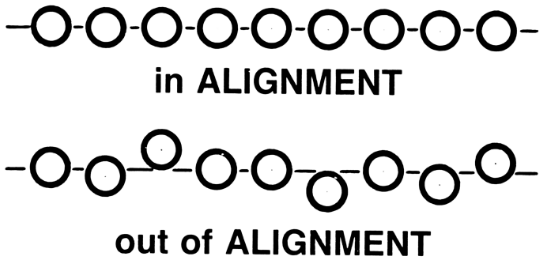
Joint Universities Accelerator School

CERN

SURVEY and ALIGNMENT in accelerators

Hélène Mainaud Durand

Introduction



What does alignment mean?

According to the Oxford dictionary: “an arrangement in which two or more things are positioned in a straight line”

In the context of particle accelerators, the things are: beam instrumentation & vacuum devices, magnets, RF components, etc.

Why aligning components?

The Earth on which we build accelerators is in constant motion

Accelerators have to be kept aligned within given tolerances to make the beam pass through

Alignment tolerances [Fisher] [Ruland]

Error of placement which, if exceeded, lead to a machine that is uncorrectable – with an unacceptable loss of luminosity

Surveying

Surveying

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This article is about measuring positions on Earth. For other uses, see Survey (disambiguation) and Surveyor (disambiguation).

Surveying or **land surveying** is the technique, profession, and science of determining the terrestrial or three-dimensional positions of points and the distances and angles between them. A land surveying professional is called a **land surveyor**. These points are usually on the surface of the Earth, and they are often used to establish maps and boundaries for ownership, locations, such as building corners or the surface location of subsurface features, or other purposes required by government or civil law, such as property sales.

A surveyor using a total station

Surveyors work with elements of geometry, trigonometry, regression analysis, physics, engineering, metrology, programming languages, and the law. They use equipment, such as total stations, robotic total stations, theodolites, GPS receivers, retroreflectors, 3D scanners, radios, handheld tablets, digital levels, subsurface locators, drones, GIS, and surveying software.

Surveying has been an element in the development of the human environment since the beginning of recorded history. The planning and execution of most forms of construction require it. It is also used in transport, communications, mapping, and the definition of legal boundaries for land ownership. It is an important tool for research in many other scientific disciplines.

Survey, Mechatronics and Measurements

Survey, Mechatronics and Measurements (SMM) group

The SMM Group develops and maintains a centralized competence in Survey, Mechatronic systems, tests and Measurement. The group is in charge of maintaining a competence in the development of radiation tolerant electronics, and provides support CERN wide for radiation tests and radiation monitoring for evaluating the dose to electronics installed in radiation areas. The group develops robotic platforms adapted to interventions in the accelerator environment, and deploys those solutions in collaboration with all groups in the Accelerator and Technology sector. SMM is able to provide computing support for data acquisition, data processing and data analysis, as well as for data storage related to all these activities.

Survey mandate :

- Geodetic aspects
- Dimensional metrology of accelerator and of experiment components
- Positioning and alignment on beam lines
- Quality controls (infrastructure, installations, components)
- The R&D related to these tasks

Our challenges

Accuracy and precision

From a few µm to mm

Difficult configuration: straight and narrow

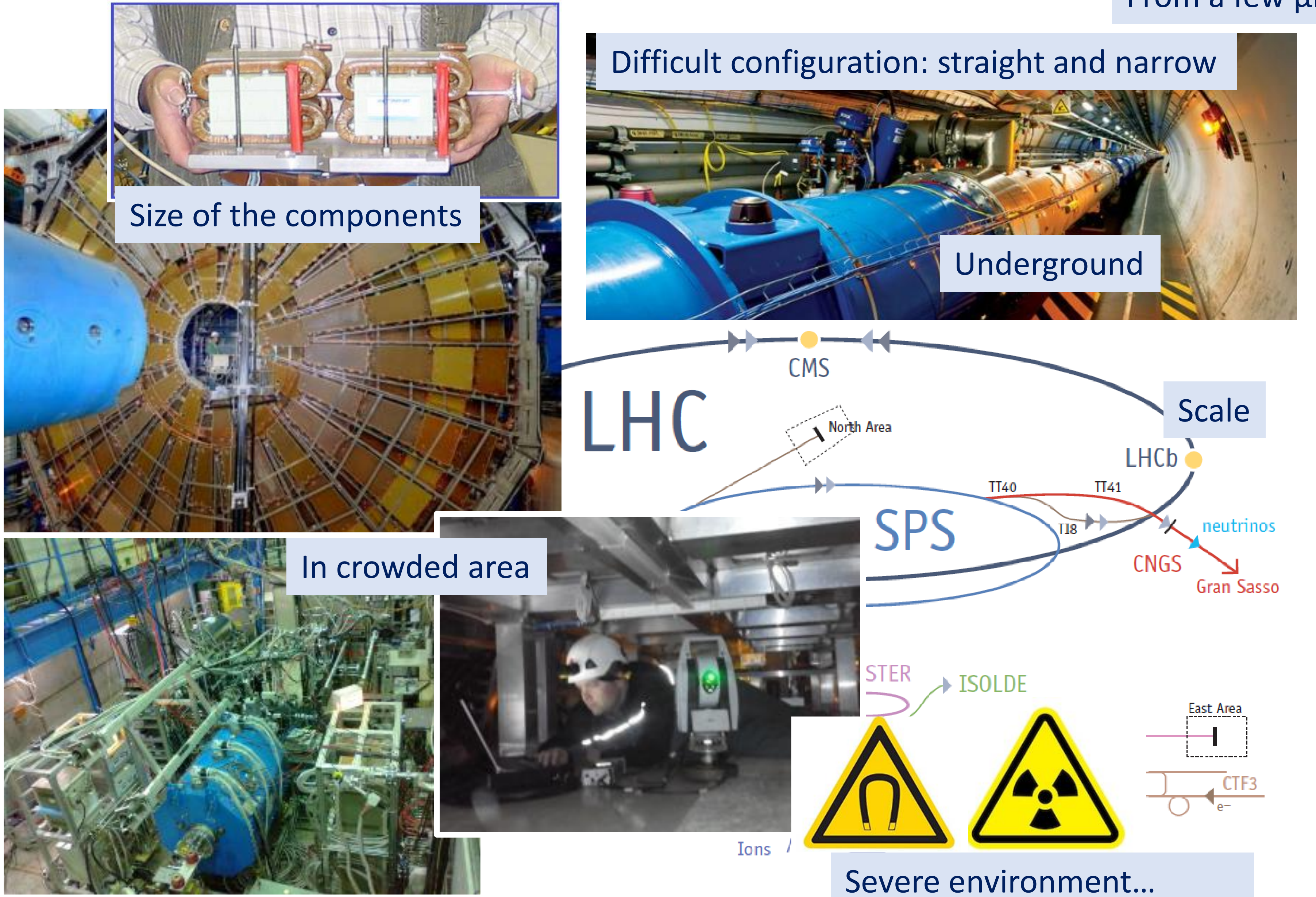
Underground

Size of the components

Scale

In crowded area

Severe environment…



Outline

- Introduction to geodesy
- Steps of alignment
- Instrumentation toolkit
- Case of the LHC
- Current challenges on HL-LHC
- Alignment R&D: case of the CLIC project

Introduction to geodesy

- Definition
- CERN Geodetic Reference Frame (CGRF) and CERN Coordinate System (CCS)
- Deflection of vertical
- Impact

Geodesy: definition

Geodesy is the science of accurately measuring and understanding three fundamental properties of the Earth: its geometric shape, its orientation in space, and its gravity field— as well as the changes of these properties with time.

Why is it so important to take it into account?

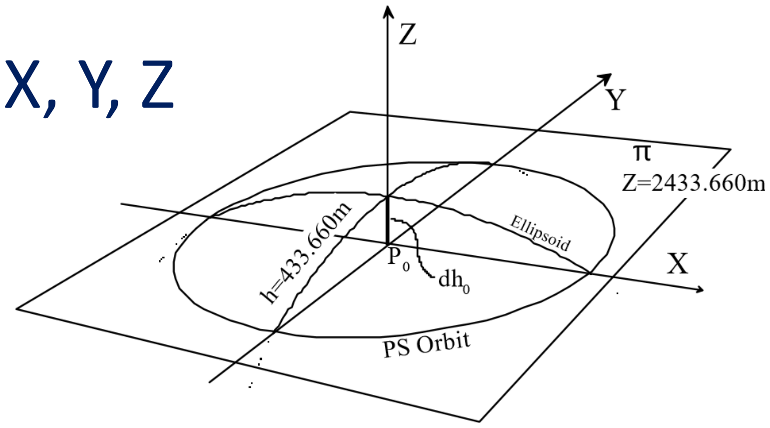
- To align components of a collider, along a plane or a straight line, we need to know the shape of the Earth very accurately
- A large part of instrumentation is set-up to perform measurements w.r.t to gravity
- We need to define the relative position of all area on surface and underground: sites, buildings, tunnels, accelerators, experiments

Geodesy: CERN reference systems

To link 2 different objects in space, a reference system has to be defined in which the position of each object can be referenced. It has to be combined with a coordinate system to give their position.

Example at CERN:

- CERN Coordinate System (CCS): Cartesian system X, Y, Z
- CERN Geodetic Reference Frame (CGRF):
  - Reference surface which is fitting the shape of the earth
  - Depends on the accuracy requested
  - And of the size of the project

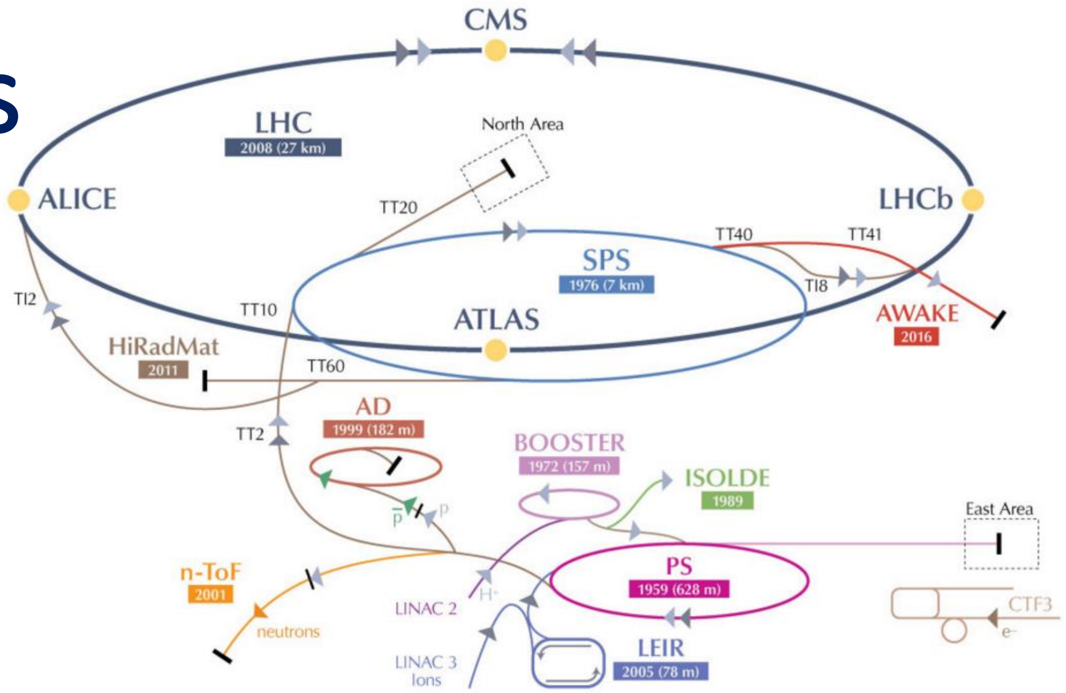


CERN CCS and PS orbit

Geodesy: reference systems

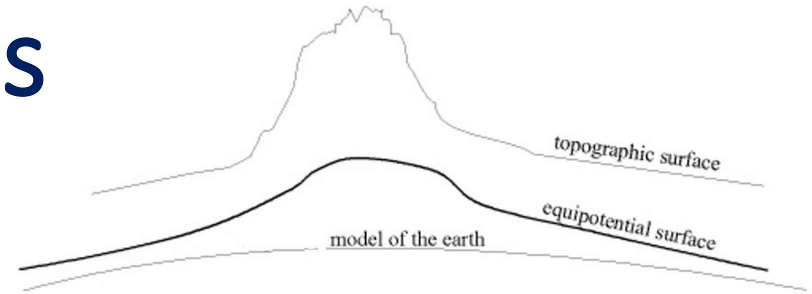
Different datums:

PS (circumference = 628 m)
➔datum = plane



SPS (circumference = 7 km)
Horizont. & vert. datum = sphere
New coordinate: H height w.r.t to the sphere

Geodesy: CERN reference systems



CERN Geodetic Reference Frame [Jones]:

Two surfaces to model the shape of the Earth:

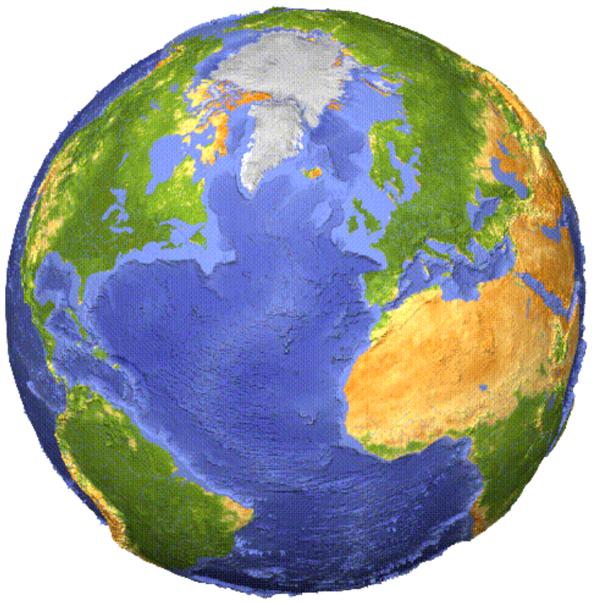
- A horizontal geodetic datum: typically a mathematical surface
- A vertical geodetic datum→ geoid, a natural surface. The geoid is the gravity equipotential surface representing mean sea level, that is everywhere normal to the gravity vector (plumb line).

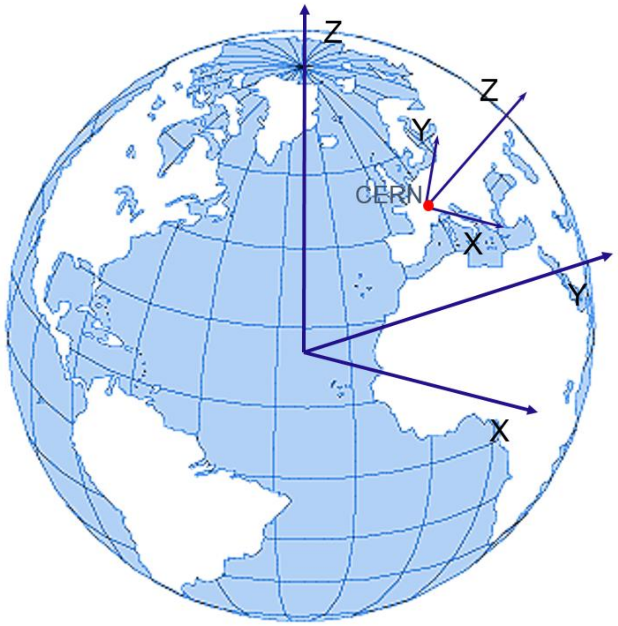
The geoid is irregular due to local mass anomalies (mountains, valleys or rock of various density)

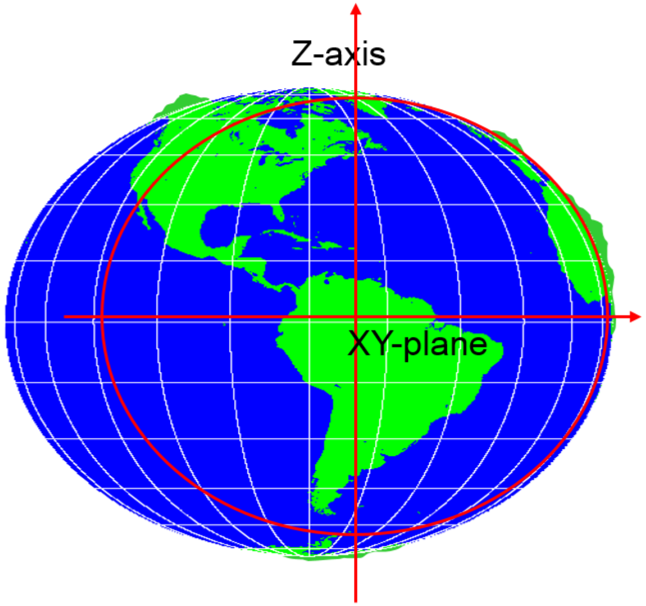
Latitude and longitude provide a good horizontal reference but a mathematical surface is not accurate enough for heights as it does not take into account the deflection of vertical

Geodesy: reference systems

For the LHC accelerator (circumference = 27 km), the Earth is an ellipsoid







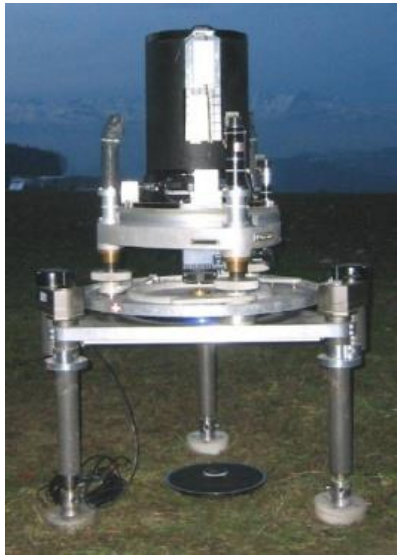
Horizontal geodetic datum = ellipsoid
Vertical geodetic datum = geoid (shape of a paraboloid)

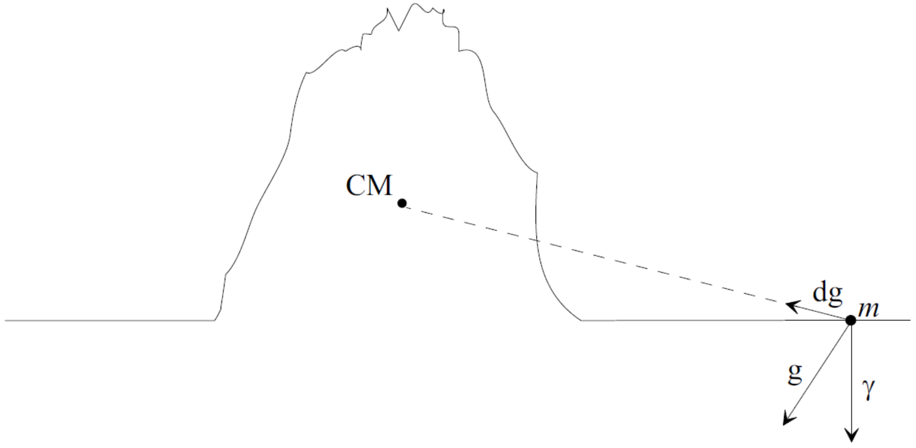
Geodesy: deflection of vertical

The deflection of vertical is the angle of divergence between the gravity vector (normal to the geoid and the normal to the ellipsoid)

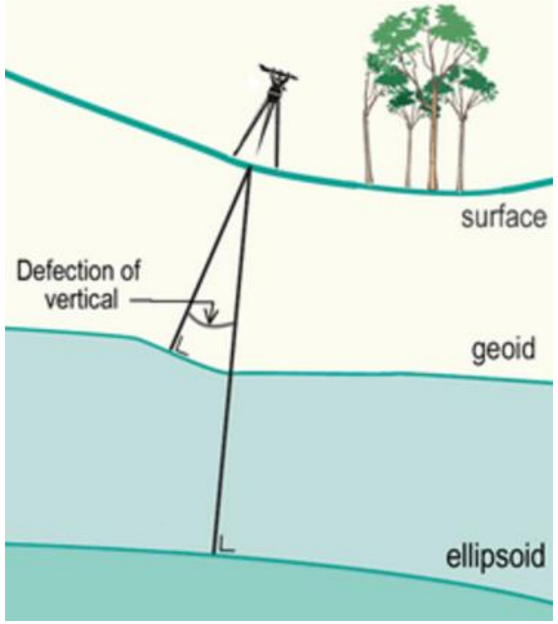
Maximum deviation of vertical: 15’’ relative to the ellipsoid of CERN system

Computation of the equipotential surfaces at any altitude with a 10x10km grid, expressed in the local origin of CERN system combined with astro-geodetic measurements using the zenithal camera of ETH Zurich





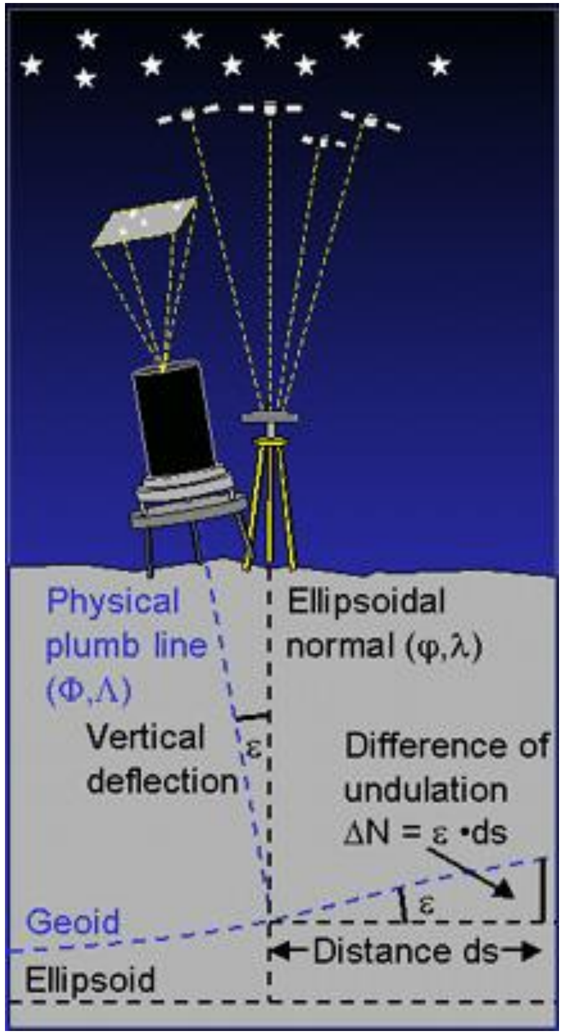
Effect of a nearby mass anomaly



Geodesy: deflection of vertical

Astro-gravimetric Equipotential Determination

SOURCES	ERROR [arcsec]		
	random	systematic	model
Astrometry			
Star Catalog (Tycho 2)	0.01-0.1	<0.01	UCAC3
Timing (GPS + Shutter)	< 0.01	-	-
Scintillation	0.1 -1.0	-	-
Anomalous Refraction	-	0.01-0.3	Ray Tracing ?
Tilt			
Instrumentation Noise	< 0.05	-	-
Celestial Calibration	-	< 0.03	-
Ellipsoidal Coordinates			
Differential GNSS	<< 0.01	-	-

