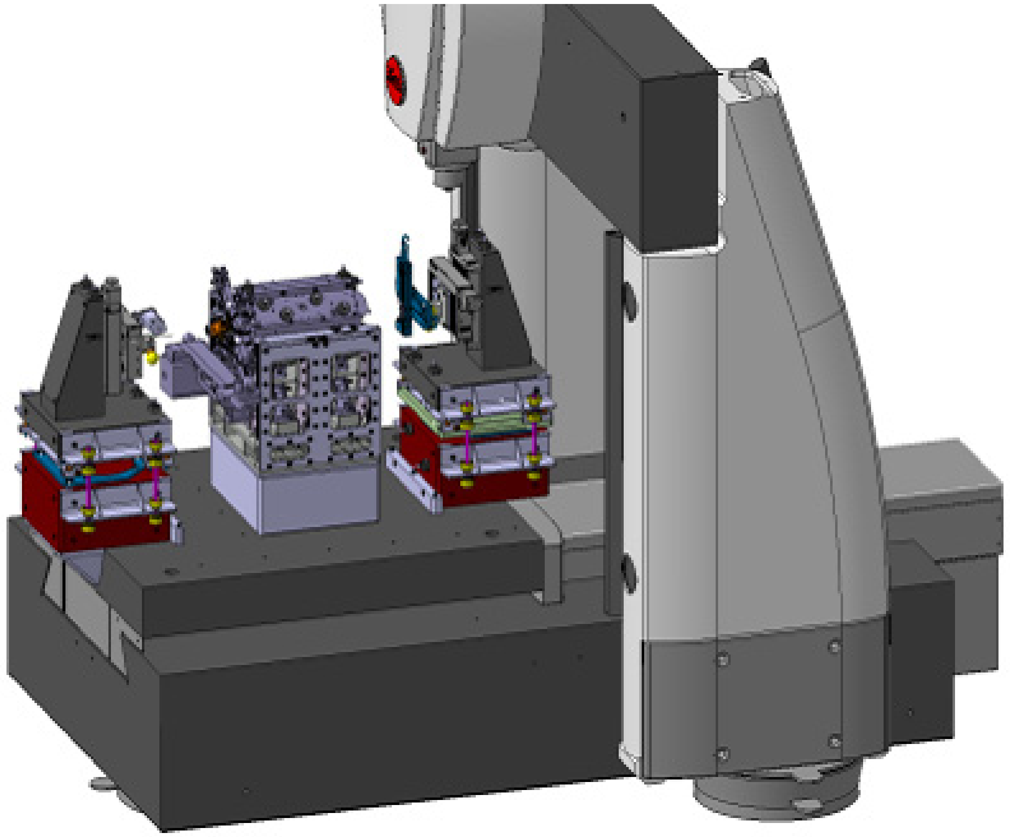
Linear displacement stages
Repeatability to position the wire < 0.1 µm
Absolute accuracy < 1 µm
Travel range : 50 mm



Sensor
Optical micrometres
Orthogonally mounted
Range: 6 mm
Repeatability: ± 0.3 µm
Accuracy: ± 0.5 µm

Technical systems

Fiducialisation

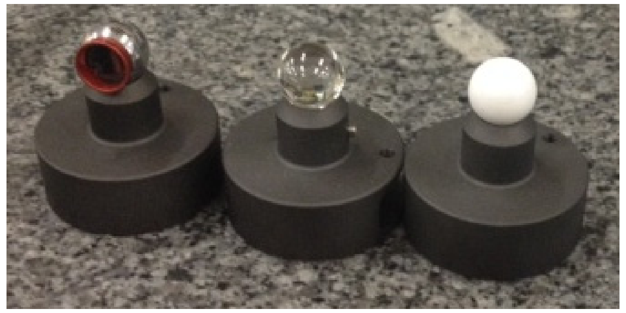


Fiducialisation

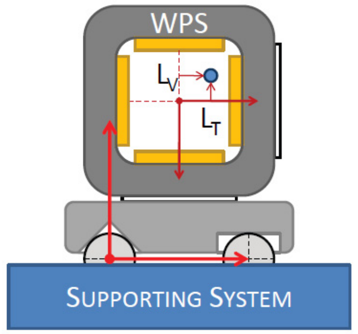
Determination of the reference axis (wire) w.r.t

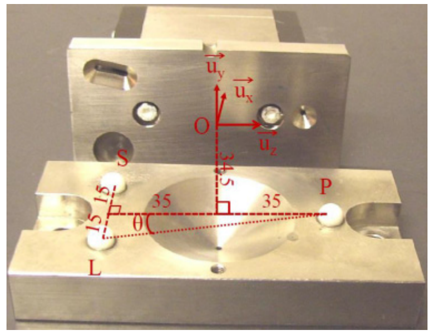
- External targets
- Sensor interface

Fiducials



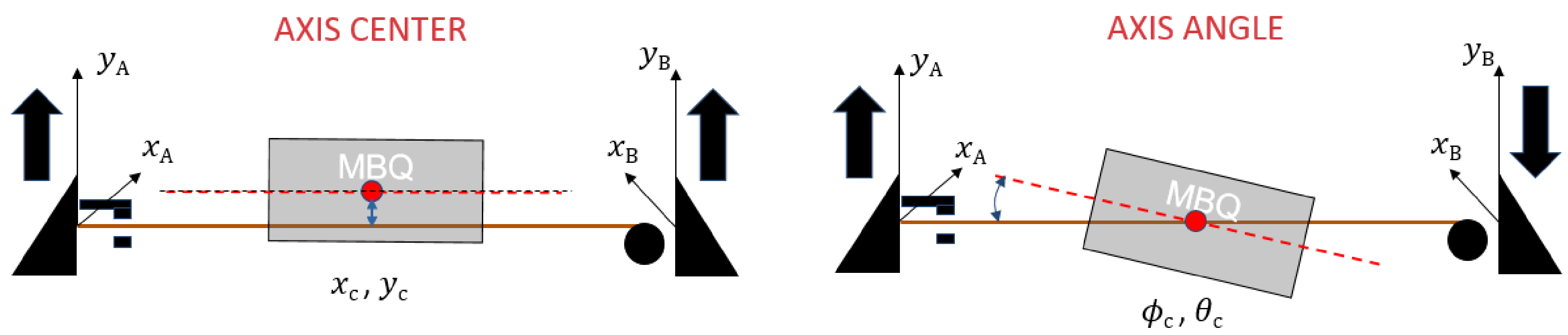
Sensor interface

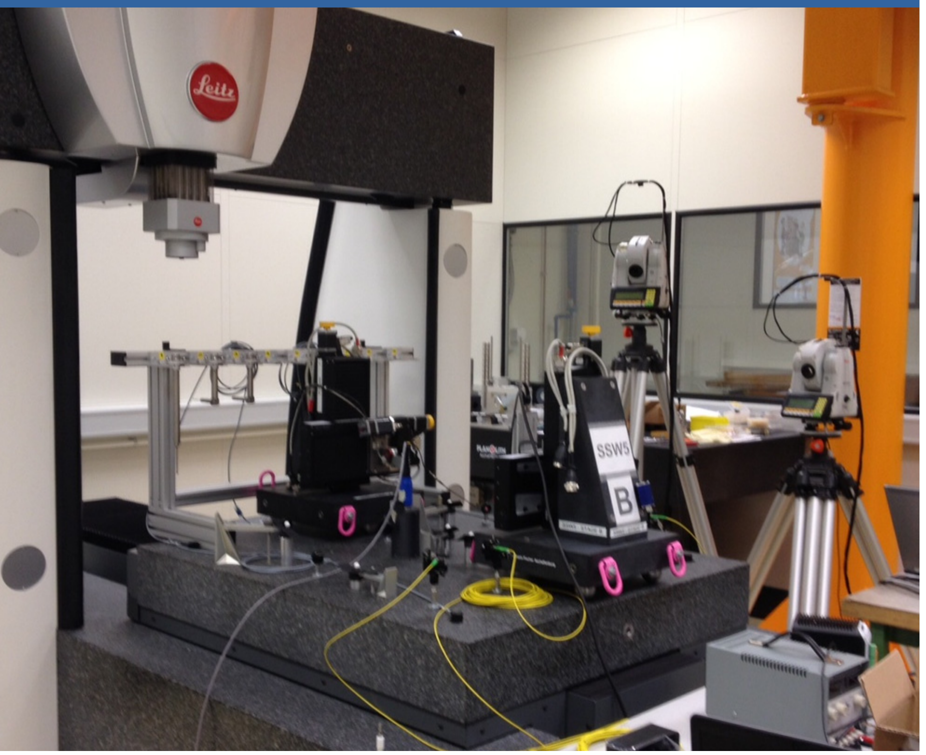




First results & preparation tests

Measurement of the magnetic axis





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

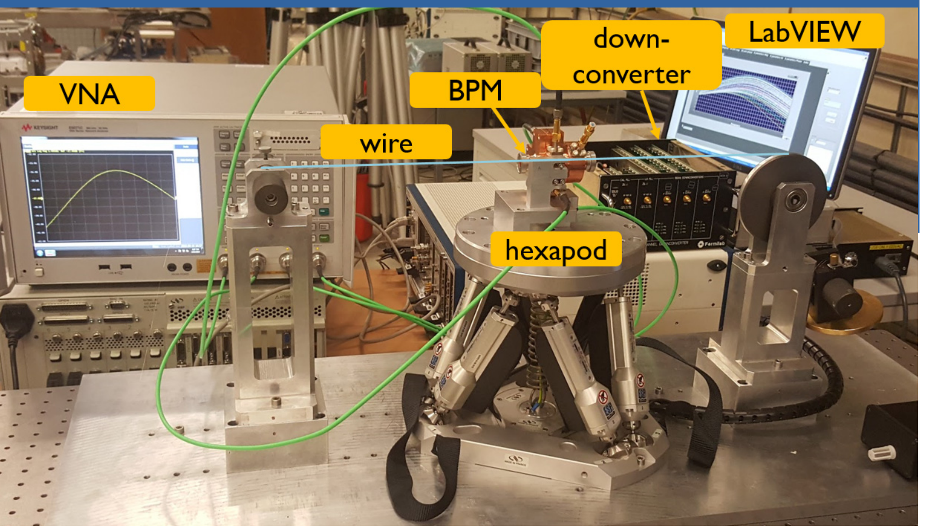
Current (A)	σ_x (µm)	σ_y (µm)	σ_ϕ (µrad)	σ_θ (µrad)
140	± 0.07	± 0.09	± 0.3	± 0.5
4	± 0.03	± 0.17	± 0.5	± 0.3