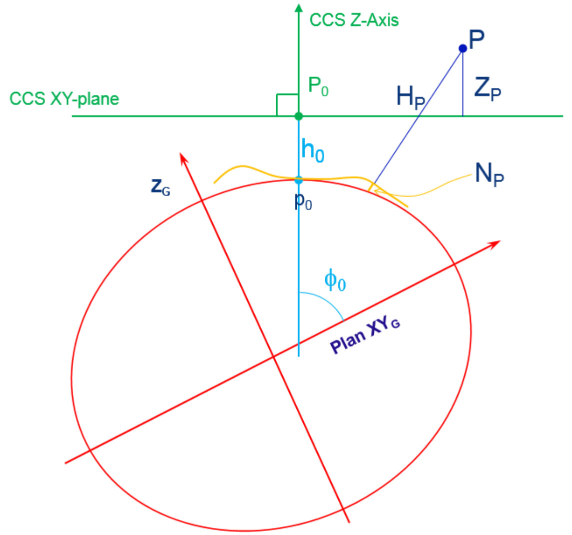


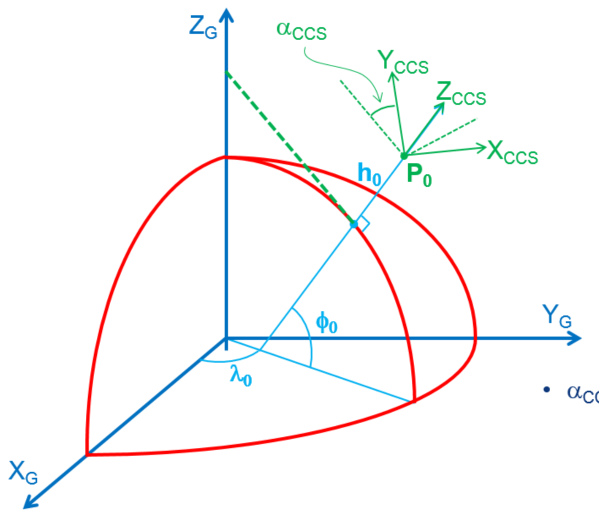
[Guillaume]

Geodesy: summary

At CERN:

- Reference frame is an ellipsoid tangent to the earth at P0
- Geoid:
  - Determined in 1985 for LEP and still used for LHC
  - Determined in 2000 for the CNGS project
- Global coordinate system is CCS





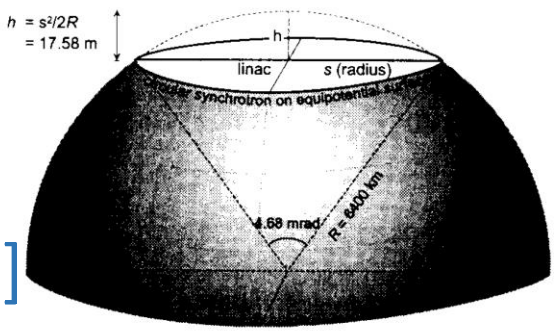
- α_{CCS} = 37.77864 Grad

Geodesy: impact

- Accelerators built in a tangential plane (slightly tilted to accommodate geological deformations)
- All points around an untilted circular machine lie at the same height.
- Linear machines cut right through the equipotential iso-lines:
- Center of a 30 km linear accelerator is 17 m below the end points
- One solution to accommodate

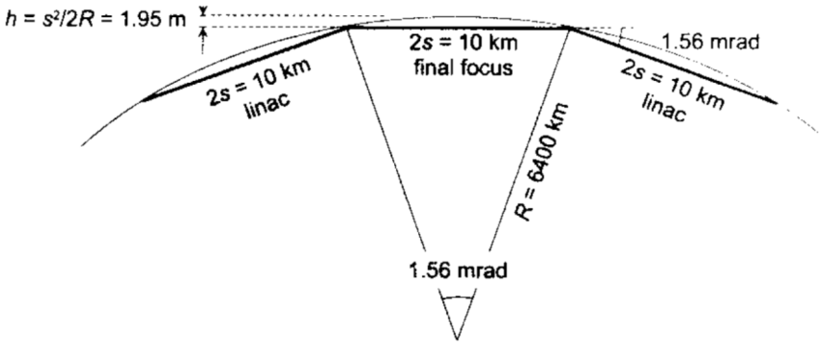
Curvature correction, plane to sphere or spheroid.

Distance [m]	Sphere H_S [m]	Spheroid H_E [m]
20	0.00003	0.00003
50	0.00020	0.00016
100	0.00078	0.00063
1000	0.07846	0.06257
10000	7.84620	6.25749
25000	49.03878	39.10929

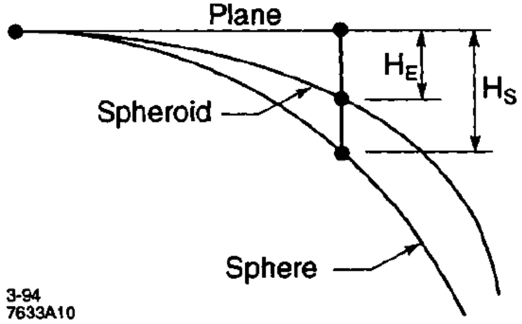


[Ruland]

Effect of earth curvature on linear and circular accelerators



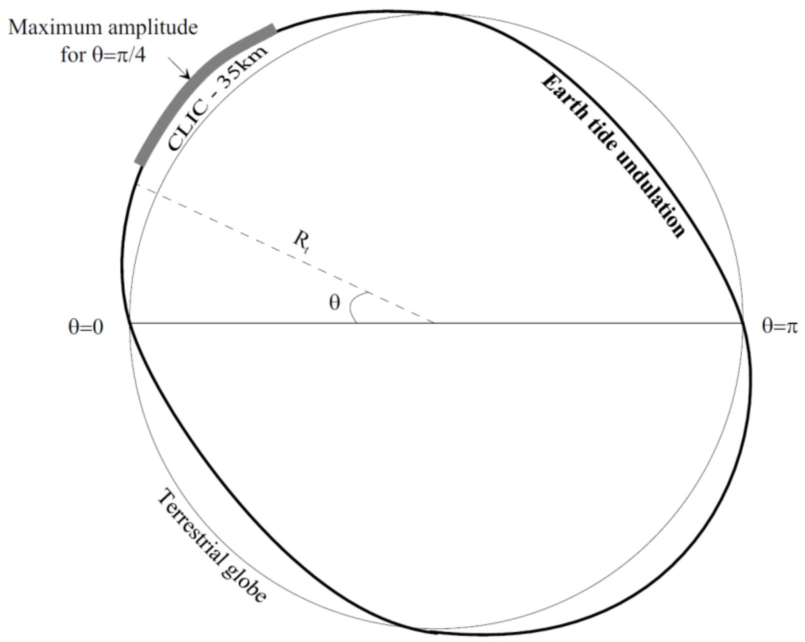
Three plane lay-out



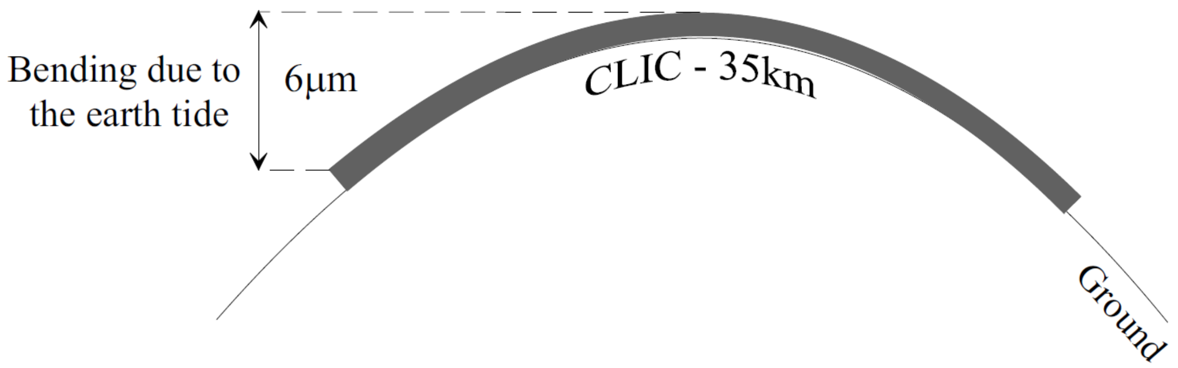
Curvature correction.

[Ruland2]

Geodesy: other data



Impact of moon and sun on ground surface



Bending of accelerator due to the periodic undulations of the Earth tides

[CLIC Note]

Steps of alignment

Definition of alignment tolerances

Definition of alignment strategy

Time scale

Installation and determination of surface geodetic network

Transfer of reference in the tunnel

Installation and determination of an underground geodetic network

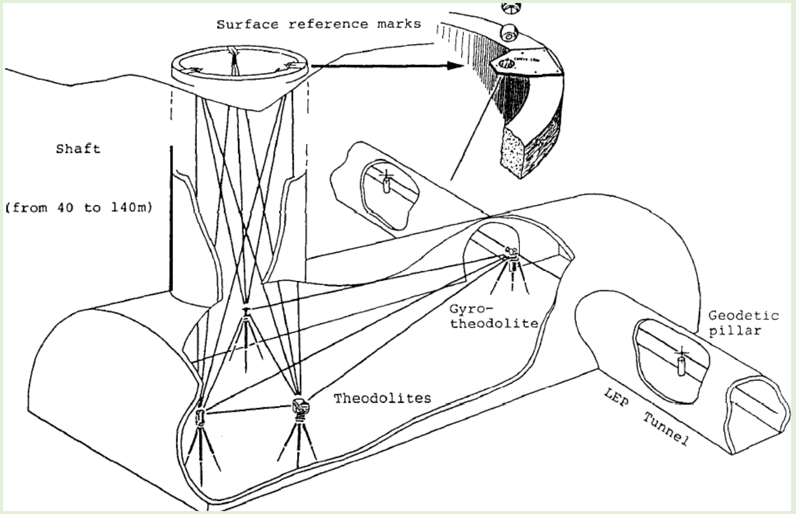
Fiducialisation of the components

Definition of their theoretical trajectory

Absolute alignment of the components

Relative alignment of the components

Maintenance of the alignment

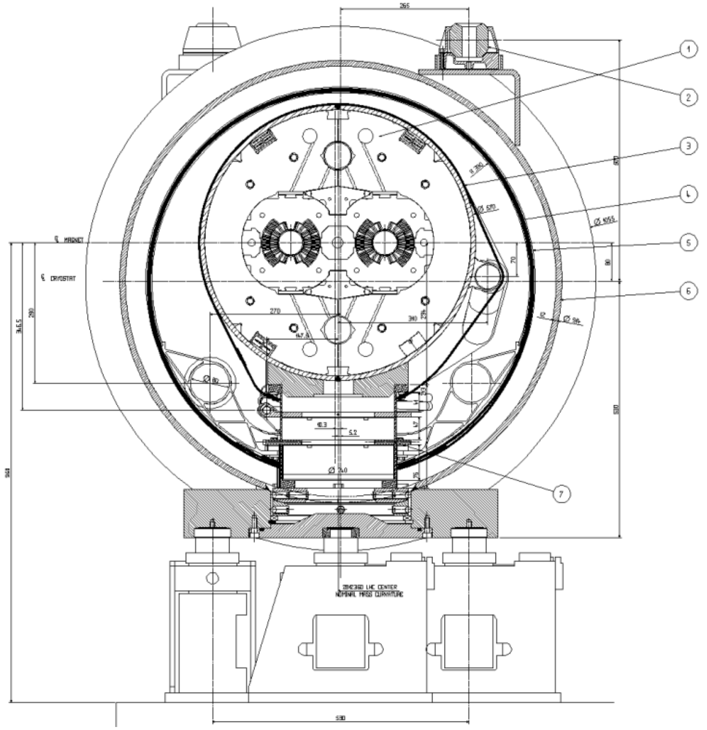


Definition of alignment tolerances

Alignment error table for the dipoles

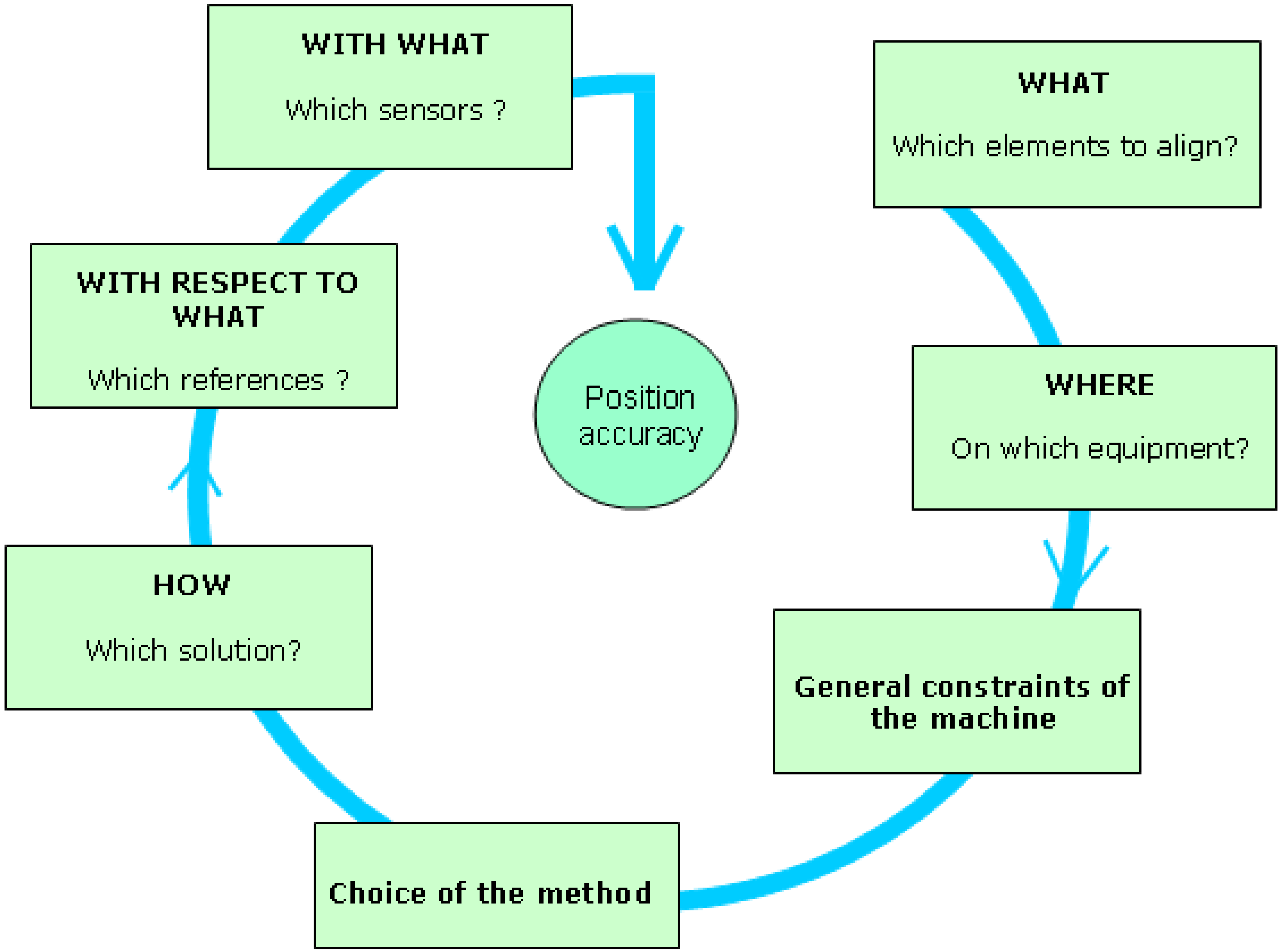
Alignment errors table for the Dipoles	***All r.m.s. values, in mm.***	(i) Mean (mm) In the plane of the fiducials	(ii) Ends (mm)	%	(iii) Correctors (mm)
Cold mass construction	Mean magnetic axis/ideal geom. axis	0.1 (1)			
	Auxiliary fiducials / ideal geom. axis	0.2 (1) (2)	0.2	6.2%	
	Magn. axis / Spool pieces fiducials				0.1
	Magn. axis of spool pieces / ideal geom. axis of the dipole				0.2
	Cold bores / ideal geom. axis of the dipole	0.33 (2)	0.1	1.6%	
Beam screen	Beam screen / cold bore axis	0.3 (2)	0.3		
Cold mass in the cryostat	Thermal effects on the cold posts	0.1 (1) (2)	0.2	6.2%	0.2
	Ovalisation and straightness of the cryostat	0.2 (1) (2)	0.4	24.9%	0.4
	Mesures of the fiducials / ideal mean axis	0.1 (1) (2)	0.2	6.2%	0.2
	Adjustment of the central post	0.2 (1) (2)	0.2	6.2%	0.2
positioning in the tunnel	Radial pos. of the fiducials / theoretical orbit	0.28 (1) (2)	0.56	48.7%	0.56

(i)	(1)	Mean magnetic axis / theoretical orbit	0.48 mm r.m.s.
(i)	(2)	Mechanical aperture limitation in the dipole	0.65 mm r.m.s.
(ii)		Mechanical aperture limitation at the ends without beam screen	0.80 mm r.m.s.
(ii)		Mechanical aperture limitation at the ends with beam screen	0.86 mm r.m.s.
(iii)		Magnetic axis of the correctors / theor. orbit	0.80 mm r.m.s.



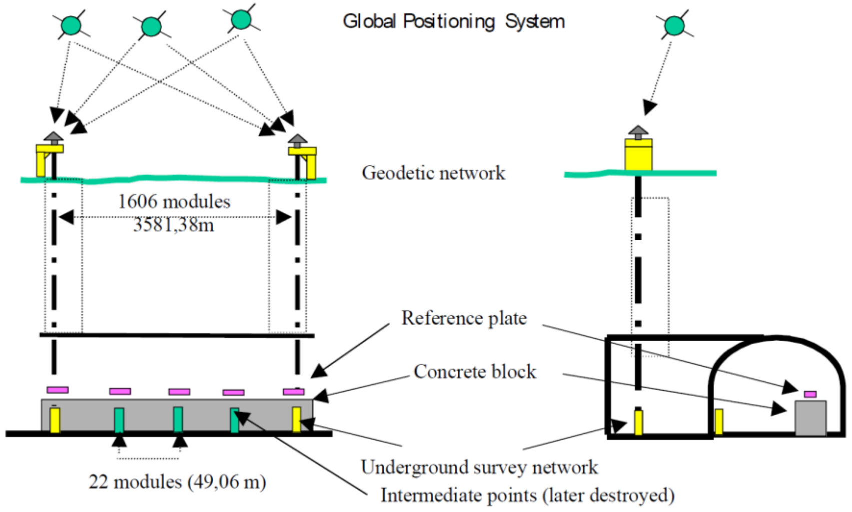
[Quesnel]

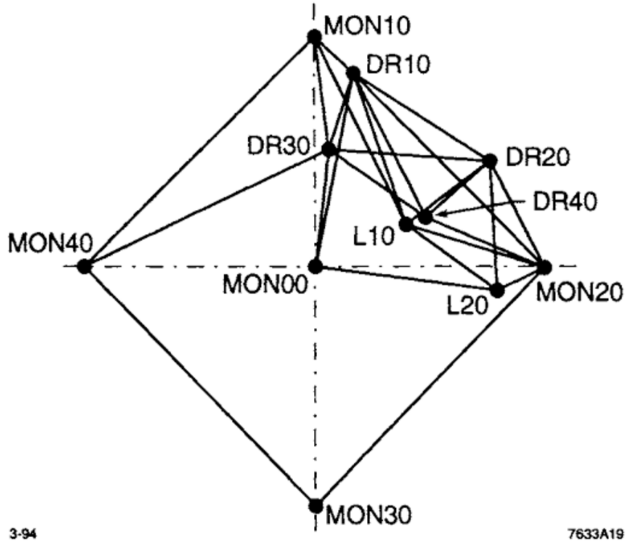
Definition of alignment strategy



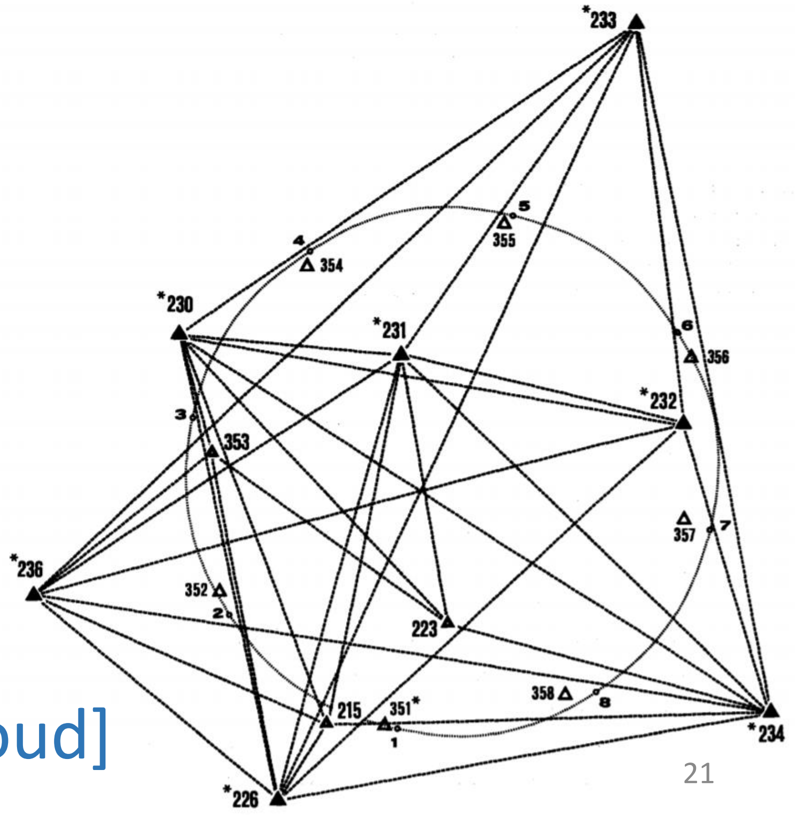
Surface geodetic network

- Installation of a geodetic network on surface + pillars close to each access pit
- Determination of pillars position using GPS
- Determination of vertical deflection using astronomical observations





[Ruland2] Example of surface network (Argonne APS).