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

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

First results & preparation tests

Measurement of the electric center



Signal excitation

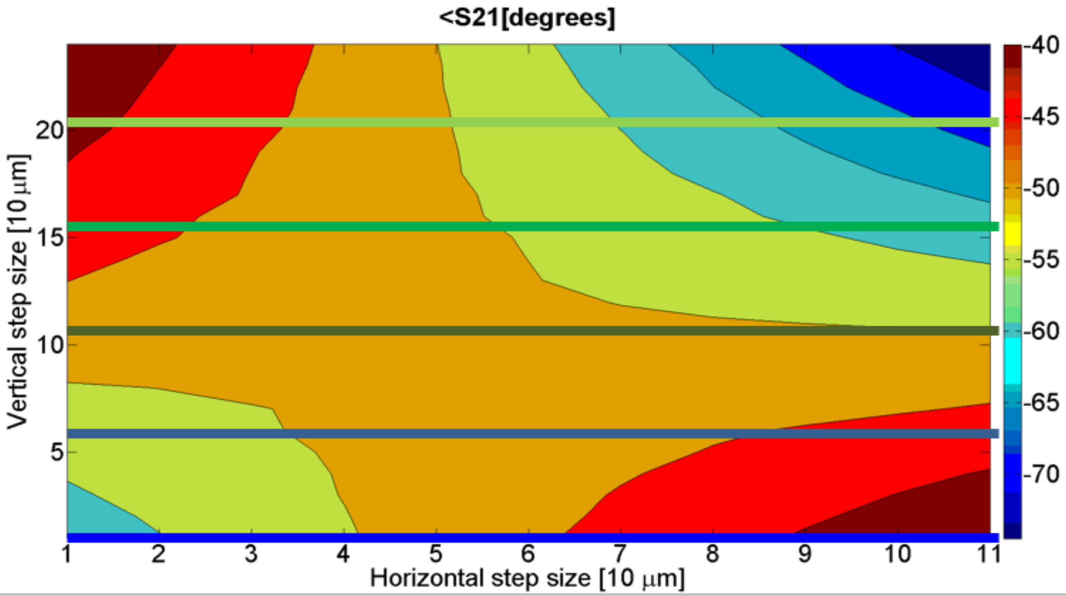
A 15 GHz signal is fed on a conductive stretched wire, causing an excitation in a similar way as the beam. By scanning the BPM, it is possible to find the signal minimum, e.g. the electrical center

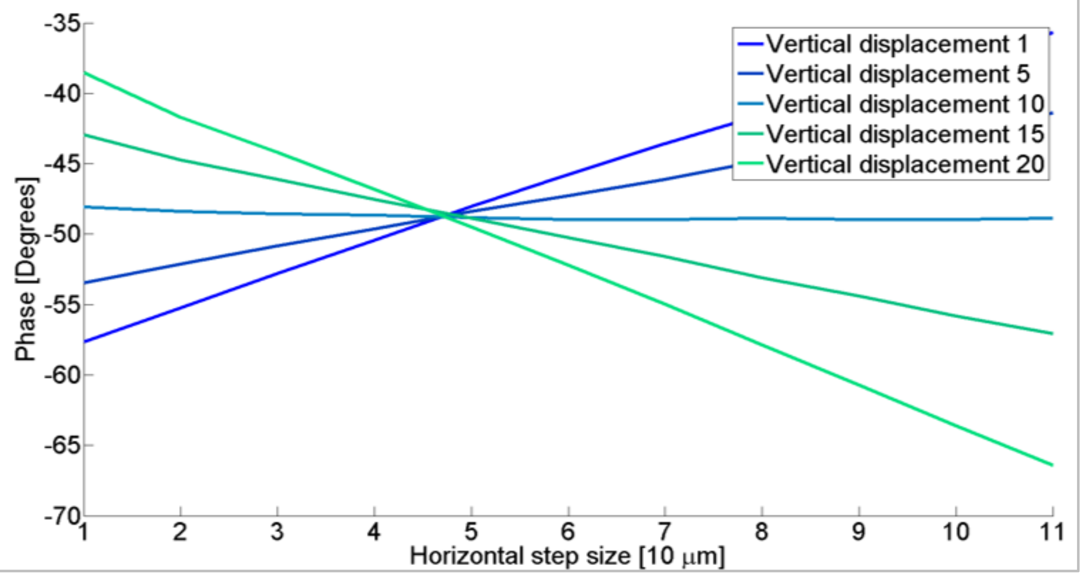
Pertubation analysis

The stretched wire is used as a passive target, while detecting/minimizing the asymmetry using amplitude and phase measurement between the 4 BPM ports.

Phase - Adjacent-port

Step size : 10um





First results & preparation tests

Determination of the wire position (CMM)

Characterization of the wire

CuBe wire characteristics	Nominal values	Sample 1	Sample 2
Electrical resistivity [μΩ/cm²/cm]	5.4 – 11.5	8.35, σ=0.02	10.86, σ=0.01
Limit tension [Kg]	0.5 – 1.3	1.176	
Micro-hardness [Vickers]	100-362	357	
Linear mass [mg/m]	64.80	66.34	65.97
Diameter [μm]	100	98.5, σ=1.4	99.2, σ=0.8
Form error circularity [μm]			> 0.5
Roughness [nm]		20.9	9.7, σ=5.4

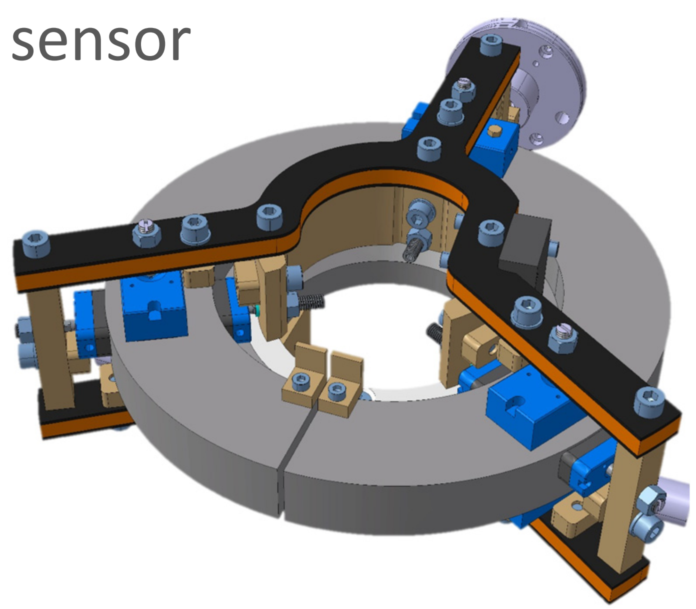
First results & preparation tests

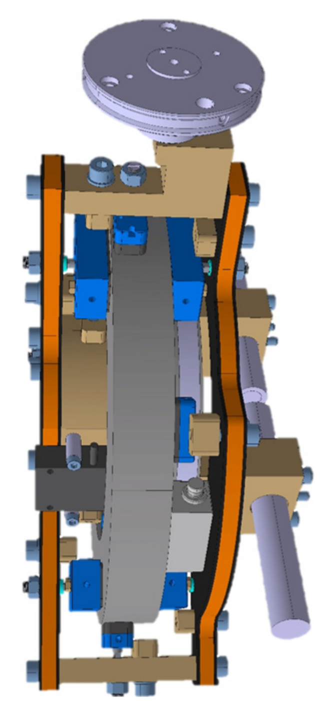
Determination of the wire position (CMM)

Characterization of the wire

CuBe wire characteristics	Nominal values	Sample 1	Sample 2
Electrical resistivity [μΩ/cm²/cm]	5.4 – 11.5	8.35, σ=0.02	10.86, σ=0.01
Limit tension [Kg]	0.5 – 1.3	1.176	
Micro-hardness [Vickers]	100-362	357	
Linear mass [mg/m]	64.80	66.34	65.97
Diameter [μm]	100	98.5, σ=1.4	99.2, σ=0.8
Form error circularity [μm]			> 0.5
Roughness [nm]		20.9	9.7, σ=5.4