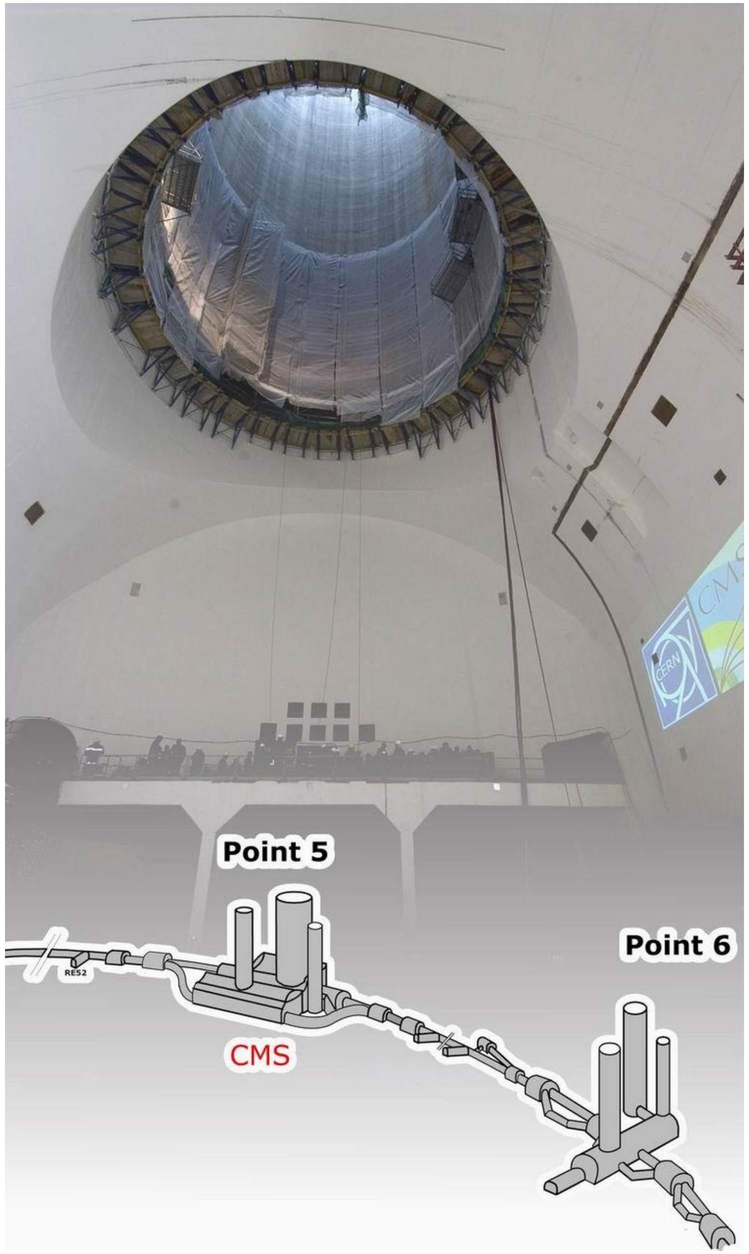


[Mayoud]

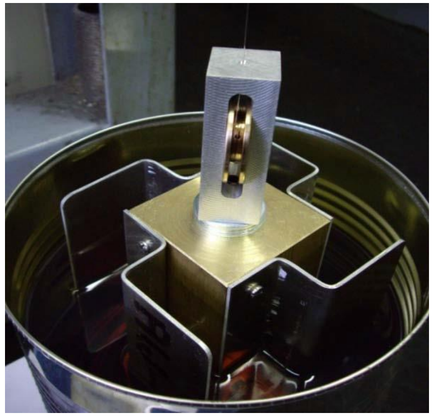
Transfer of geodetic network

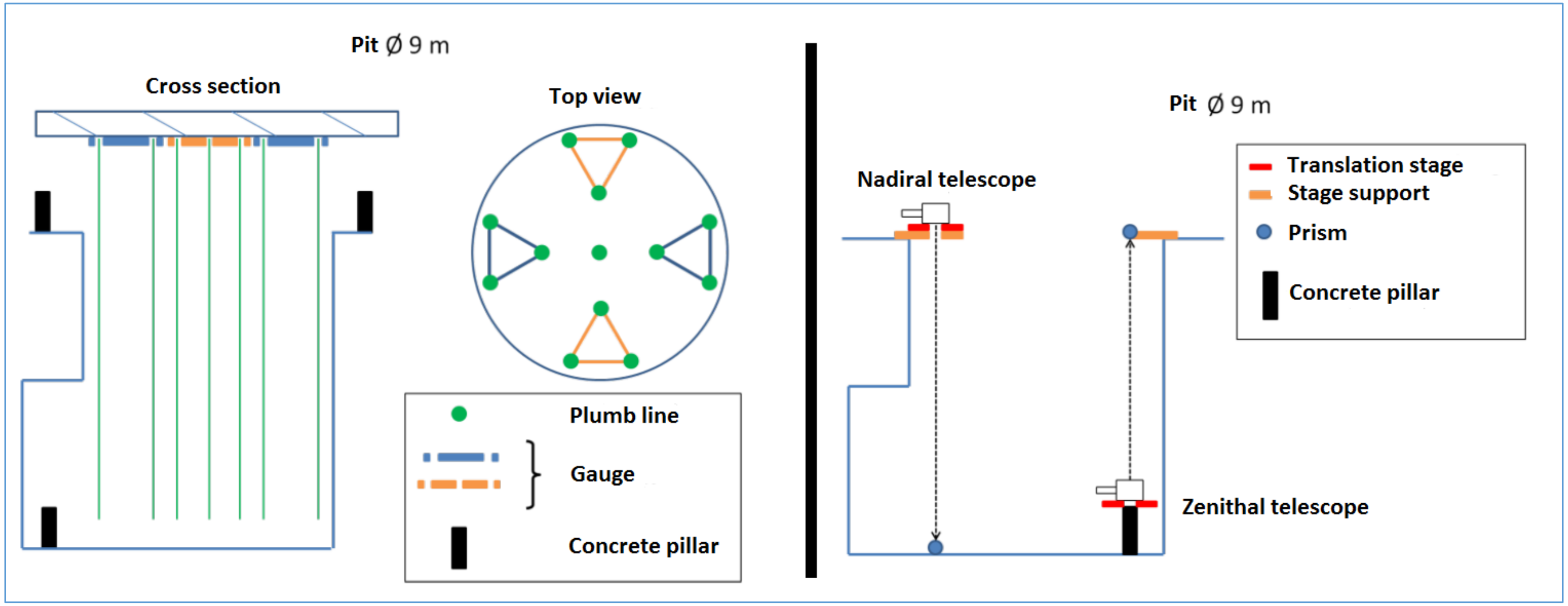
Survey monuments are installed close to each pit on the surface, measured by GPS means. The equipotential of gravity will be determined at the surface level by a combination of high accuracy gravimetric measurements and zenithal camera measurements.

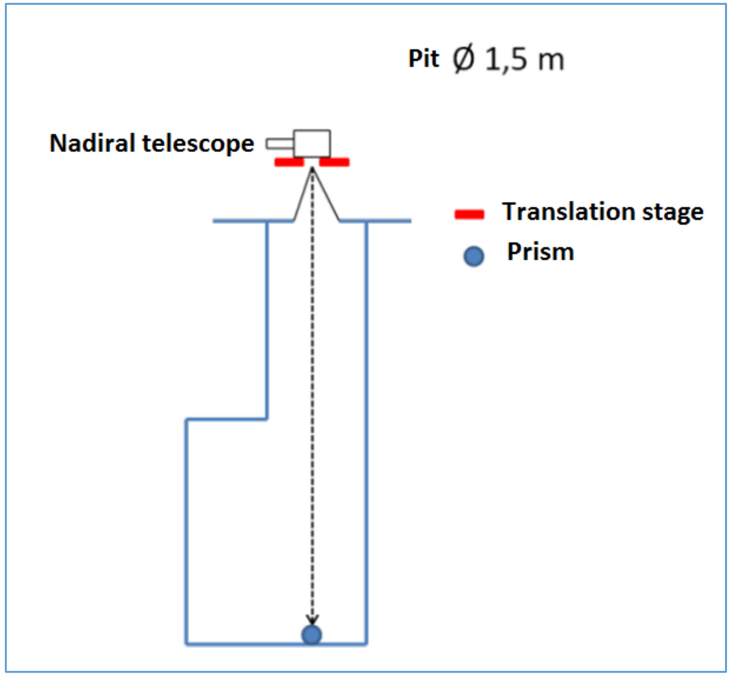
These reference points will be transferred from the surface to the tunnel through pits, using a combination of 3D triangulation and trilateration measurements coupled with angular measurements w.r.t. plumb line. These methods were validated in a LHC pit (depth of 65 m), with an accuracy of 0.5 mm.



Transfer of geodetic network







Nadiral telescope = optical plumb line [Hugon]

Combination of several means of measurements to decrease the impact of refraction (bending of the straight path of light)

Underground geodetic network

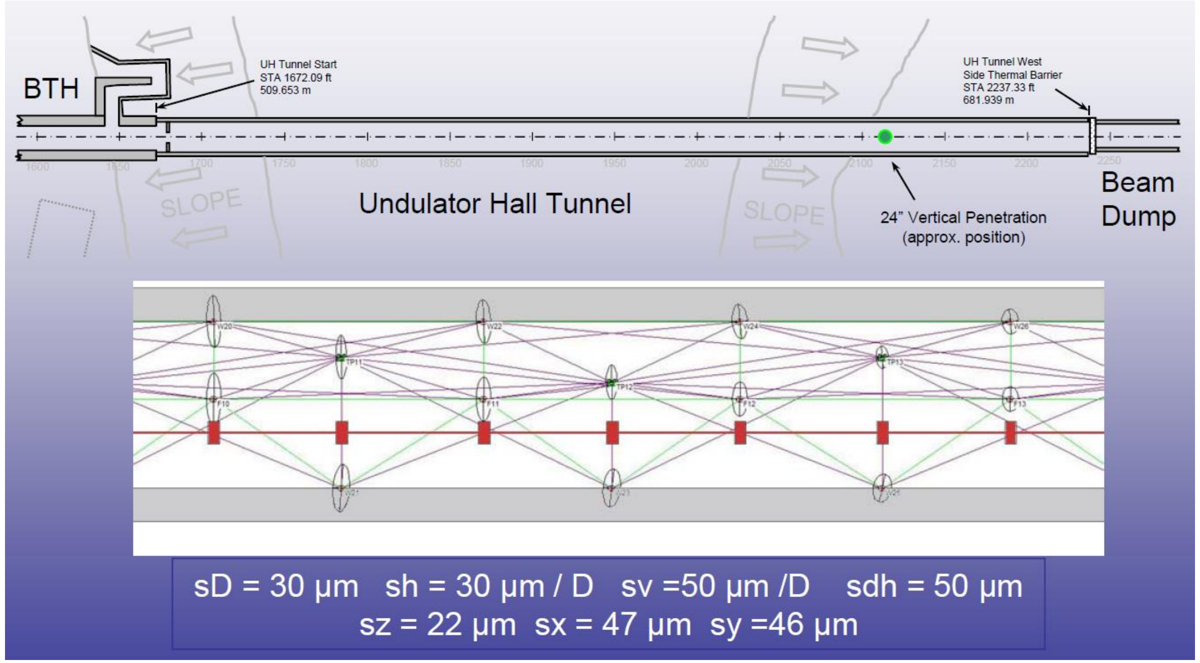
The underground networks consist of dense networks of monuments, preferably in the floor or on the walls. Several means are proposed for their determination: total station, direct levelling, gyro-theodolite measurements, in order to reach:

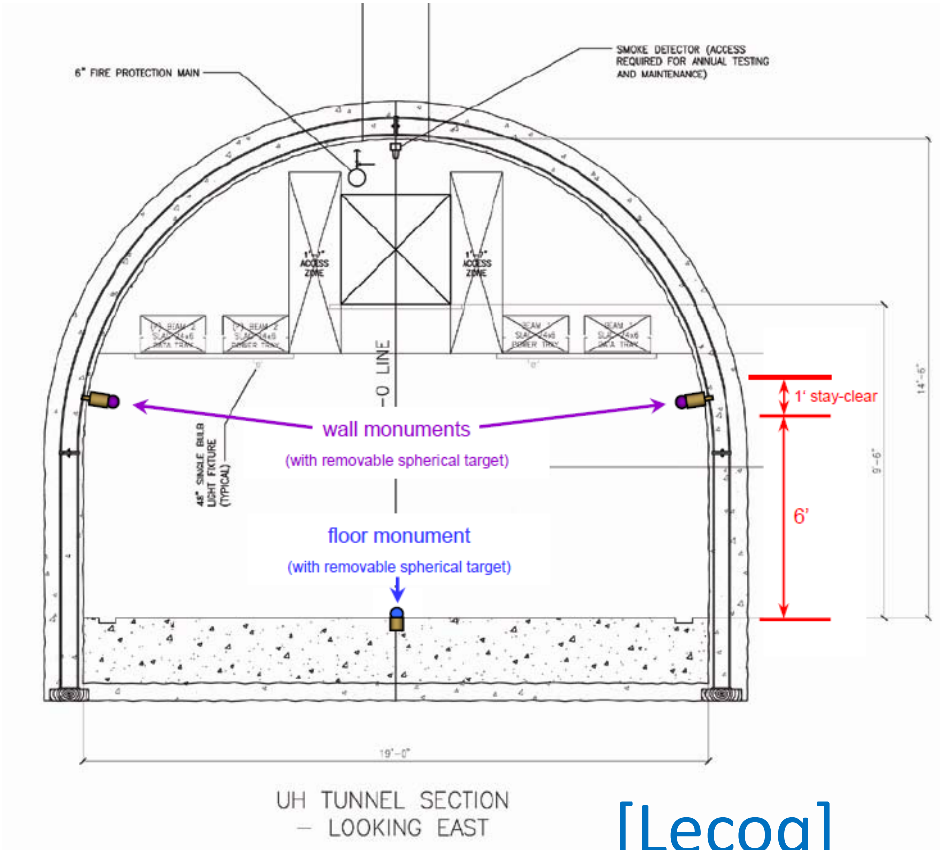
- an absolute accuracy of 3-4 mm along 3 km
- a relative accuracy in planimetry between 3 consecutive monuments of 0.3 mm r.m.s. by adding wire offset measurements and in altitude between 3 consecutive monuments of 0.1 mm.

Deep levelling references will be distributed in the tunnels. These vertical references in invar will be sealed on stable rocks, with at their extremity a mechanical interface located just below the level of the floor, and totally independent from it. Levelling measurements will be linked to these deep levelling references considered as stable along time.

Underground geodetic network

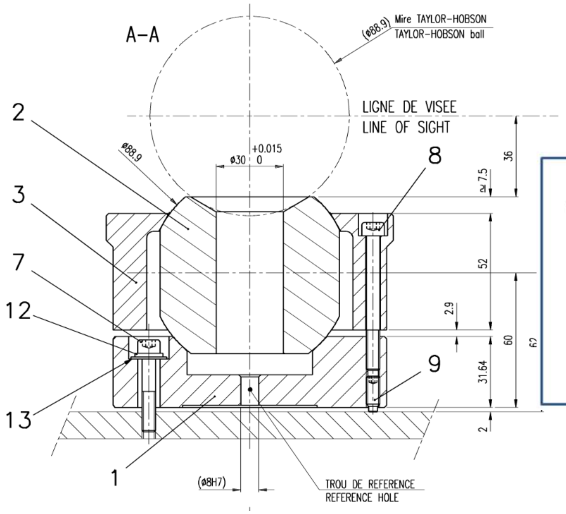
As tunnel networks are usually long & narrow, simulations allow to compute and prepare the best configuration

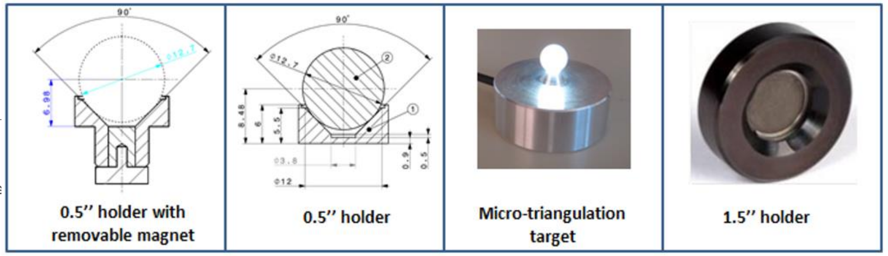




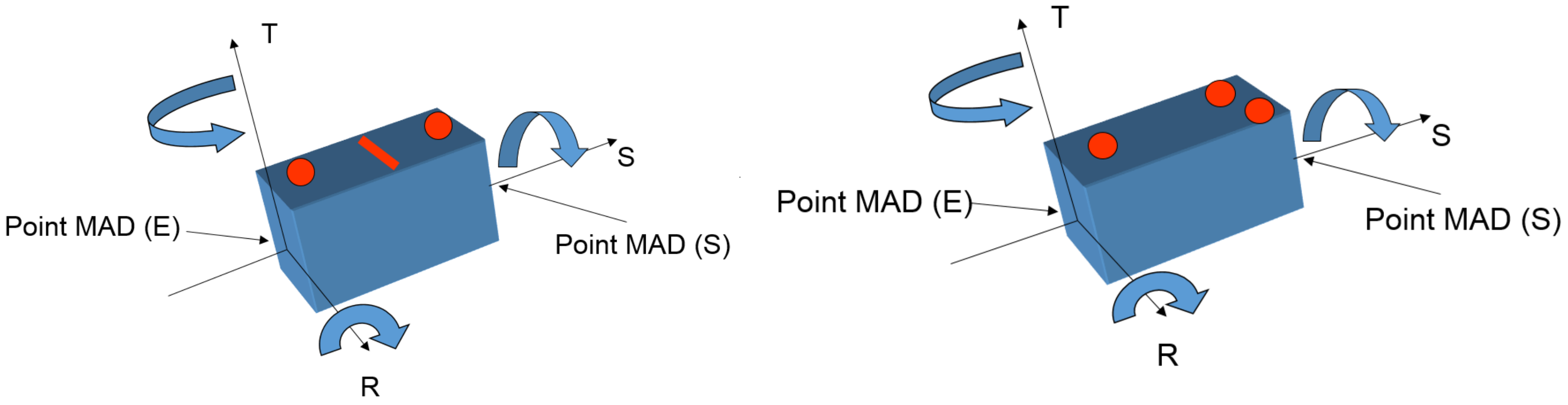
[Lecoq]

The objects to align





Each component/object to be aligned is equipped with at least two reference alignment targets and a reference for the control of the roll angle. These reference targets are called fiducials.

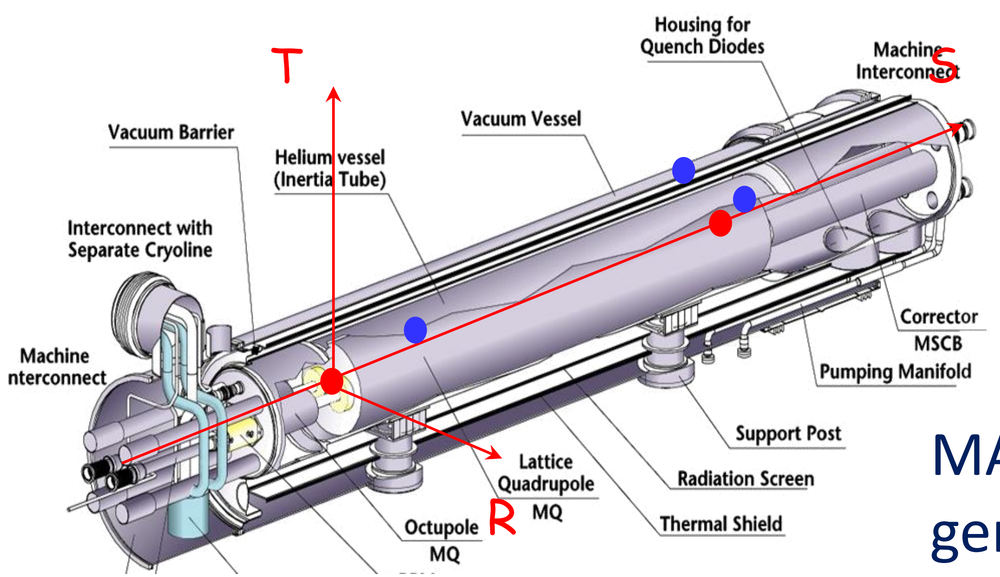


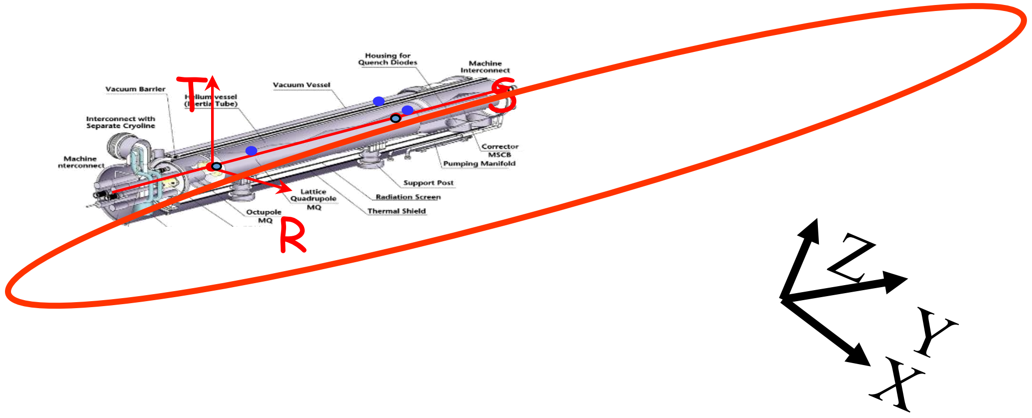
They should be located on top of the jacks to ease the adjustment, in order to minimize level arm effects.

Definition of the theoretical trajectory

To align the objects, we need their theoretical trajectory, defined by physicians, using the MAD-X software:

- First in a horizontal local coordinates system x, y, z
- Then in the CCS system





MAD-X (Methodical Accelerator Design:
general purpose tool for charged-particle optics design and studies in alternating gradient accelerators and beam lines.

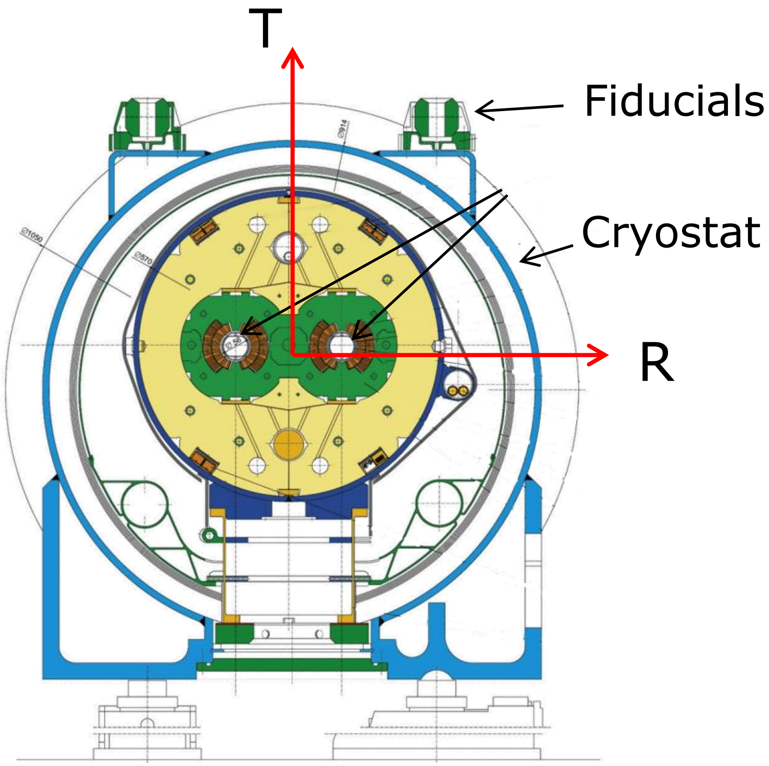
Fiducialisation

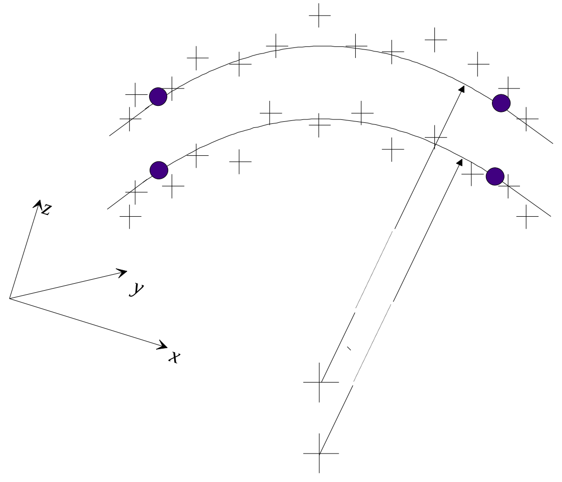
Fiducialisation is the determination of the reference axis of the component w.r.t. its external alignment targets (fiducials) accessible to survey measurements.

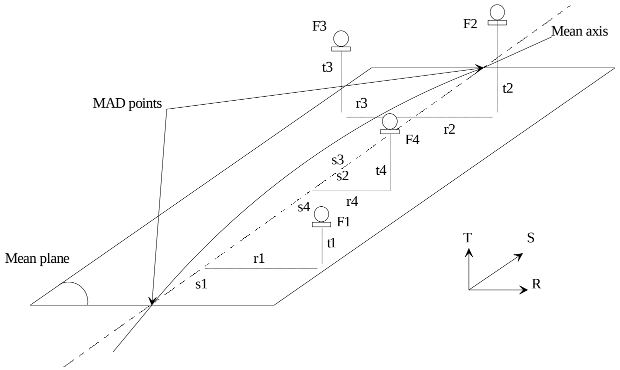
3 types of measurements according to the accuracy needed:

- Mechanical measurements using a gauge (typically for warm magnets)
- Laser tracker measurements when the requirements are of the order of 0.1 mm rms
- CMM measurements, for smaller components and requirements of the order of micrometers.

Fiducialisation







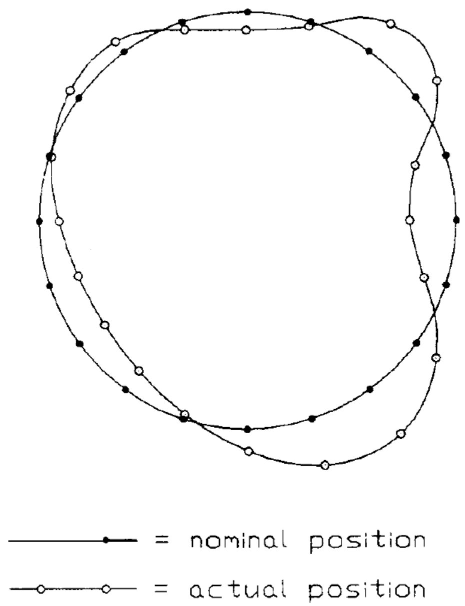
The geometric axis is defined as the best fit of a series of points located in the center of each cold bore tube (with an auto-centering device going through it) and measured from both extremities

Alignment tolerances

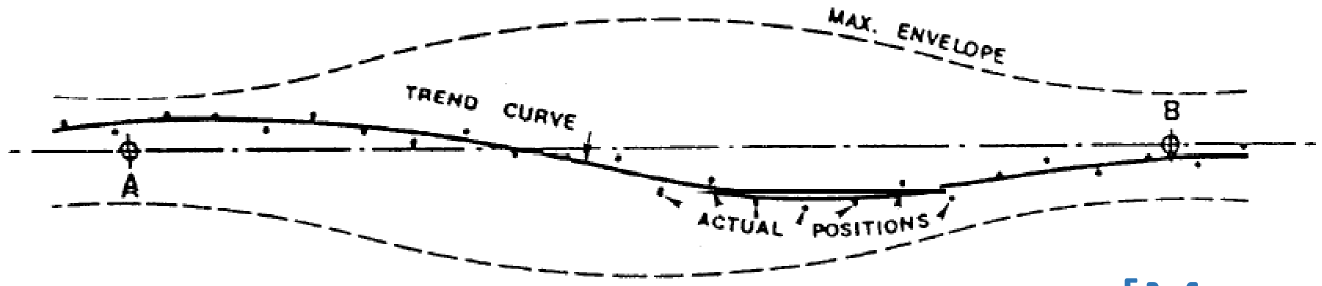
Beam simulations provide the parameters of components and position tolerances (maximum permissible displacements in the direction of the 3 coordinates and roll)

Absolute positioning tolerance: max. shape distortion by specifying how close is a component from its theoretical position

Relative positioning tolerance: alignment quality of adjacent components.



[Schwarz]



[Mayoud]

Position of magnets with respect to theoretical orbit

Alignment requests

Accelerator / collider	Epoch	Radius / circumference	Vertical (mm) @ 1σ	Radial (mm) @ 1σ
PS ring	50's	100 m / 650 m	± 0.3	± 0.6
SPS	70's	1 km / 6 km	± 0.2	
LEP (e+e-)	80's	5 km / 27 km	± 0.2 – 0.3	
LHC (hh)	90's	5 km / 27 km	± 0.15	

Along a given window

Absolute alignment

Sequence of tasks:

- **Marking on the floor:** consists of marking the vertical projection of the geometrical mean of the beam line, the position of the elements, the interconnection points and the vertical projection of the head of jacks on the floor.
  Accuracy ~ ± 2 mm

- **Positioning of the jacks:** the stroke of jacks compensates the errors of the floor, the errors in their positioning, cryostat construction errors and ground motion during the life of the accelerator. The jacks are positioned within ± 2 mm. Then, the jacks are sealed on the floor and their position is checked again.

Absolute alignment

Sequence of tasks:

- **First positioning:** it takes place once the components are installed on their jacks. Each component is aligned independently with respect to the underground geodetic network. A component is considered aligned once its fiducials have reached their theoretical position.

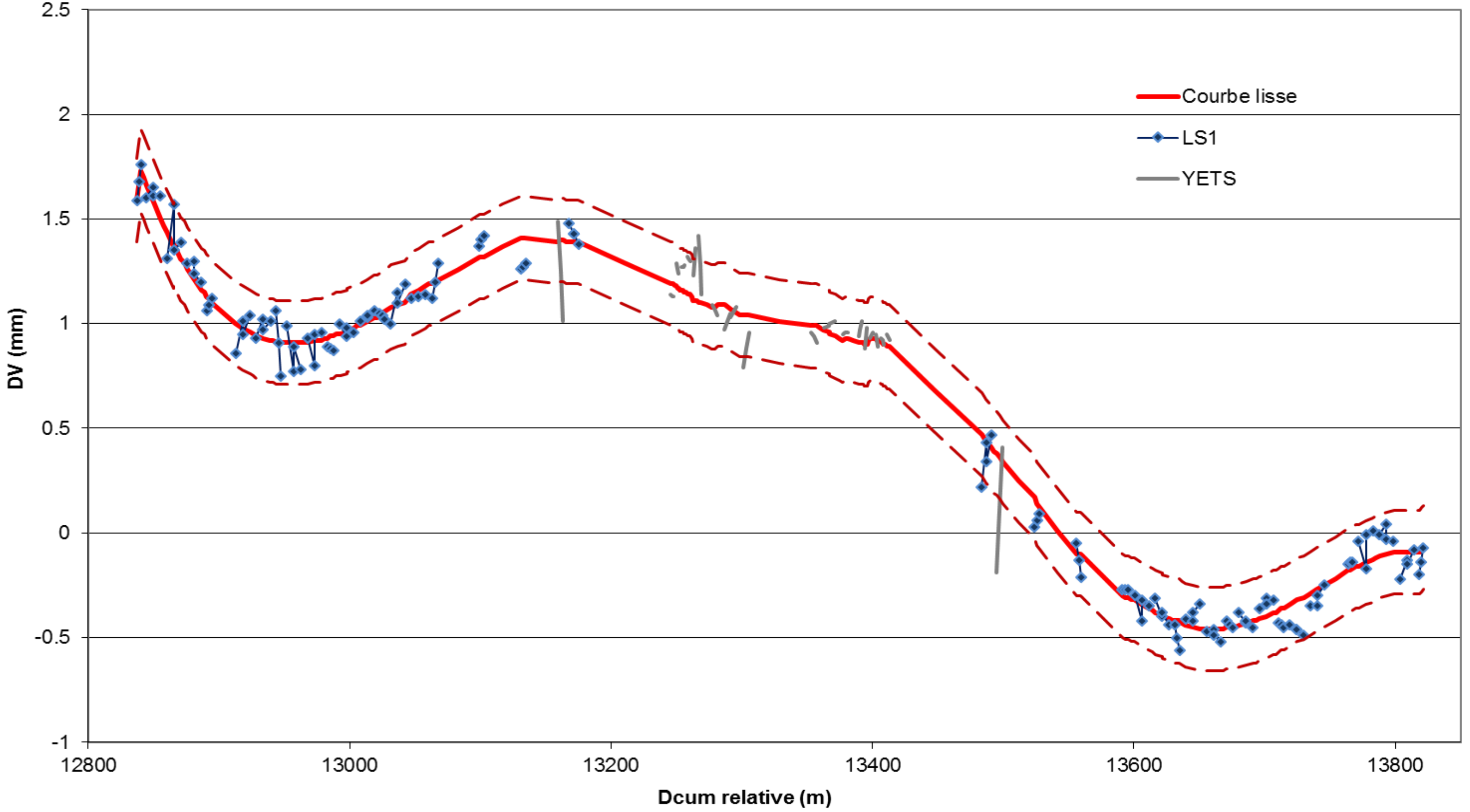
- At the same time, a small local smoothing from magnet to magnet is carried out to decrease the influence of the small relative errors between the points of the geodetic network.

Relative alignment

Smoothing: the process can only start once the magnets are connected, under vacuum and are cold down, so that all the mechanical forces are taken into account. The objective is to obtain a relative radial and vertical accuracy of 0.15 mm over a distance of 150 m.

The smoothing initially corrects both residual errors in the first positioning and ground motion.

Vertical smoothing of LSS5

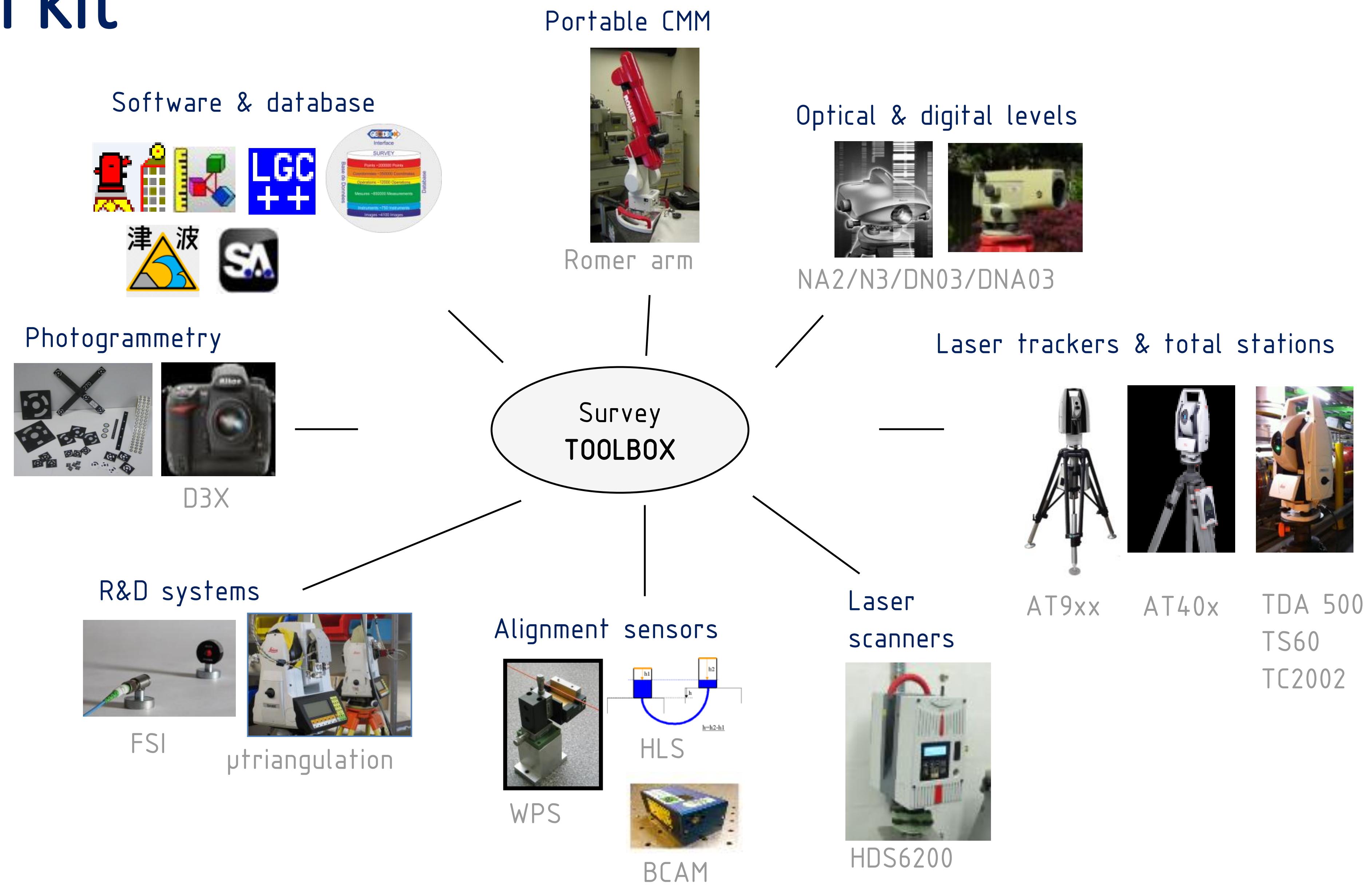


Once we have:

- A coordinate reference system,
- The theoretical alignment position of the fiducials in the system
- Components equipped with the fiducials

We need the instrumentation & devices to determine the position of components and adjust them in the tunnels…

Our tool kit

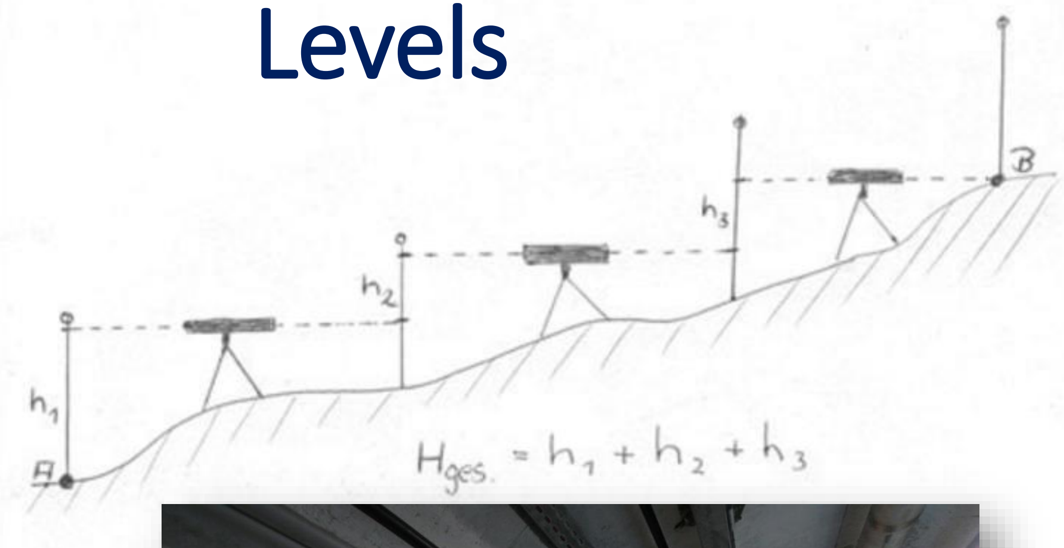


Portable CMM
Romer arm
Software & database
LGC ++
SA
Optical & digital levels
NA2/N3/DN03/DNA03
Photogrammetry
D3X
Survey
TOOLBOX
Laser trackers & total stations
AT9xx
AT40x
TDA 500
TS60
TC2002
R&D systems
FSI
μtriangulation
Alignment sensors
WPS
HLS
BCAM
Laser
scanners
HDS6200

Instrumentation toolkit

- Determination of the position
  - Standard instruments
    - Levels
    - Laser tracker
    - Total station
    - AT40x
    - Photogrammetry
  - Alignment systems
- Adjustment

Levels



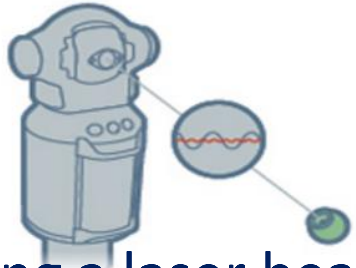
Leica NA2 & NA2K levels

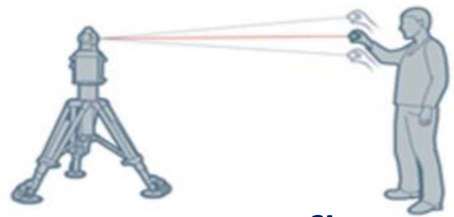
- Art. No. Leica NA2 automatic level: 352036
- Art. No. Leica NAK2 360 automatic level: 352038
- Art. No. Leica NAK2 400 automatic level: 352039

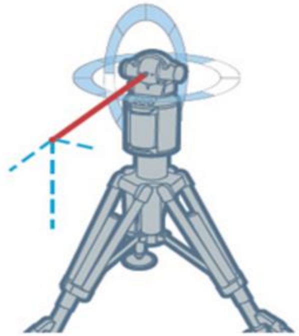
Technical Data	NA2 / NAK2
Standard deviation for 1 km double-run levelling, depending on type of staff and on procedure	up to 0.7 mm
With parallel-plate micrometer	0.3 mm
Telescope	erect image
Standard eyepiece	32 x
FOK73 eyepiece (optional)	40 x
FOK117 (optional)	25 x
Clear objective aperture	45 mm
Field of view at 100 m	2.2 m

A level is an instrument with a telescope that can be leveled with a spirit bubble. The optical line of sight forms a horizontal plane at the same elevation as the telescope cross hair. By reading a graduated rod held vertically, you can deduce the difference of height between points.