Design of a non contact & high-accuracy sensor





Choice of the measuring shape sensor

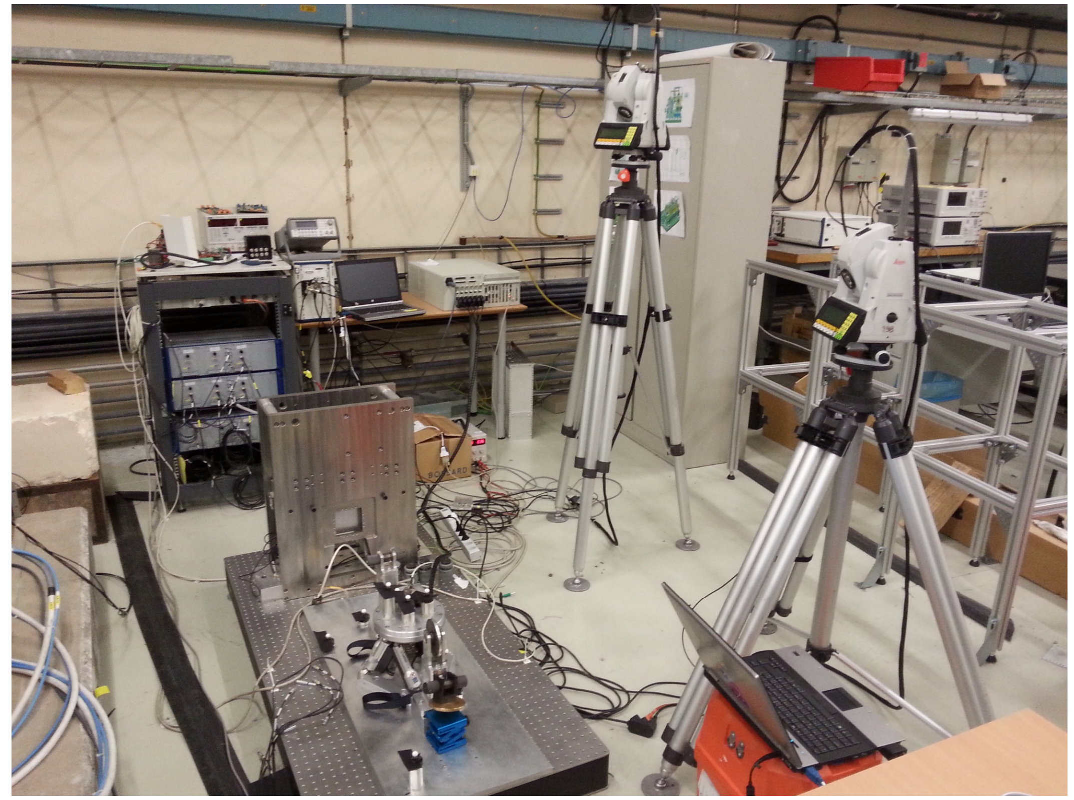
Chromatic confocal technology

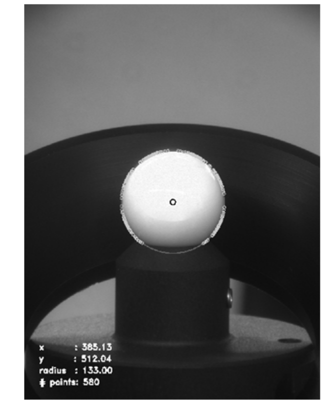
- *Repeatability measurements on a Ø 0.1 mm steel gauge*
- *3 types of sensors tested: σ from 96 to 112 nm*
- *Other parameters considered as cost, delivery time*

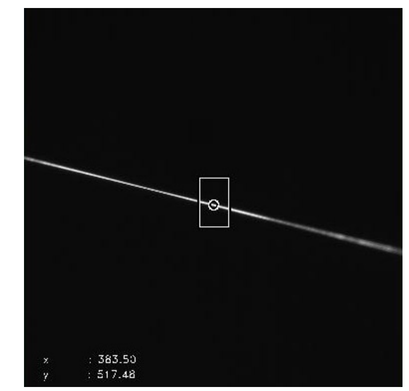
Study of 2 algorithms: wire detection & wire reconstruction