Laser tracker







(Bob Bridges)

- Measure 3D coordinates by tracking a laser beam to a retro-reflective target
- Combination of two techniques:
  - A distance meter to measure absolute distance (laser interferometer or Absolute Distance Meter, based on the time of flight of an infrared beam)
  - Angular encoders to measure the laser tracker’s two mechanical axes

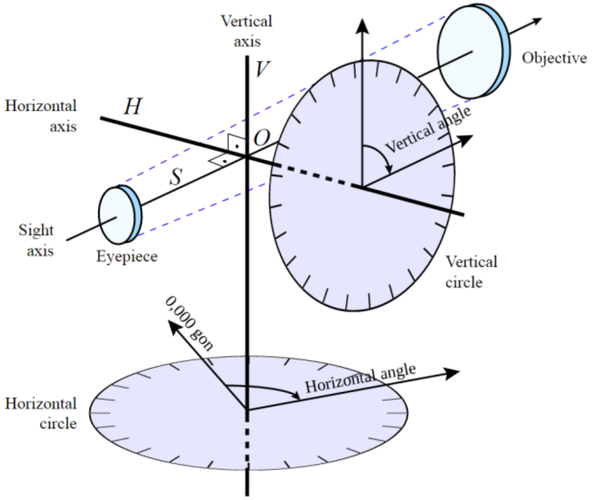
Accuracy *	$U_{x,y,z}$ = +/-15 µm + 6 µm/m

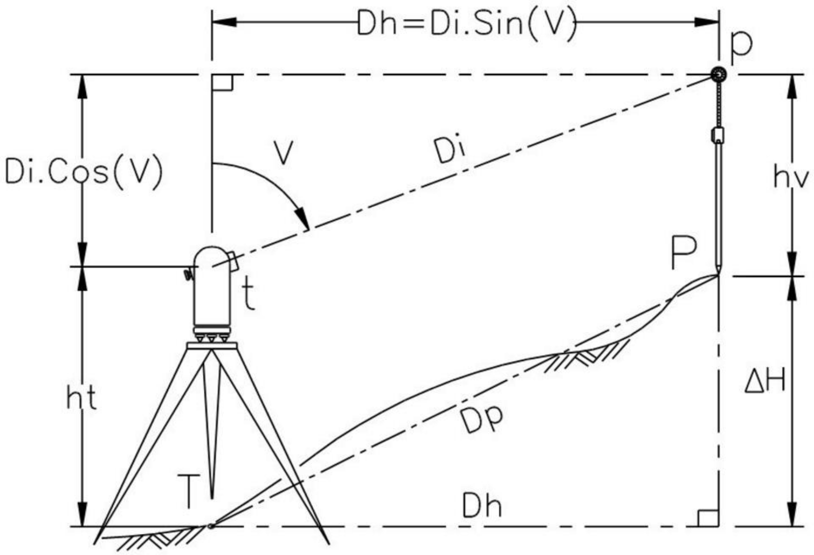
* All accuracies are specified as maximum permissible errors (MPE) and calculated per ASME B89.4.19-2006 & draft ISO10360-10 using precision Leica 1.5” Red Ring Reflectors up to 60 m distance unless otherwise noted.

Angle accuracy	+/-15 µm + 6 µm/m
Distance accuracy AIFM	+/-0.5 µm/m
Dynamic lock on	+/-10 µm
Orient to Gravity (OTG)	$U_{z(OTG)}$ = +/-15 µm + 8 µm/m

Total station

Same combination of two types of measurements:
- Angle measurements based on encoders
- Distance measurements using Electronic Distance Measurements (EDM)





Common Specifications for TDM/TDA5005 and TM5100A	
Angular measurement	
Standard deviation per ISO17123-3, 1 σ [1]	0.5" (0.15 mgon)
Units of measurement	360° sexagesimal, 400 gon 360° decimal, 6400 mil
Display (smallest selectable unit)	0.01 mgon; 0.1", 0.00001°, 0.00001 mil

Specifications TDM/TDA5005	
Point accuracy (total RMS ≈ 1 σ) [2] at 20 m (65 ft) measuring volume	≤ 0.3 mm (0.012")
Distance measurement	*(integrated in the TDM5005 and TDA5005)*
Standard deviation (absolute) per ISO17123-4, 1 σ	1 mm + 2 ppm (0.04" + 2 ppm) over the entire measurement range
Typical distance accuracy at 120 m (365 ft) measuring volume[3]	
Reflective tape	± 0.5 mm (0.02")
Corner cube reflector	± 0.2 mm (0.008")
Units of measurement	m, mm, feet, inch
Display (smallest selectable unit)	0–5 decimal places, dependent on the selected unit

LEICA AT40x

- Between a total station & laser tracker
  - Distance meter (0.02 mm)
  - Horizontal & vertical encoders of TDA5000(1,5 dmgr)
  - Measurement up to 160 m

Absolute Distance Performance*

Resolution: 0.1 µm

Accuracy: +/- 10 µm (+/- 0.00039”)

Repeatability: +/- 5 µm (+/- 0.0002”)

Absolute Angular Performance*

Resolution: 0.07 arc seconds

Accuracy: +/- 15 µm + 6 µm/m (+/- 0.0006” + 0.000072”/ft)

Repeatability: +/- 7.5 µm + 3 µm/m (+/-0.0003” + 0.000036”/ft)

U_{xyz} Coordinate Uncertainty*

The measurement uncertainty of a coordinate “U_{xyz}” is defined as the deviation between a measured coordinate and the nominal coordinate of that point. This measurement uncertainty is specified as a function of the distance between the laser tracker and the measured point.

Reflector:

+/- 15 µm + 6 µm/m (+/- 0.0006”+0.000072”/ft)

*Maximum Permissible Error (MPE)

A 3D portable CMM

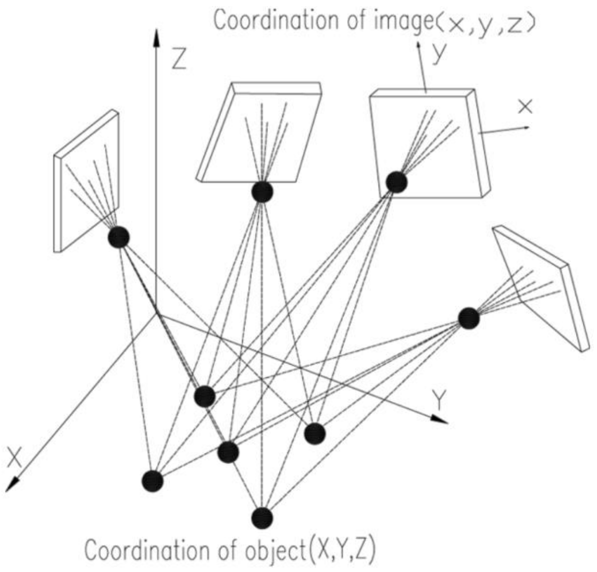
		B89.4.22		ISO 10360-2		
Model	Measuring range	Point repeatability	Volumetric accuracy	MPEp	MPEe	Arm weight
7312	1.2 m / 3.9 ft.	0.014 mm / 0.0006 in.	± 0.025 mm / 0.0010 in.	8 µm	5+L/40 ≤ 18 µm	10.2 kg / 22.5 lbs
7512	1.2 m / 3.9 ft.	0.010 mm / 0.0004 in.	± 0.020 mm / 0.0008 in.	6 µm	5+L/65 ≤ 15 µm	10.8 kg / 23.8 lbs

Photogrammetry

Photogrammetry: science of making measurements from photographs

Advantages of photogrammetry

- Image acquisition needs no stable station
- Flexible use following object size
    - Components < 1 m (1 sigma < 50 micron)
    - Components up to 15-25 m (1 sigma < 0.5 mm)
- Mobile System
    - Off-site interventions in factories
    - Various assembly halls and experimental caverns
- Limited measurement time for large amount of points
    - Short interruption for installation, production process



Photogrammetry

Digital photogrammetry since 1997 at CERN
- Fully automated processing
- Underexposed, convergent images
- High redundancy, reliability
- Blunder detection at measurement and adjustment level

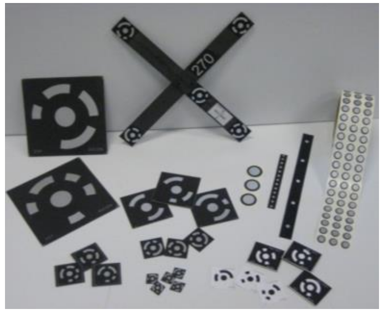
Reference points signalised by targets (increased precision)
- CERN Reference Hole 8mm H7

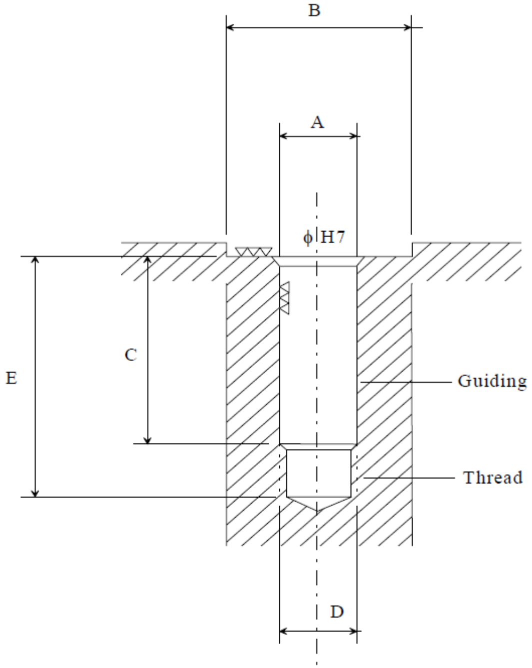
Used in combination with other systems
- scale, link to accelerator geometry

Used in all LHC experiments and others

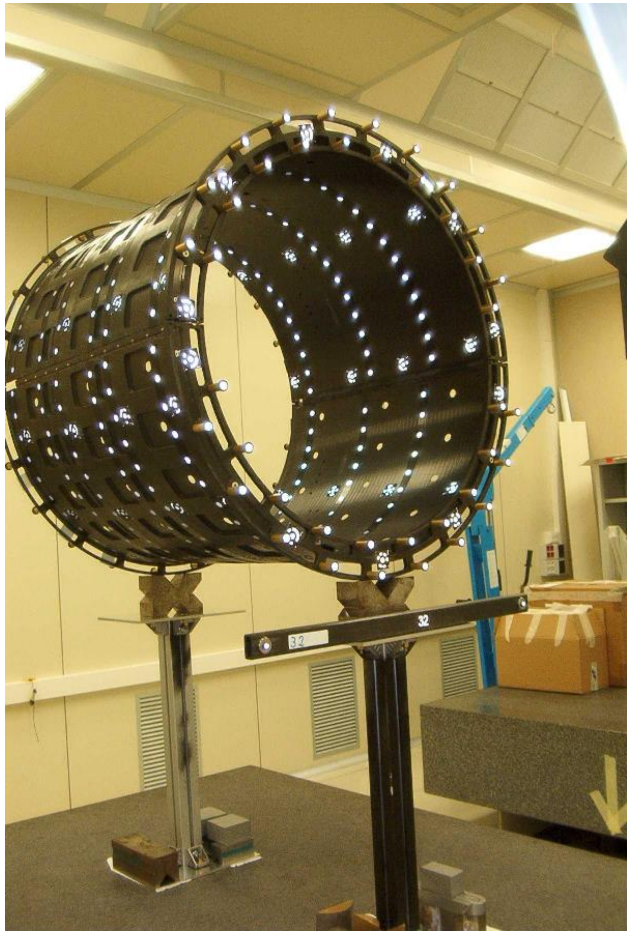
Nikon D2X

Targets

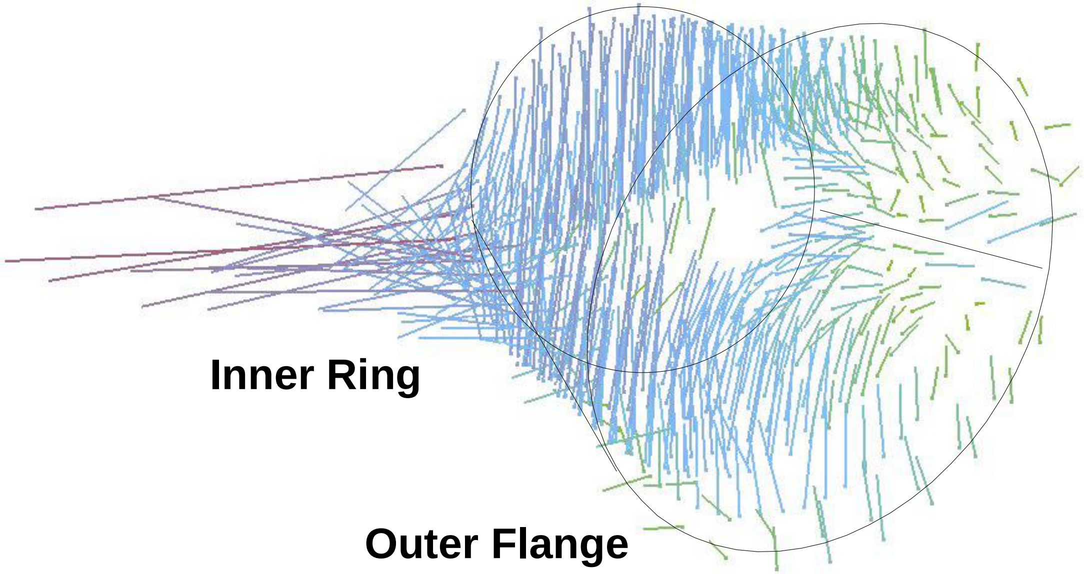




Photogrammetry: applications



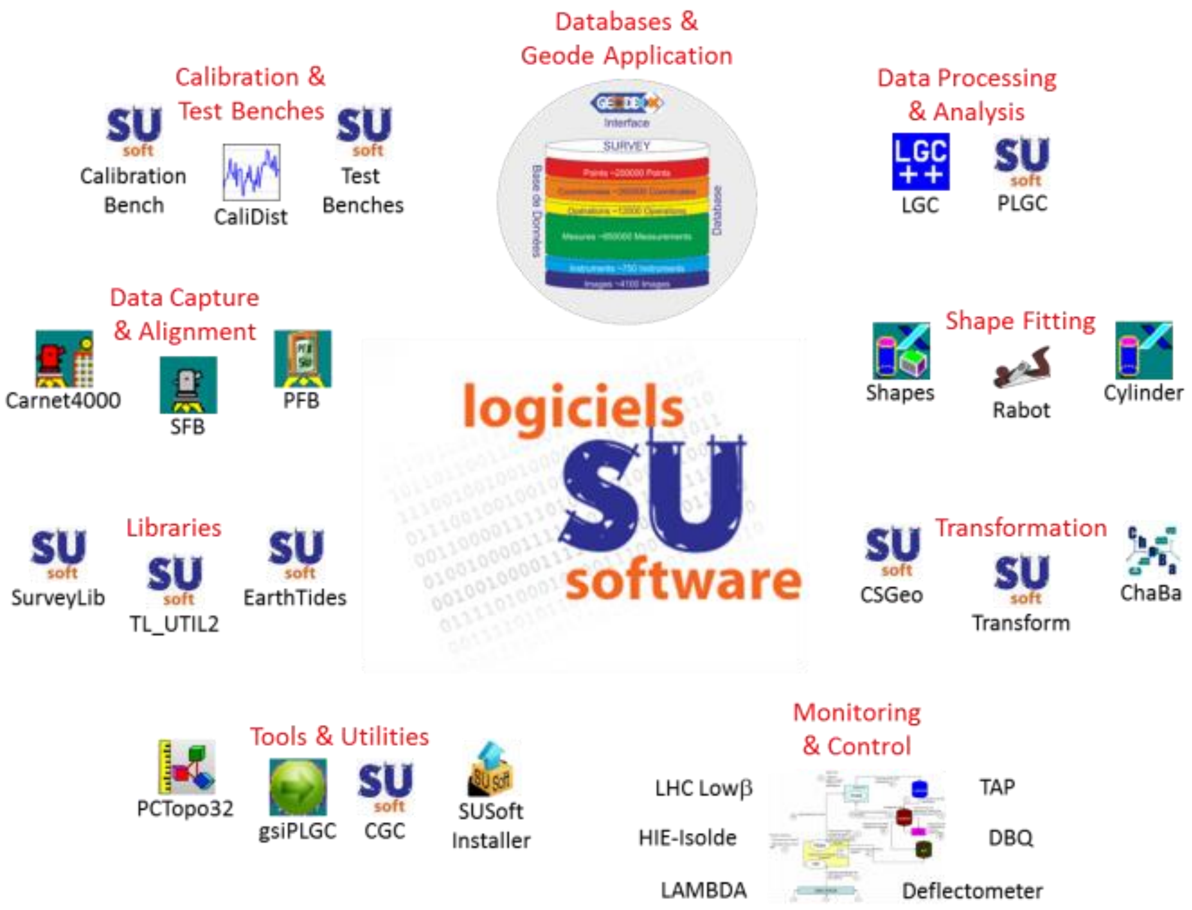
CMS Tracker Barrel



Max. difference to best-fit cylinder

- +1.49 mm
- - 0.95 mm
- Deformation max. 0.38 mm
- Comparison on identical points

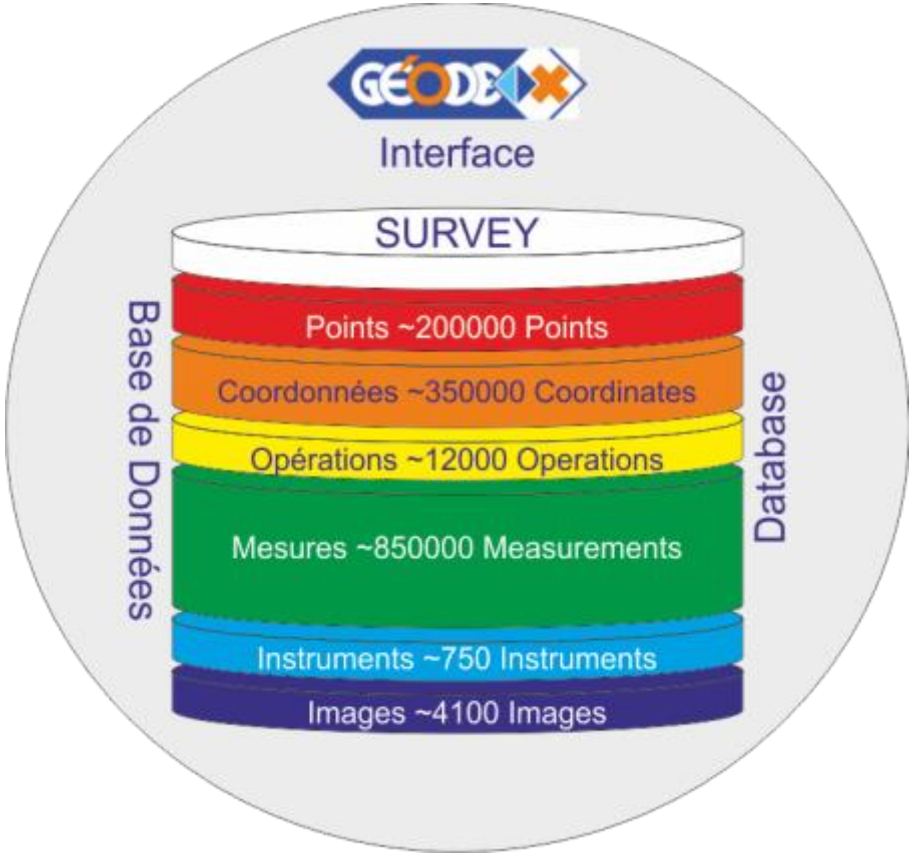
Software and Database Applications



Data processing& analysis

- Local 3-D adjustment on the ellipsoid GRS80;
- Altitudes are referred to the known local geoid and are converted into ellipsoidal heights;
- Generalized least-squares processing of all types of available data
- All angular measurements, observed relative to the local horizon, are re-expressed in the CCS through an appropriate rotation matrix;
- Direct levelling data is processed as vertical distances
- Statistical and variance analysis of the results;
- Generation of random and/or systematic perturbations for simulations;
- Preparation of files for weighted Helmert transforms;

Survey database



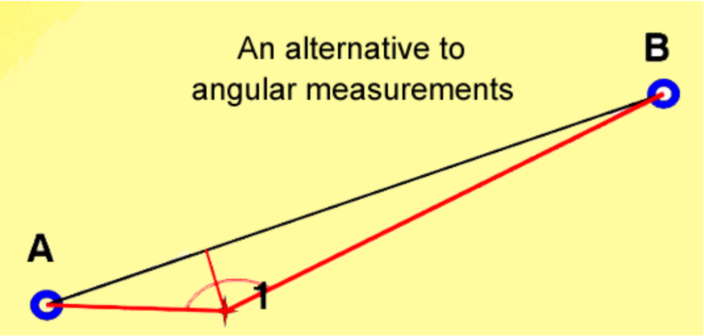
- Principal Client
  - Survey Team

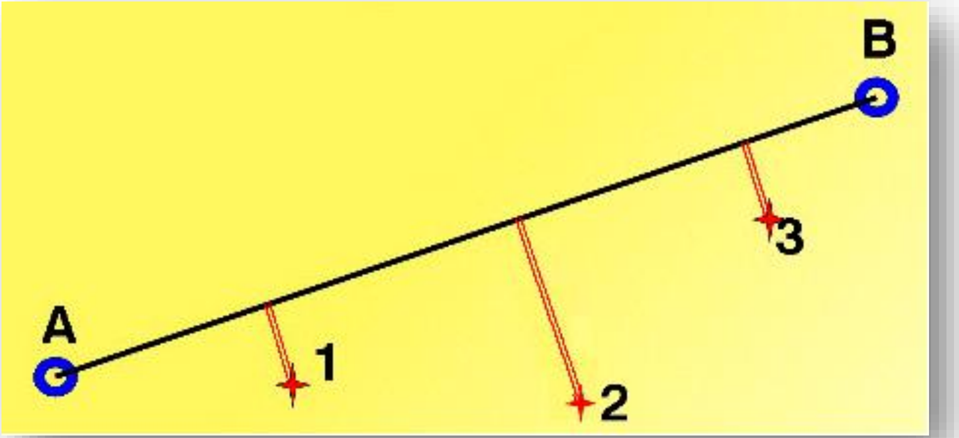
- Other Clients
  - Operators, Layout, Integration, GIS (Geographic Information Service)

Instrumentation toolkit

- Determination of the position
  - Standard instruments
  - Specific alignment systems
    - Wire offsets
    - BCAM
    - Hydrostatic Levelling System (HLS) & applications
    - Wire Positioning System (WPS) & applications
    - Drawbacks of WPS & HLS
    - Laser based alignment systems
- Adjustment

Wire offset measurements





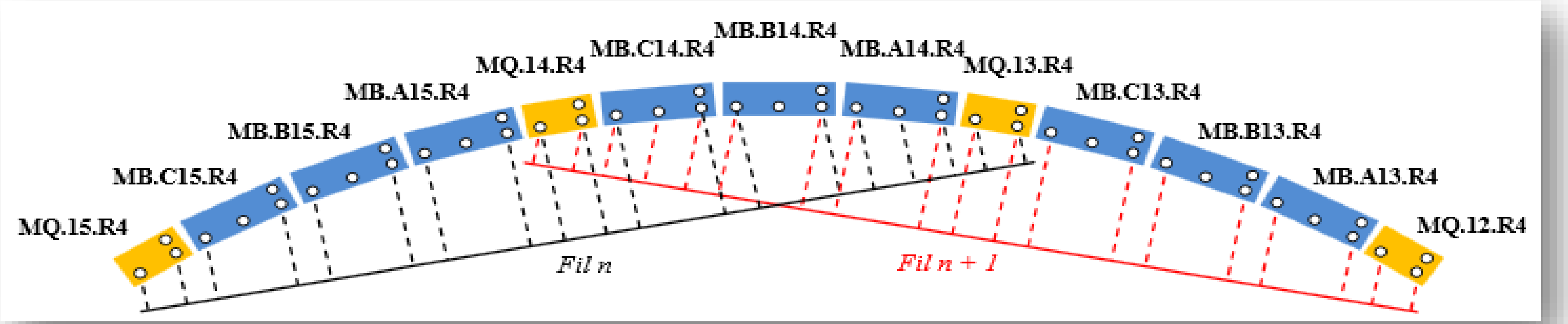
Measurement of the shortest distance between a point and line [AB]

Manual device
Accuracy 0.07mm

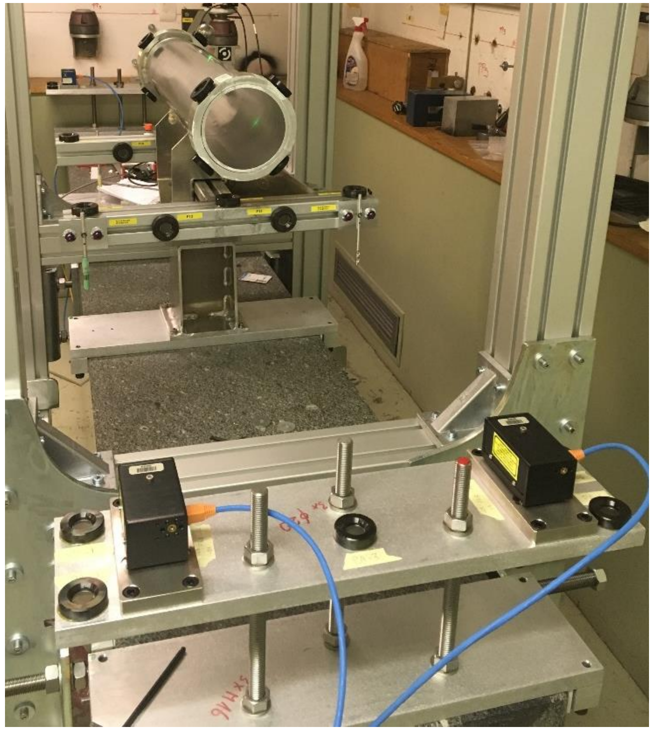
Automatic device
Accuracy 0.1mm

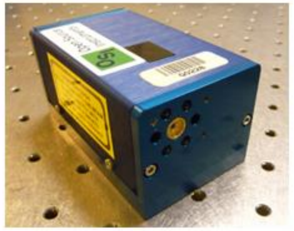
How to use a stretched wire in a circular collider?

- Wire length: 120 m
- Overlapping area to get redundancy
- Precision independent from the length of the wire
- Wire must be protected from air currents.
- Speed of measurements > 400 m/day, 80 points / day.

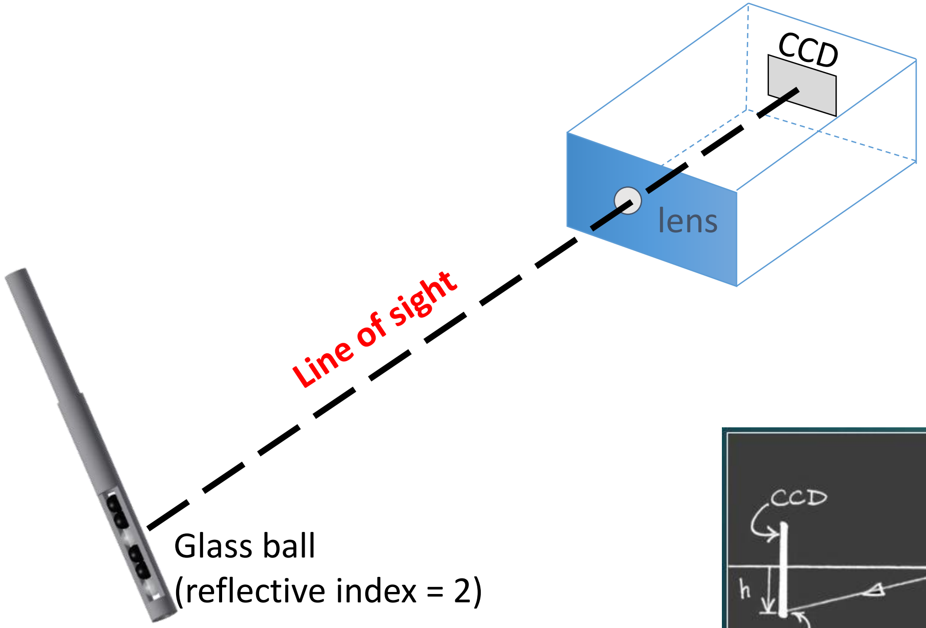


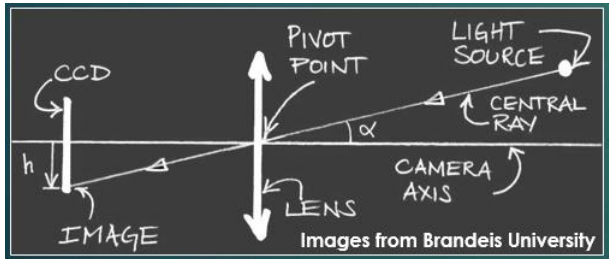
BCAM : Brandeis Camera Angle Monitor





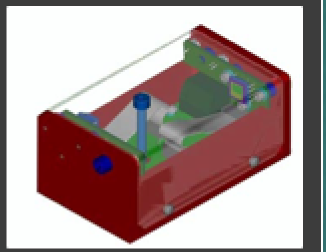
Based on image acquisition of reflective targets





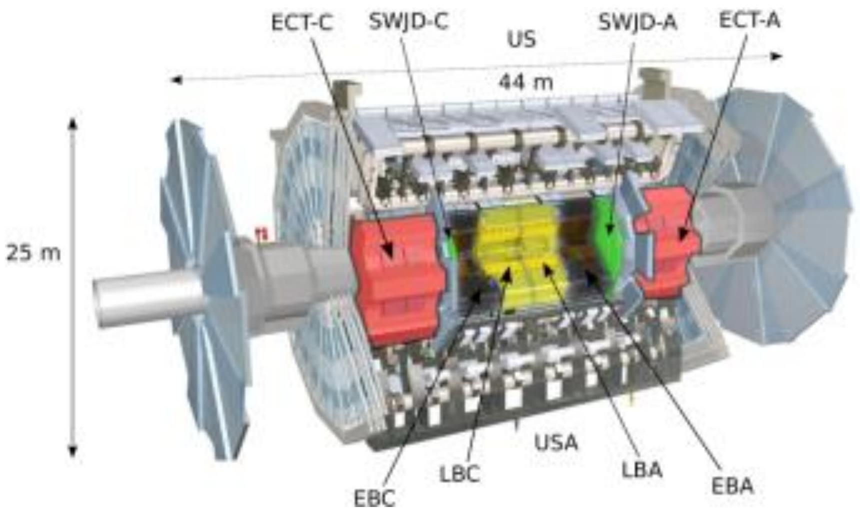
BCAM:

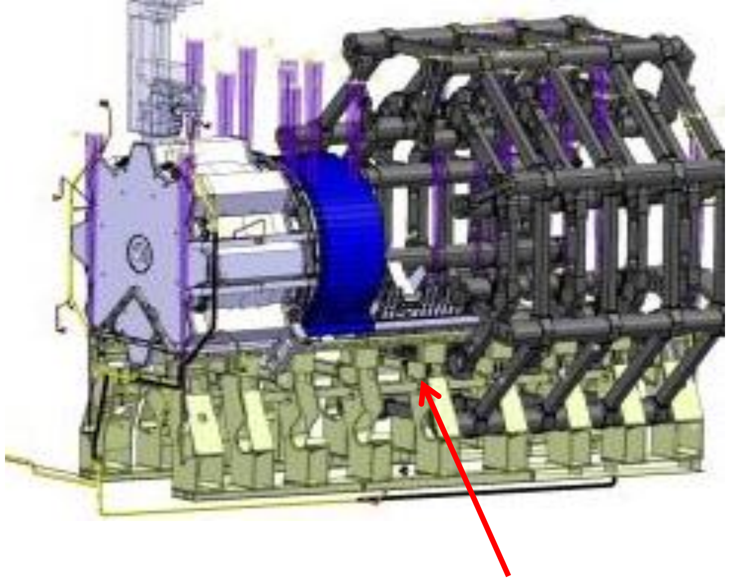
- ✓Viewing window = 30×40 mrad;
- ✓Precision = 5 μrad;
- ✓Non-magnetic;
- ✓Accept a total of 400 Gray.



Monitoring

- To gain time
- Improve accuracy
- No access needed





Requirements:

- Monitor and speed up closure
- Gain in precision for re-positioning
  - Relative repositioning at 0.3 mm (1σ)
  - Movement follow-up at 0.1 mm
- Cover 6 DOF per moving detector
- Cycle < 30 sec.
- Resist to 1 Tesla magnetic field
- Radiation dose of 2 Gy for lifetime

System is based on:

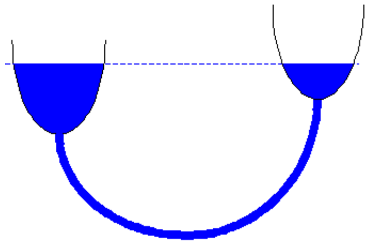
- 28 BCAMs on feet/rails system
- 44 passive targets (prisms)

[Gayde]

Instrumentation toolkit

- Determination of the position
    - Standard instruments
    - Specific alignment systems
        - Wire offsets
        - BCAM
        - Hydrostatic Levelling System (HLS) & applications
        - Wire Positioning System (WPS) & applications
        - Drawbacks of WPS & HLS
        - Laser based alignment systems
- Adjustment

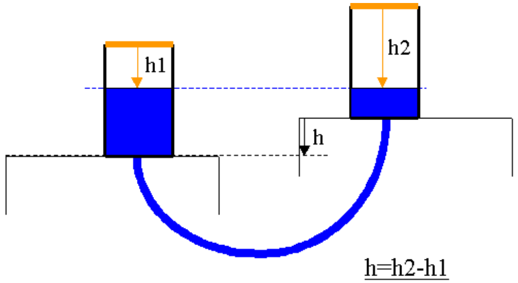
Hydrostatic Levelling System (HLS)



Based on communicating vessels

Water network = reference surface

1 sensor is installed on top of each vessel to measure the distance to the water surface contactless



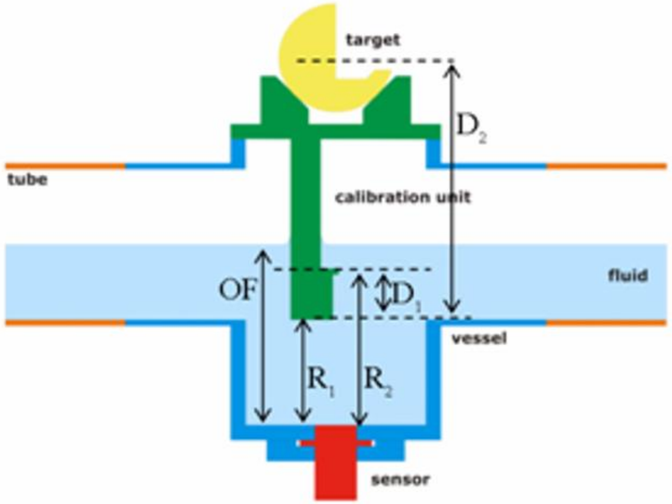
$$C = \frac{\varepsilon_o \varepsilon_r S}{d}$$