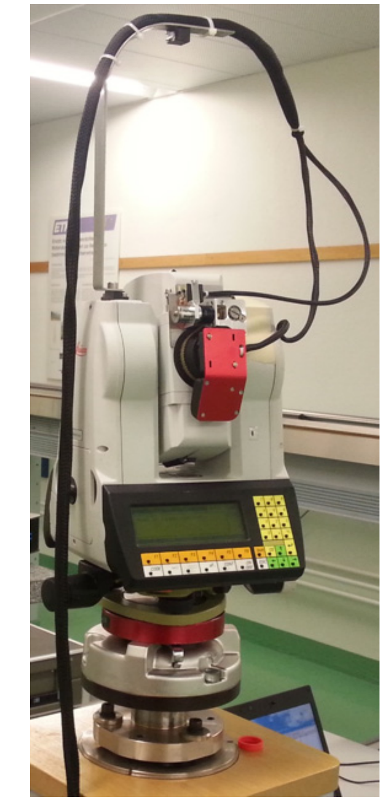
First results & preparation tests

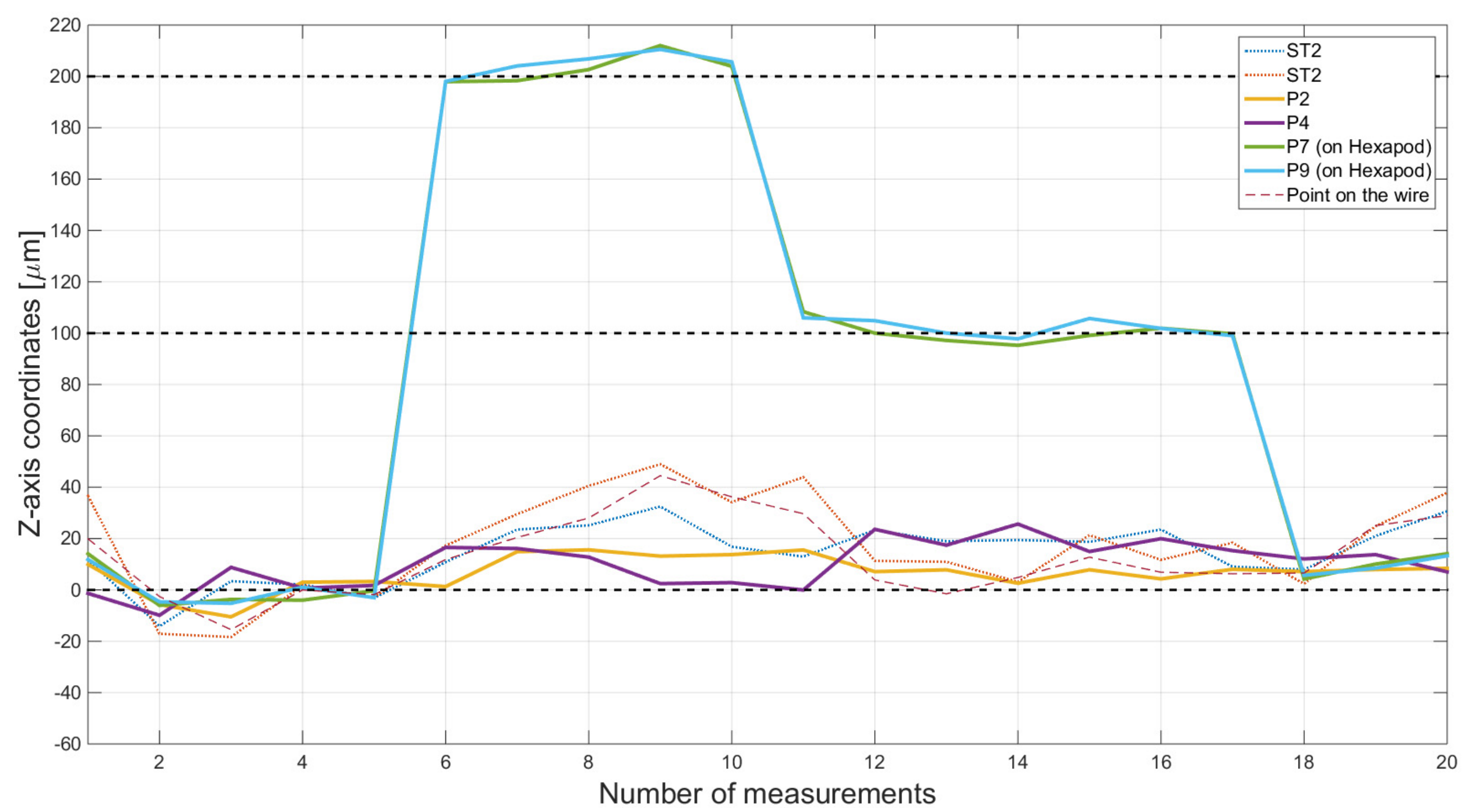
Determination of the wire position (micro-triangulation)











First results show a very good coherence between hexapod displacements & micro-triangulation measurements.

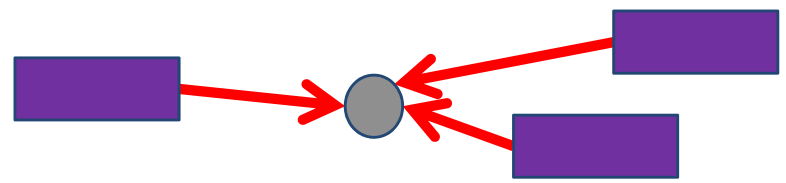
Scale factor to be integrated.

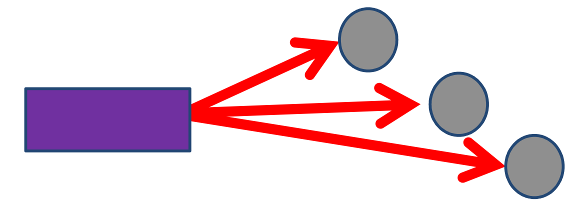
Hélène Mainaud Durand
IPAC 16 09-13/05/2016

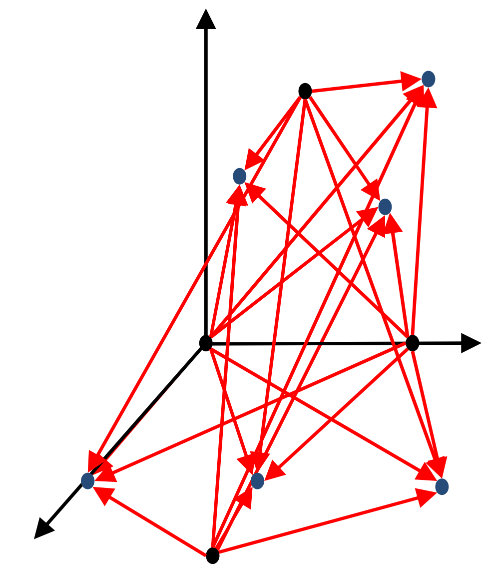
First results & preparation tests

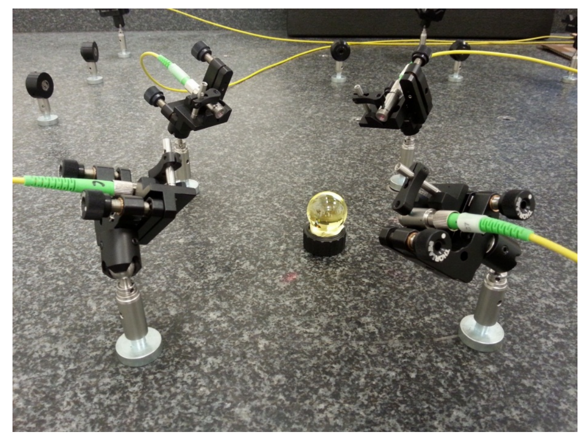
Determination of the wire position (FSI)