Resolution: 0.2 mm

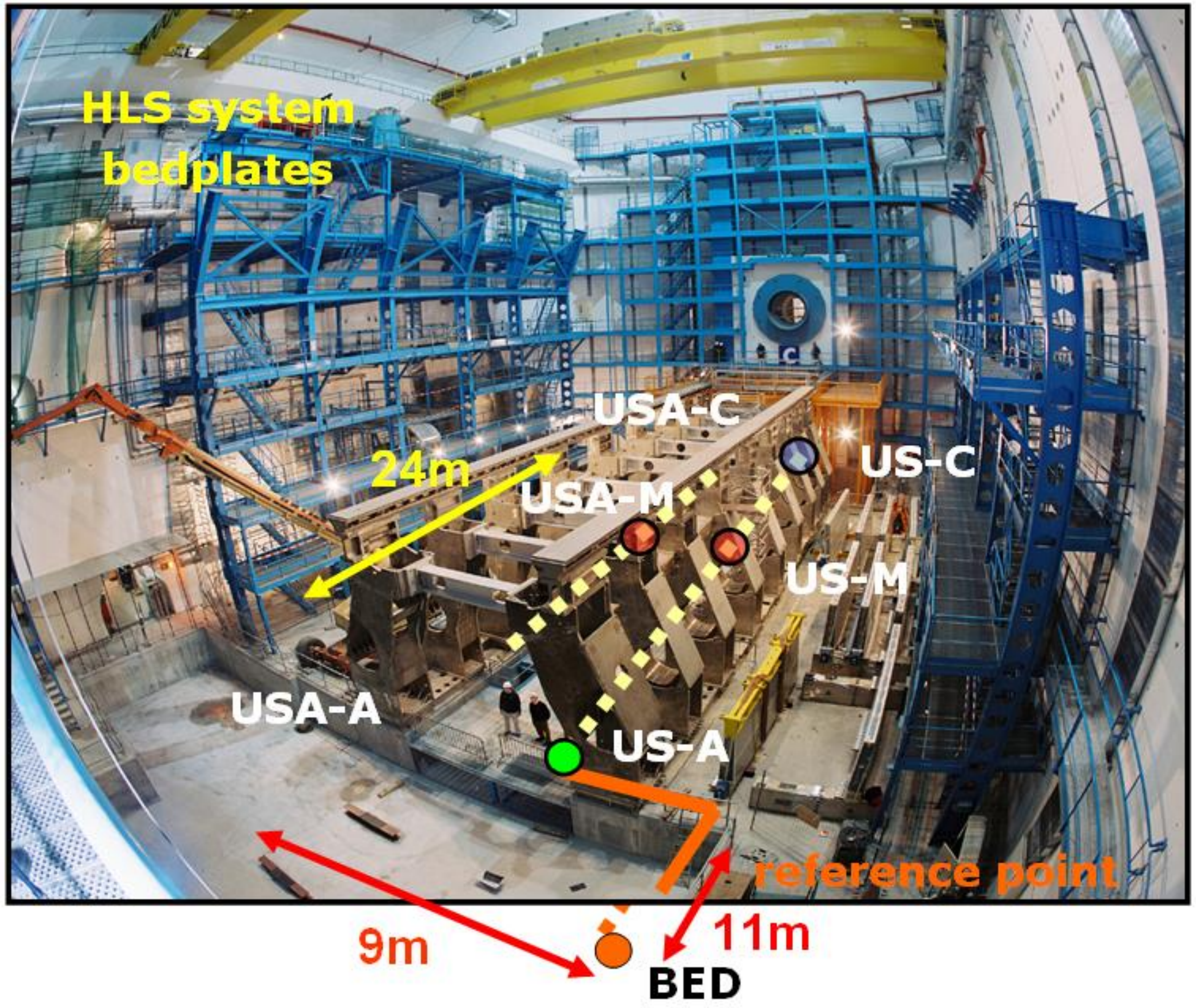
Measurement range: 5mm

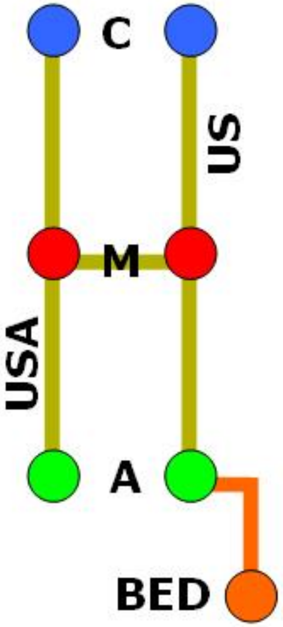
Repeatability: 1 mm

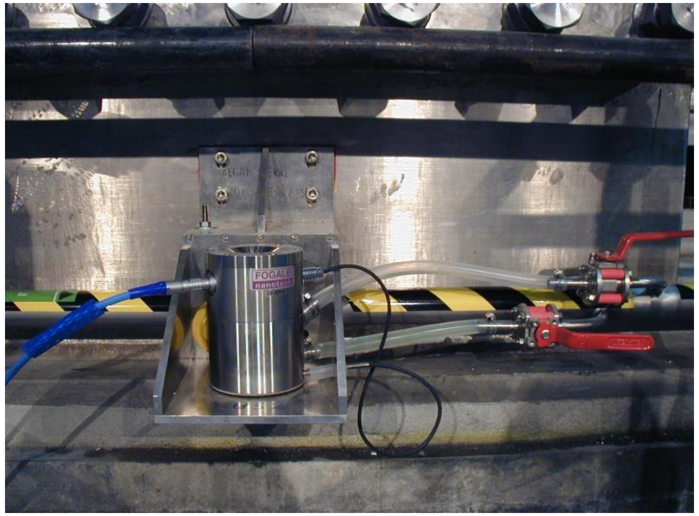
Bandwidth: 10 Hz



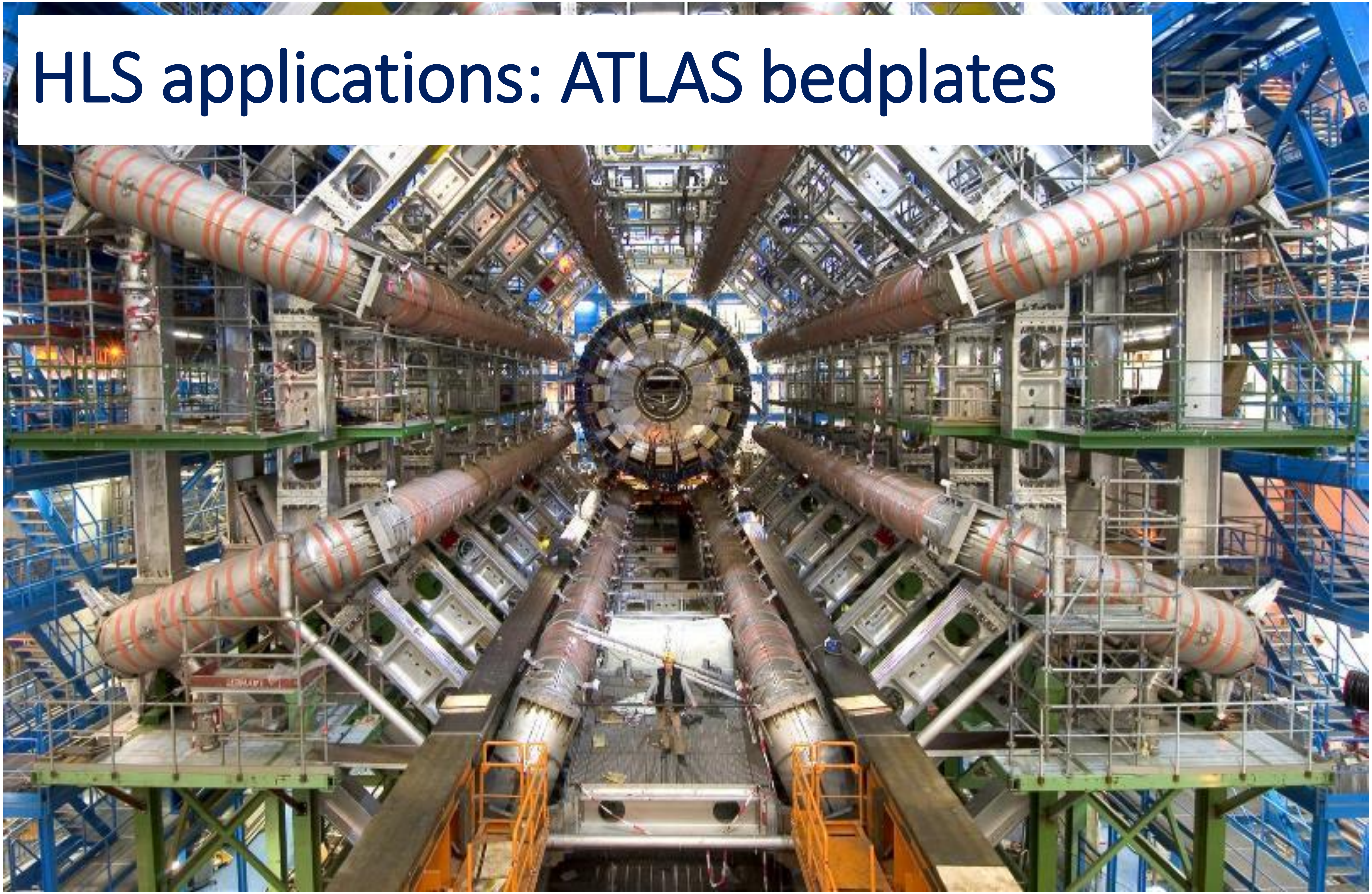
HLS applications: ATLAS bedplates



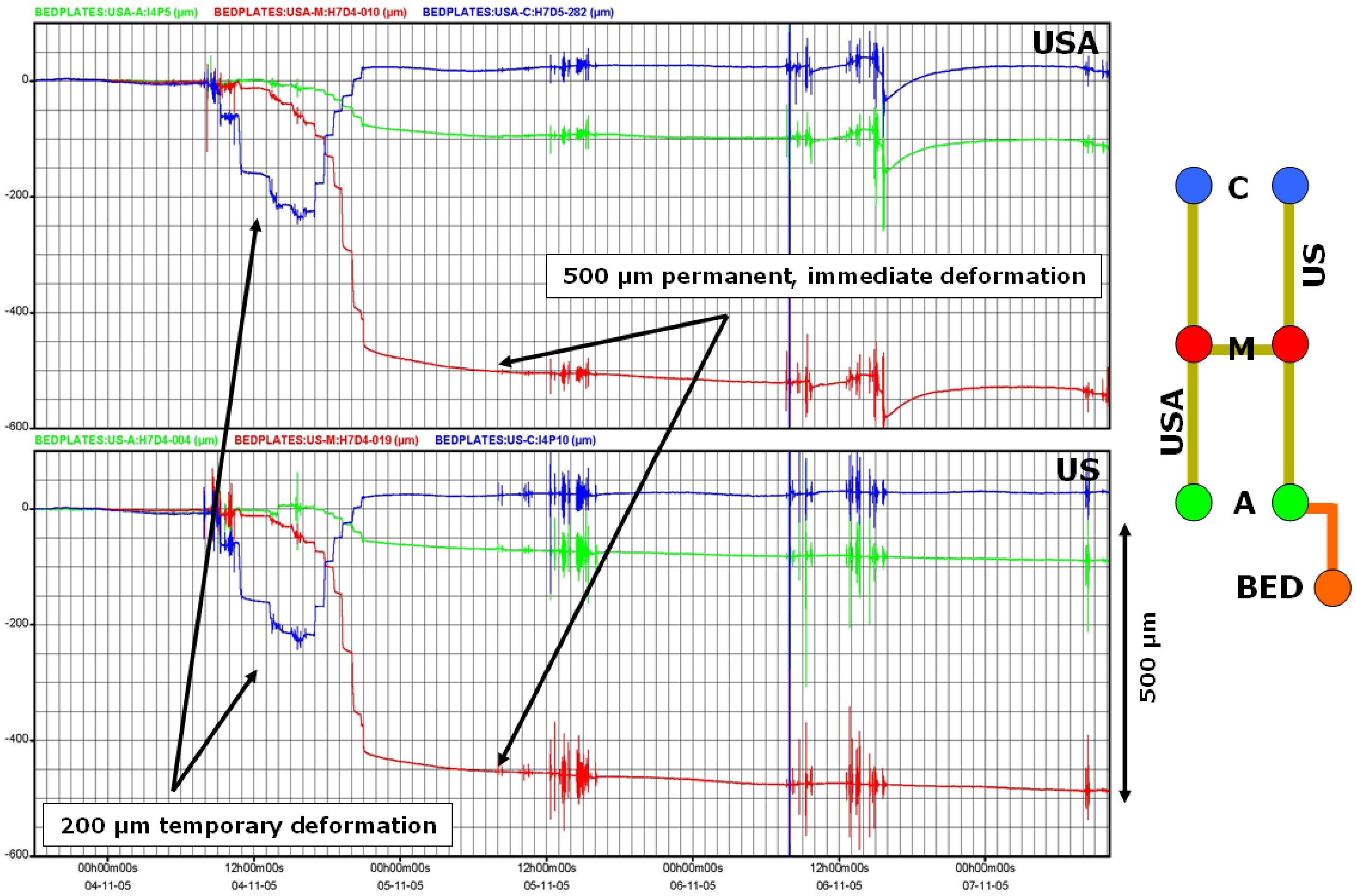




HLS applications: ATLAS bedplates

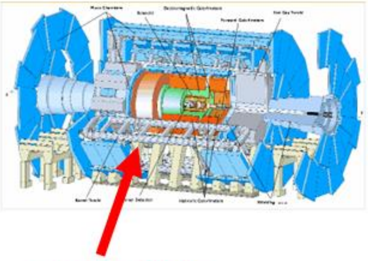


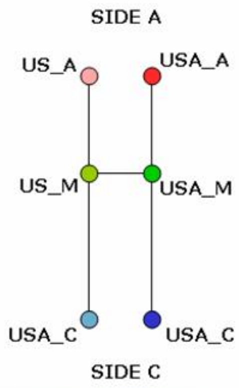
HLS applications: ATLAS bedplates

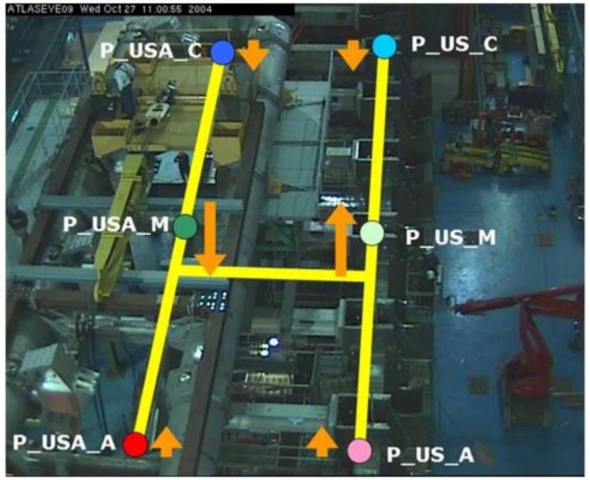


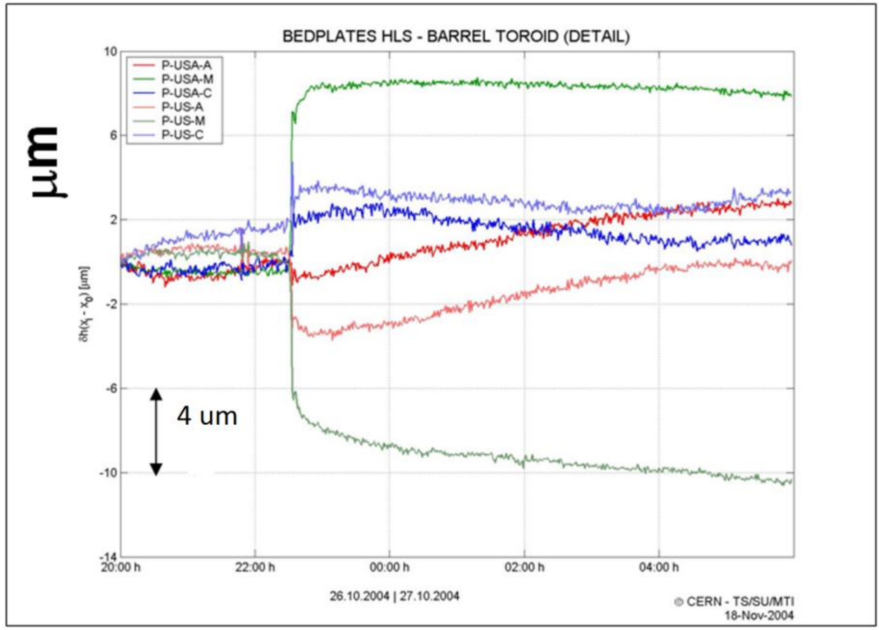
HLS applications: ATLAS bedplates

HLS MEASUREMENT – BARREL TOROID COILS INSTALLATION



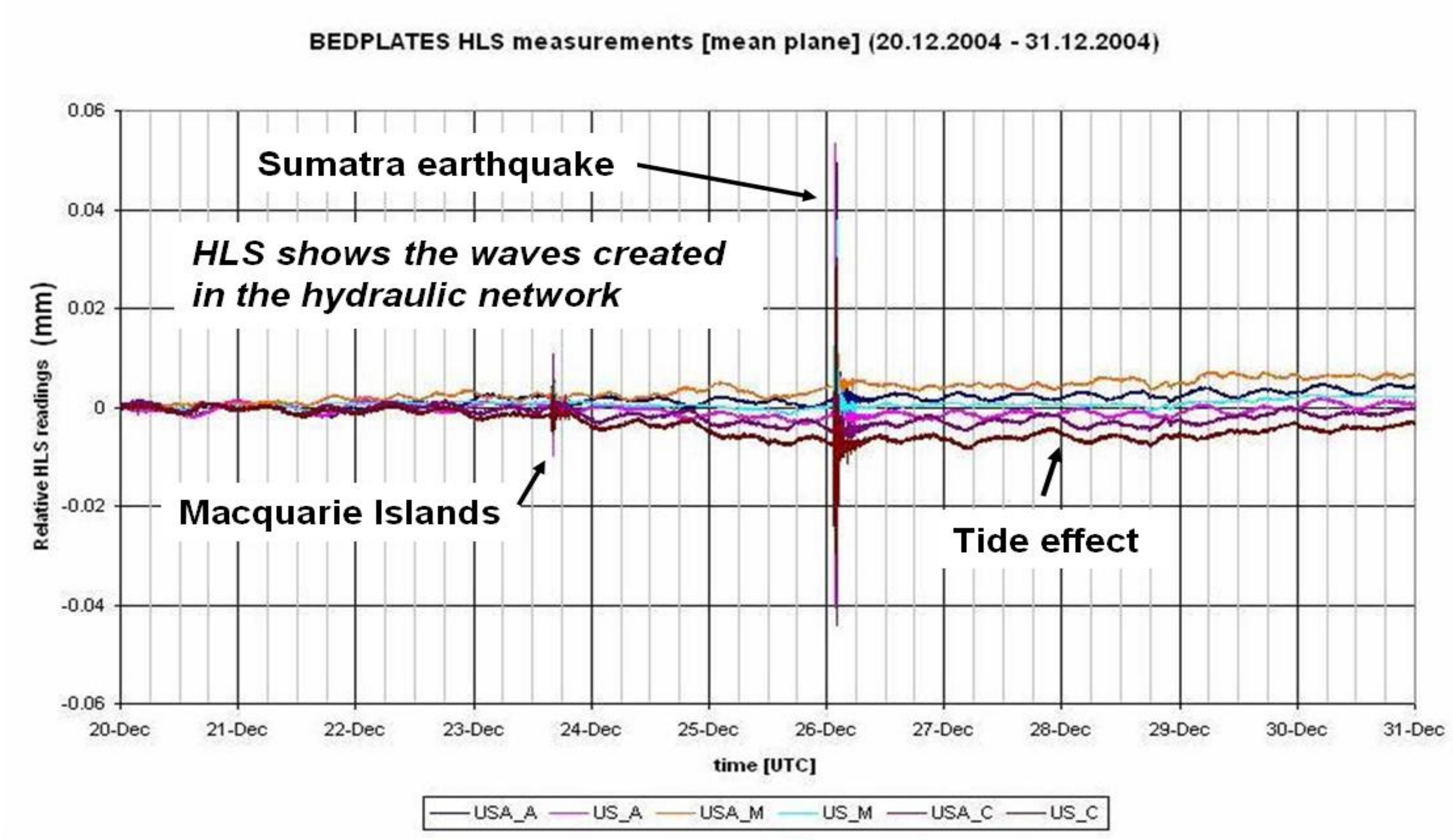






Installation of one BT coil (24m long, 100t)
…
effect on the Bedplates measured with the HLS

HLS – EXTRA PHENOMENA RECORDING – EARTHQUAKES



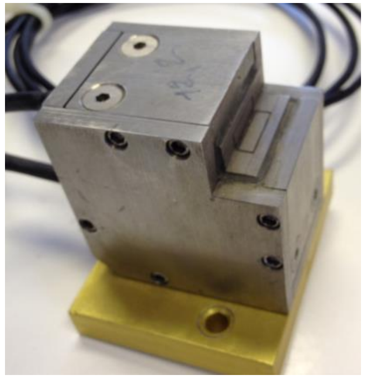
~70 earthquakes seen from Dec 2005 with the HLS installed at CERN

Instrumentation toolkit

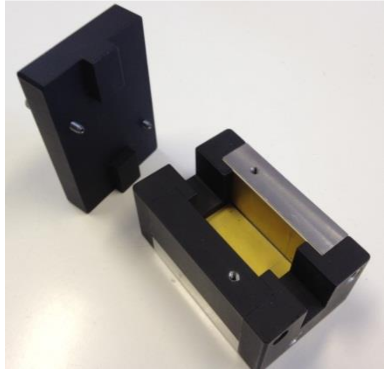
- Determination of the position
  - Standard instruments
  - Specific alignment systems
    - Wire offsets
    - BCAM
    - Hydrostatic Levelling System (HLS) & applications
    - Wire Positioning System (WPS) & applications
    - Laser based alignment systems
- Adjustment

Wire positioning System (WPS)

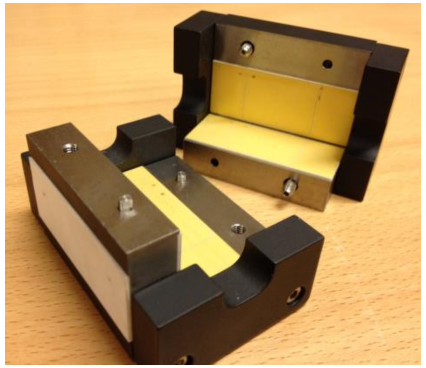
Prototype (1990)



Version 1 in 1994

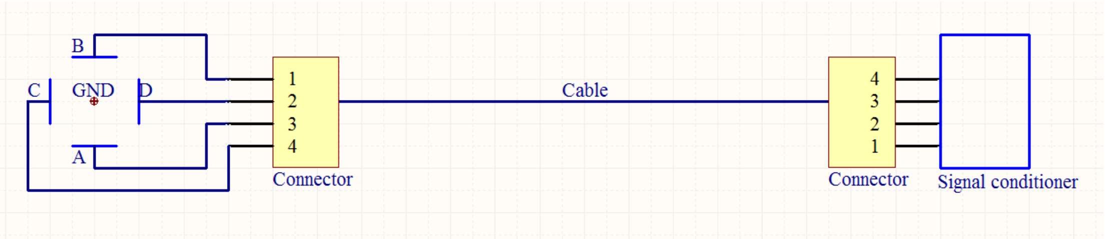


Version 2 in 2000



Version 2 CERN

Differential capacitive sensors



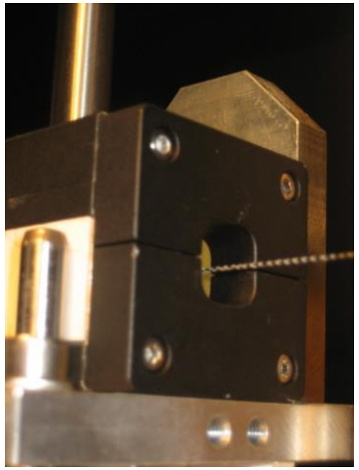
$V, I, digital: pos.value$

A capacitive measurement system converts a change in position, or properties of the dielectric material into an electrical signal (analog or digital).

WPS: associated wire

Carbon Kevlar

Carbon PEEK/PES



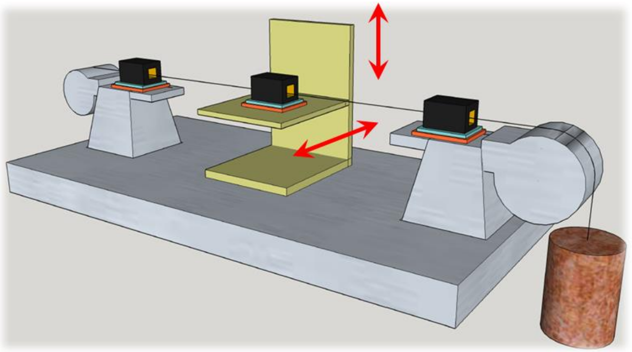
Carbon peek wire:

- Diameter: 0.4 mm
- Linear mass: 235 g/km
- Breaking tension: 230 N
- Conductivity > 0.025 m/Ω.mm2

Other types of wires under study:

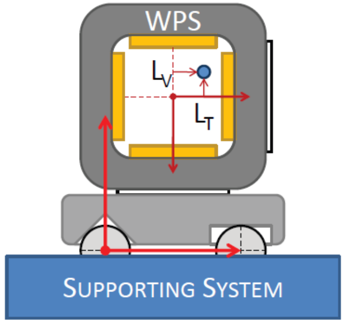
- Vectran (multifilament yarn spun from Liquid Crystal Polymer)
- Metallization of vectran by silver plasma coating

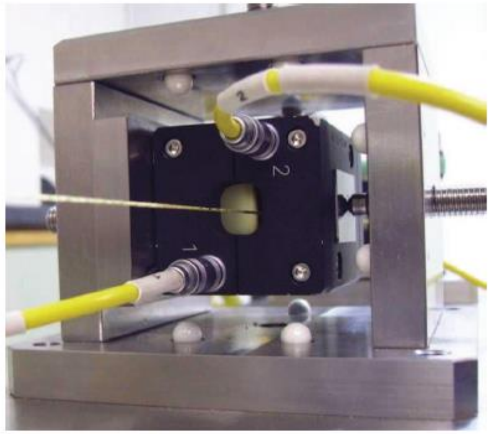
WPS performances

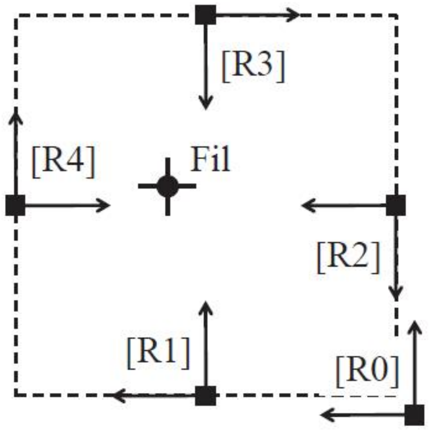


Voltage: 0-10 V

Full Range : +/- 5 mm







[Thouzé]

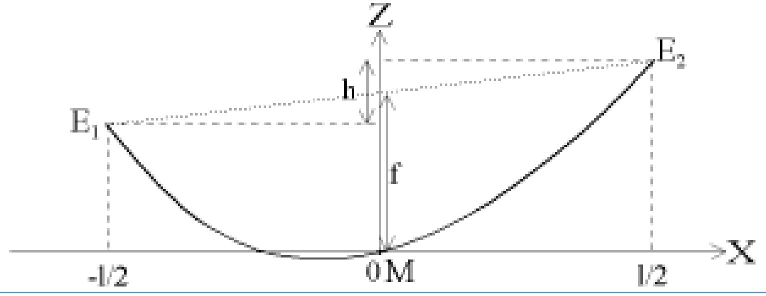
CERN

Repeatibility : +/- 1 μm (1σ)

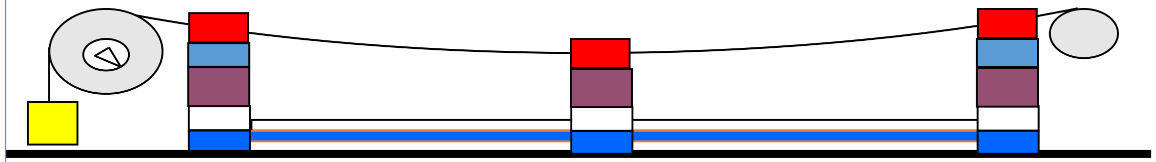
Linearity : 2 μm / mm (1σ)

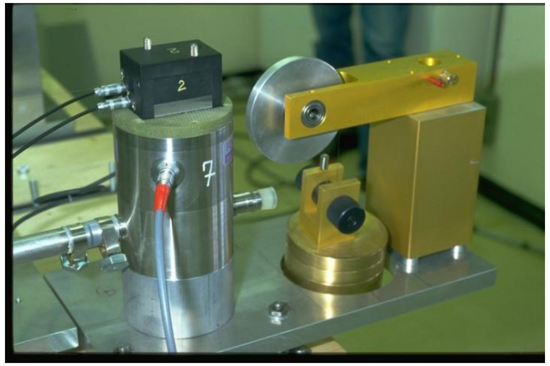
Accuracy : 5 μm (1σ)

WPS: impact of sag



$$Z = \frac{4f}{l^2}(X + \frac{lh}{8f})^2 - \frac{h}{16f}$$

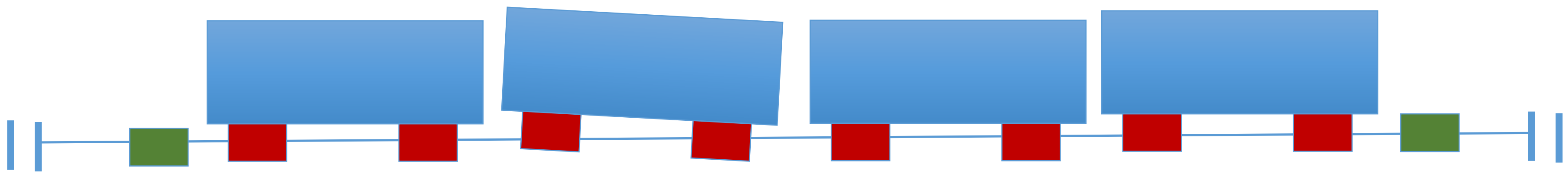




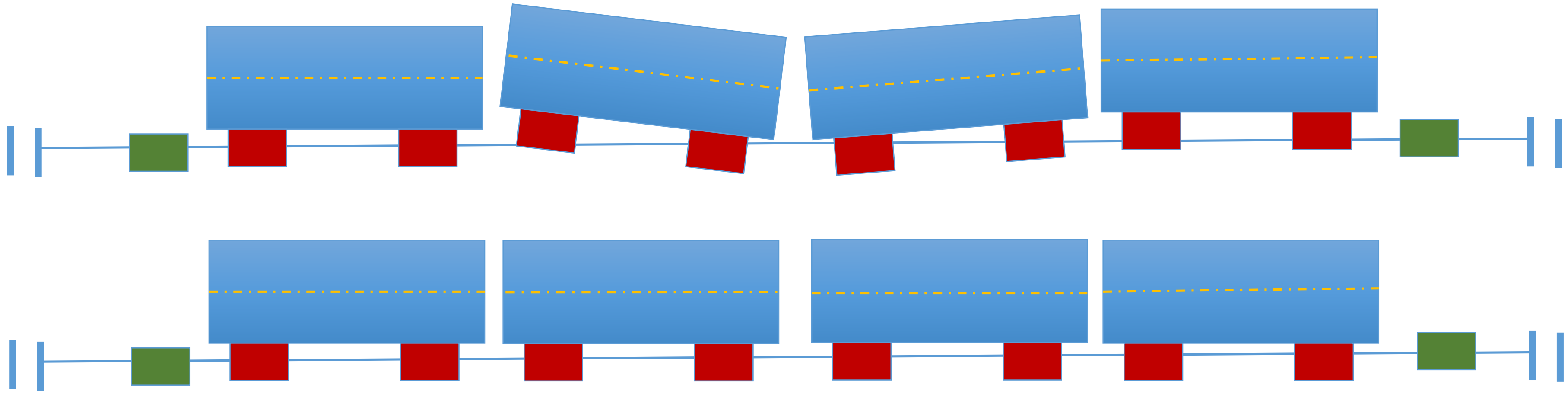
Modelisation of the wire sag by using a combination of HLS and WPS sensors to determine the difference of height on 3 points along the wire