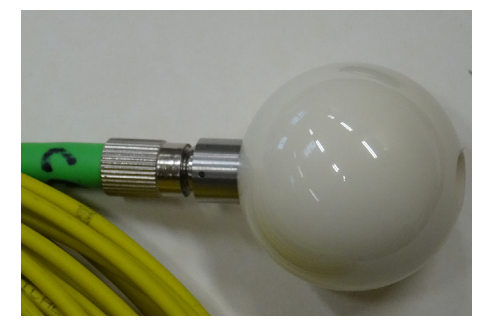
Objective: perform multilateration measurements

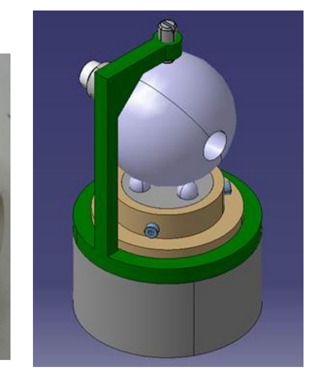








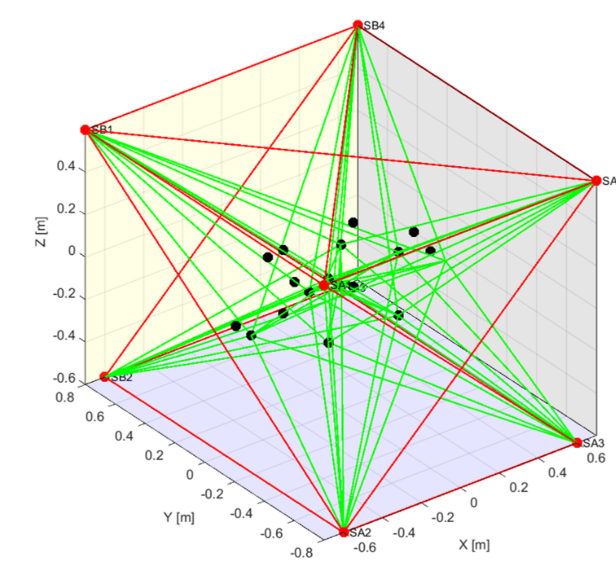




Initial simulations concerning configuration performed, with 8 stations and 17 targets

Compatibility tests in the environment of the CMM performed:

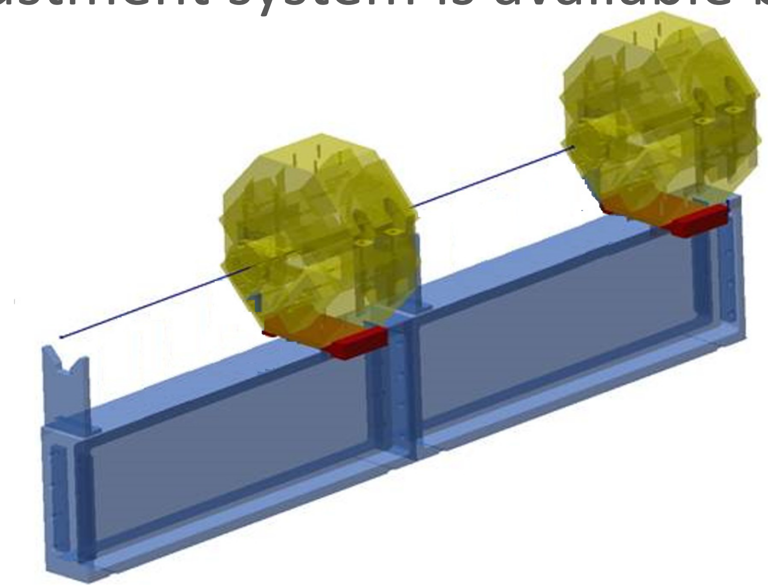
- No long term drift
- No measurements during a displacement of CMM.



Perspectives

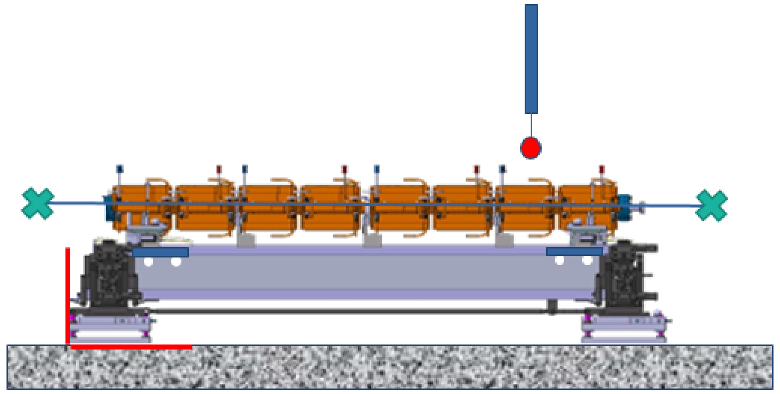
Extrapolation on other cases & projects

Alignment of several components on the same support at a CMM uncertainty of measurement using a stretched wire, provided an adjustment system is available below each component



More accurate
Less time consuming
Ready to be aligned
Interchangeability between girders
Relax the manufacturing tolerances of girders

Combined with absolute sensor (kinematic mount), the support can be pre-aligned within a few micrometers in a tunnel over tens of meters.



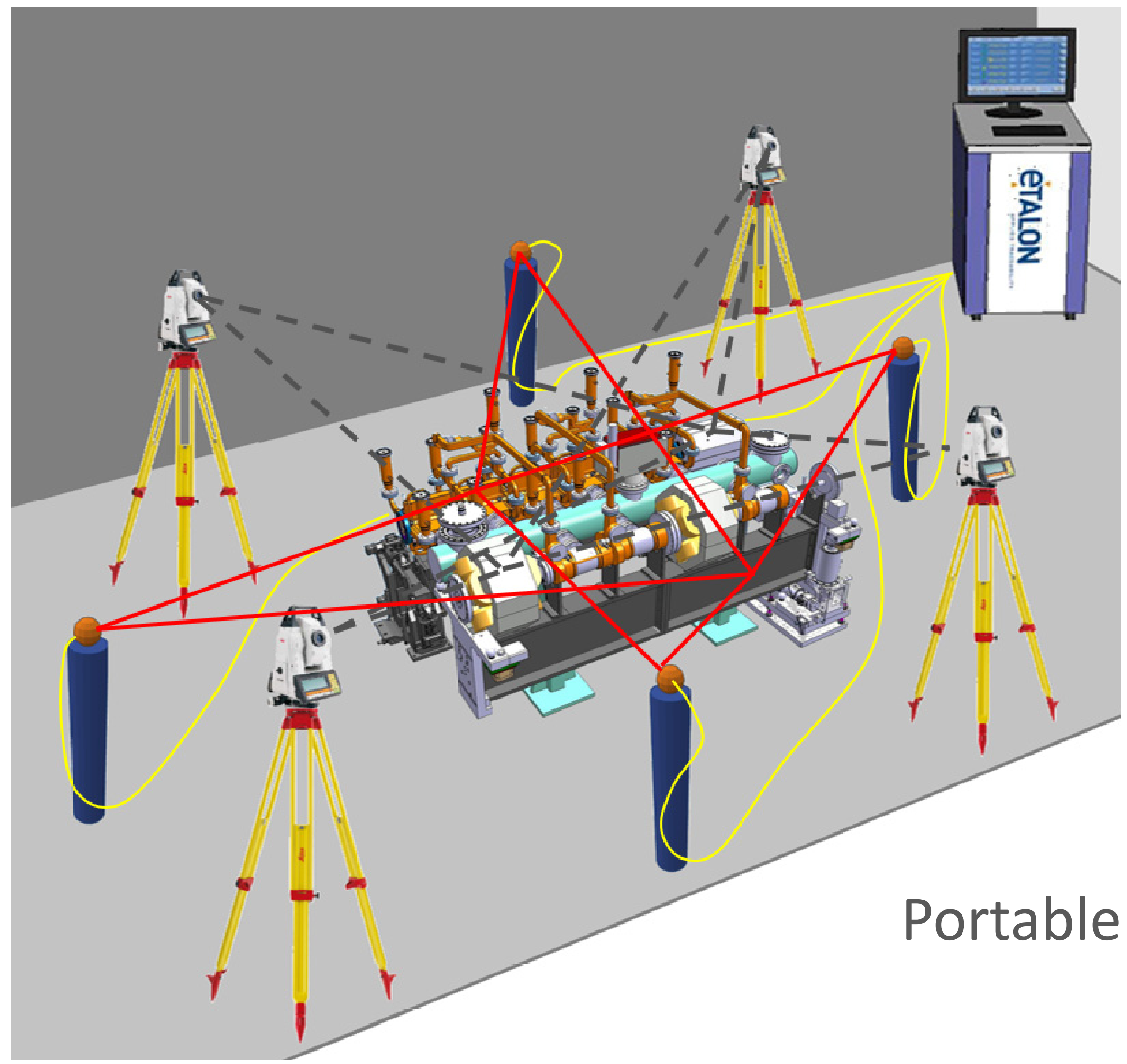
Determination of the electro-magnetic axis of AS using a stretched wire:

- Simulations have shown that a resolution of 1 µm is possible
- Confirmed by first measurements

Perspectives

Extrapolation on 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.

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, before being integrated in the PACMAN final validation bench
- The tools & methods can be extrapolated to other projects

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, before being integrated in the PACMAN final validation bench
- The tools & methods can be extrapolated to other projects

This is the technical dimension of the project, but there is another dimension:

•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

Any questions?

IPAC 16
09-13 May 2016

PACMAN is a team work

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

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

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