WPS: two configurations

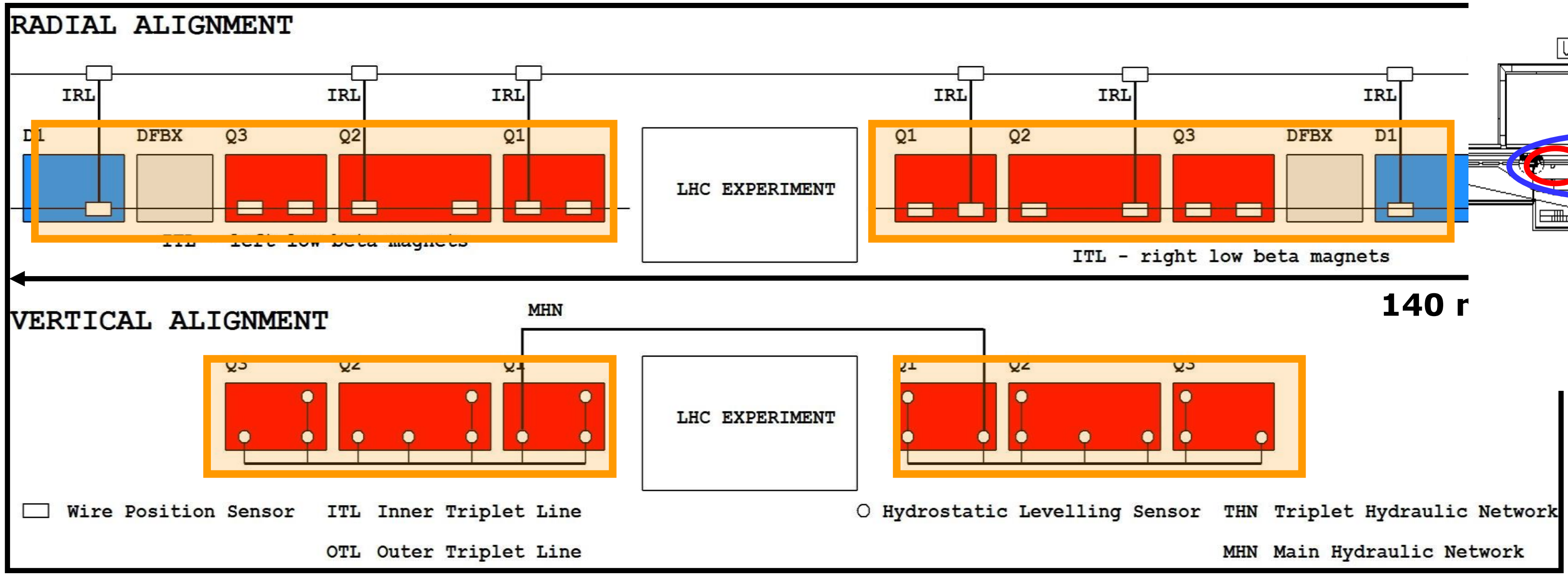
"Relative" alignment (monitoring)

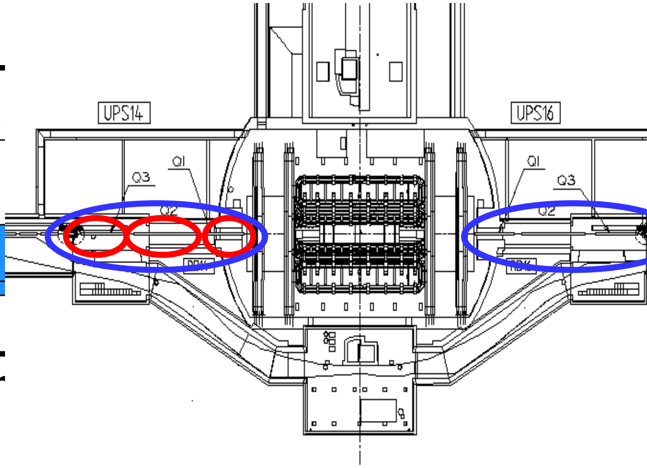


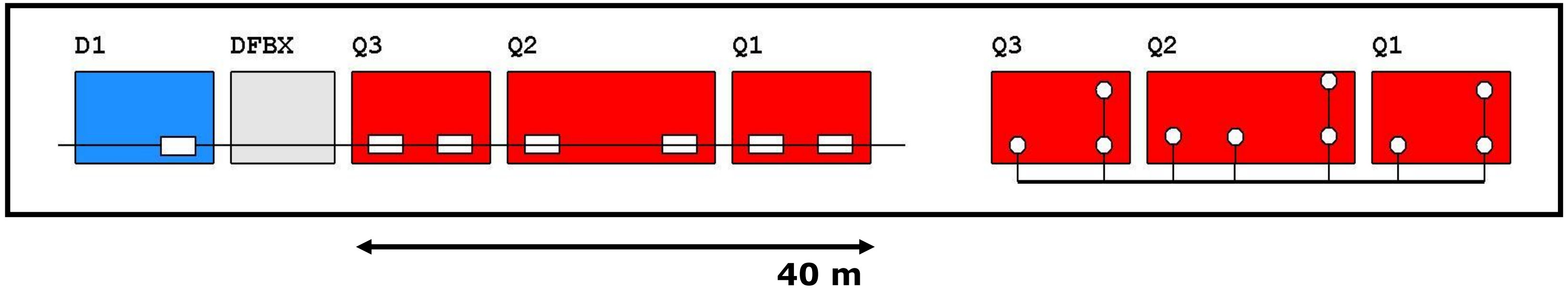
"Absolute" alignment (pre-alignment)



WPS & HLS: alignment of LHC inner triplets



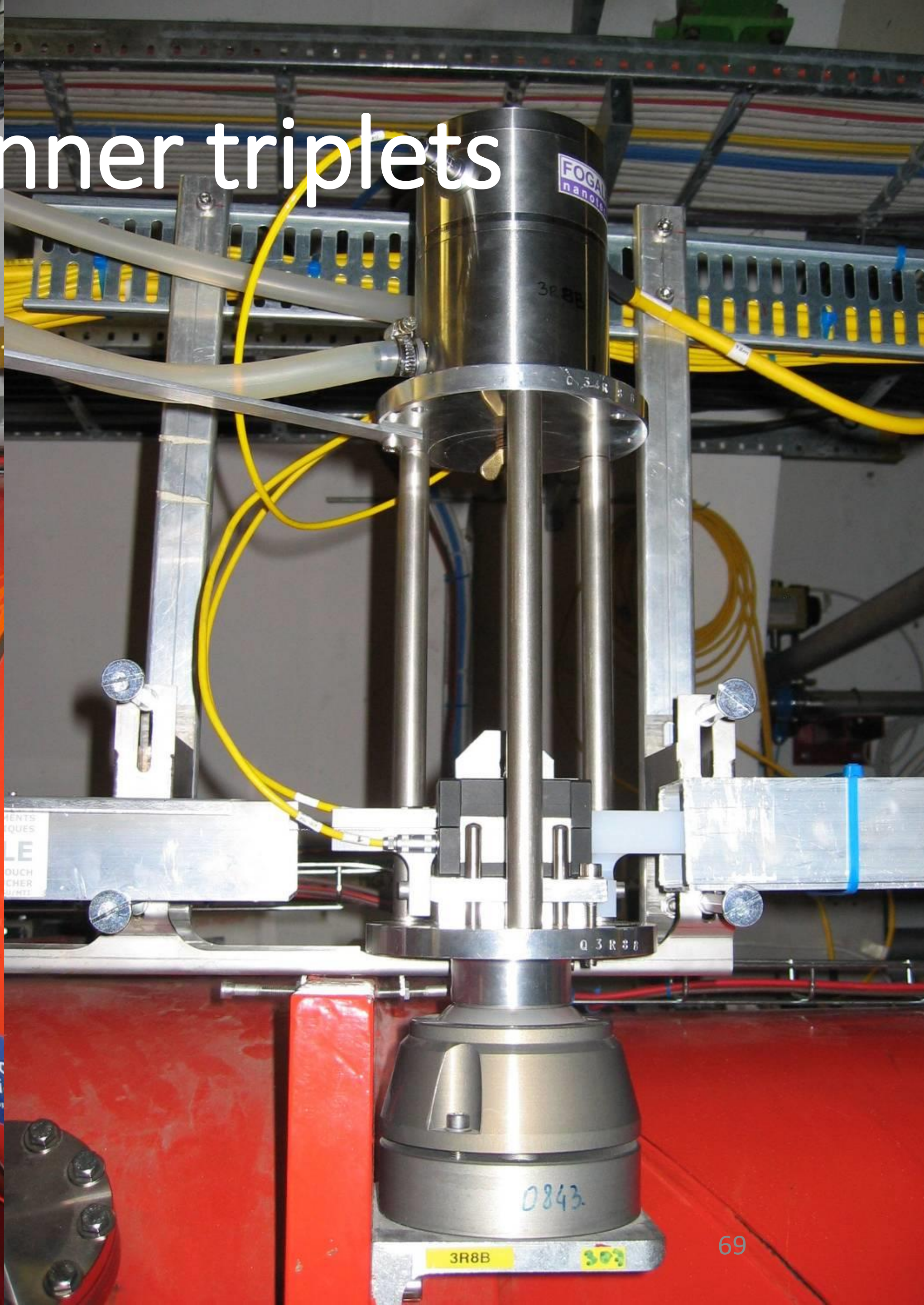




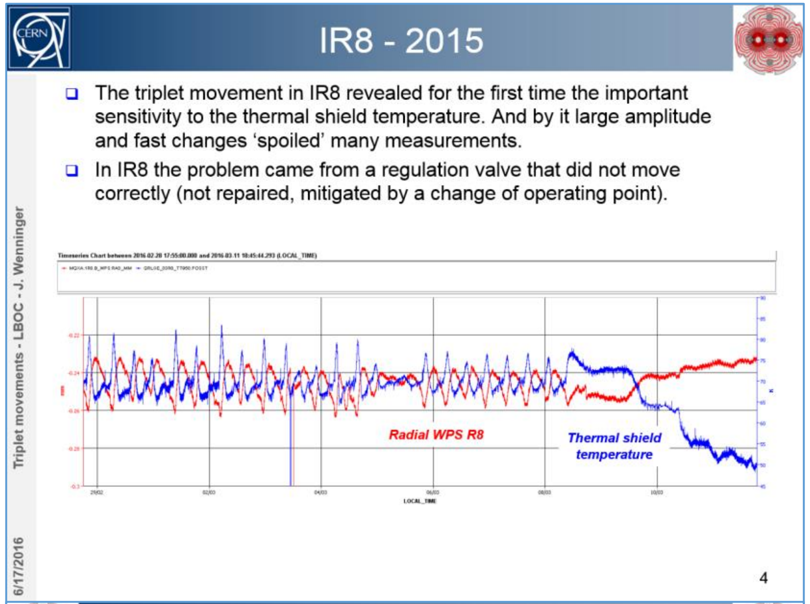
low beta triplet

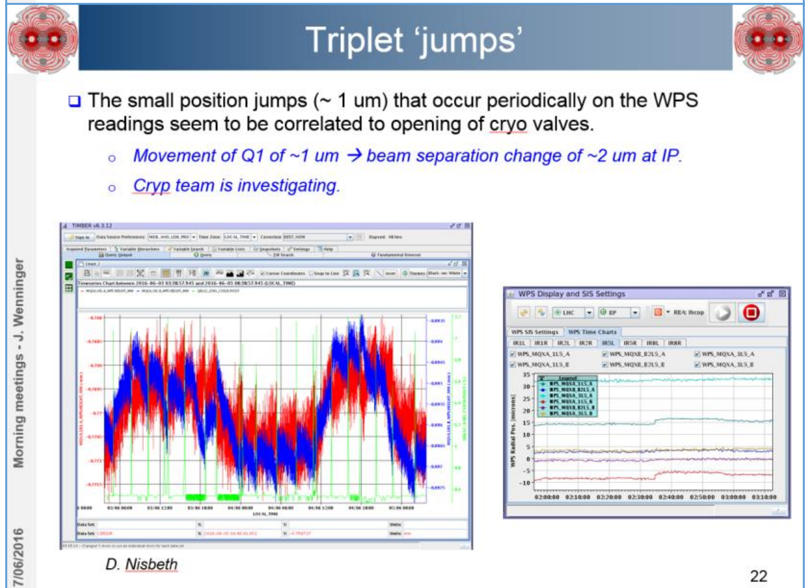
Courtesy of A. Herty

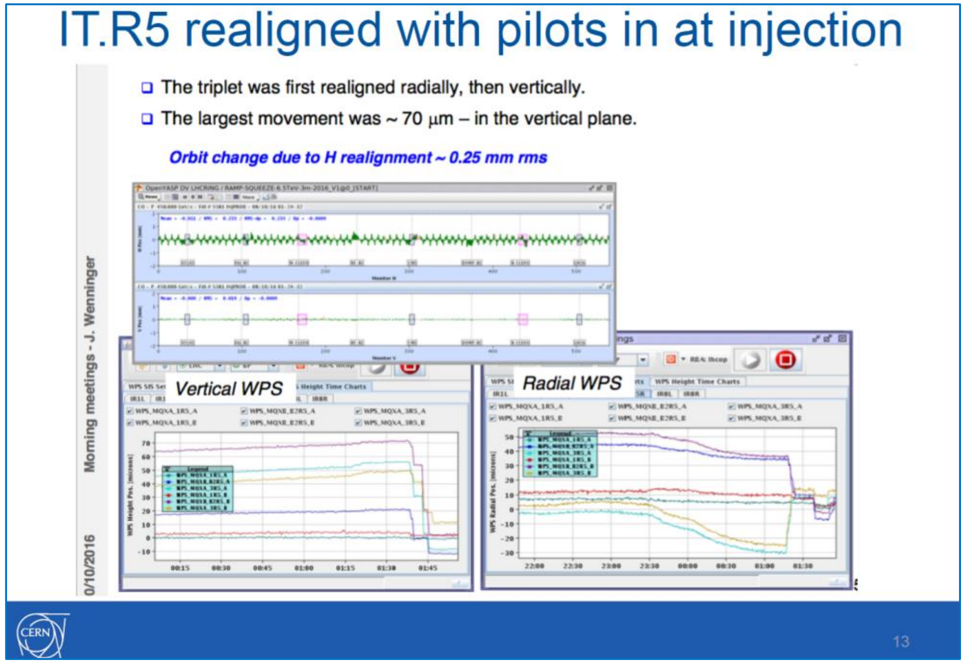
WPS & HLS: alignment of LHC inner triplets



WPS & HLS: Alignment of LHC inner triplets







- LHC sensors readings under the spot line: used by OP to have a better understanding of the displacements observed on the beam
- Triplet 5R realigned with pilot beam on. First time in the world !!!

LCLS case (SLAC)

Alignment Diagnostic System (ADS)

- *Goal: Monitoring of*
  - *X, Y Position of each Quadruple*
  - *Roll, Pitch and Yaw of each Undulator Segment*

Component Monitoring Tolerance	Value	Unit
Horizontal / Vertical Quadrupole and BPM Positions	0.7	µm
Roll of Undulator Segment	1000	µrad
Pitch of Undulator Segment	16	µrad
Yaw of Undulator Segment	30	µrad

- *Composition:*
  - *2 wires spanning the whole undulator hall*
  - *1 water level system*

[LeCocq]

LCLS case (SLAC)

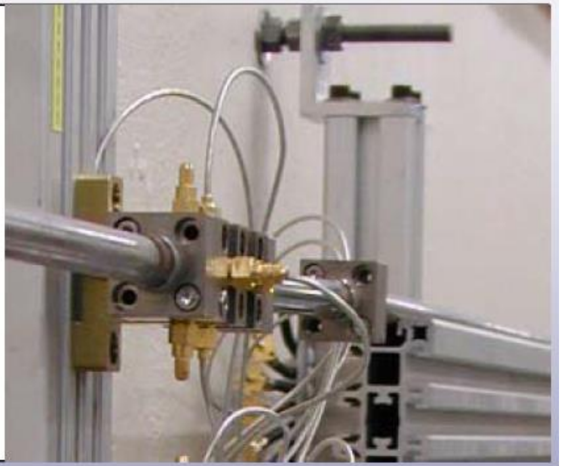
Alignment Diagnostics System – Sensors

Wire Position Monitor System (WPM)

- ***Resolution*** < 100 nm in X & Y Direction
- ***Instrument Drift*** < 100 nm per day
- ***Moving Range*** ±1.5 mm in X & Y Direction
- ***Accuracy*** 0.1 % of full Scale
- ***Availability*** Permanent, no Interrupts

X and **Y** can be measured

Owner: Franz Peters



Hydrostatic Leveling System (HLS)

Capacitive Sensor

- ***Precision*** < 1 μm
- ***Instrument Drift*** ~1-2 μm / month
- ***Accuracy*** < 0.1 % of full Scale

Ultrasound Sensor

- ***Precision*** < 0.1 μm
- ***Instrument Drift*** potentially no drift
- ***Accuracy*** < 0.1 % of full Scale

- ***Availability:*** 10 minutes settling period after movement

Owner: Georg Gassner

Y can be measured

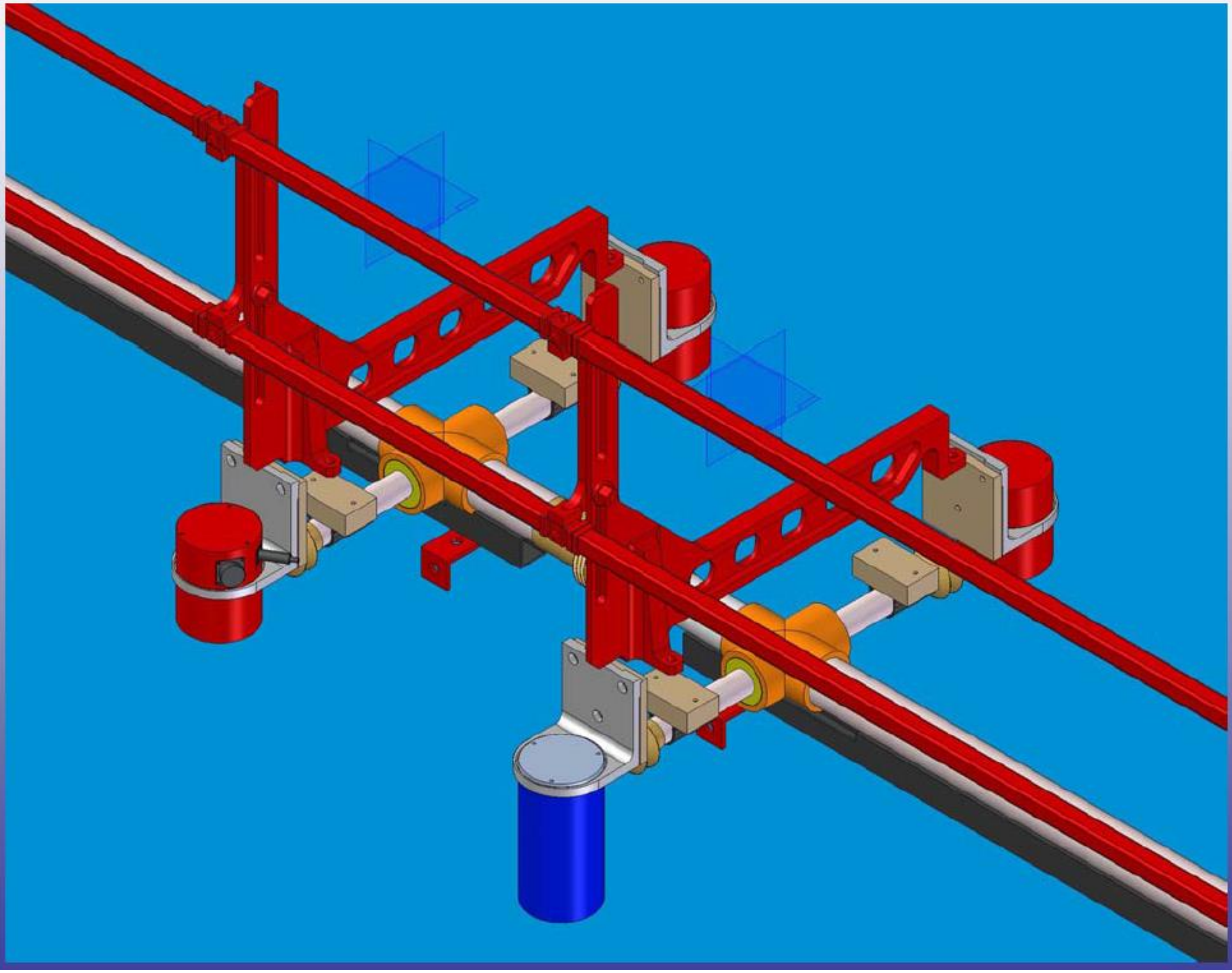
[LeCocq]

LCLS case (SLAC)

ADS Installation - Hardware

HLS

- *Piping*
  - *CPVC (FM4910) 2" and 1" schedule 40*
  - *Pipe is supported by Unistrut® to avoid sag*
- *Bellows*
  - *Gortiflex® GF-100B*
  - *Small: max length 2", min 1"*
  - *Long: max length 10", min 2"*
- *Bracket*
  - *Nickel plated steel, machined out of standard angle 0.5" thickness*

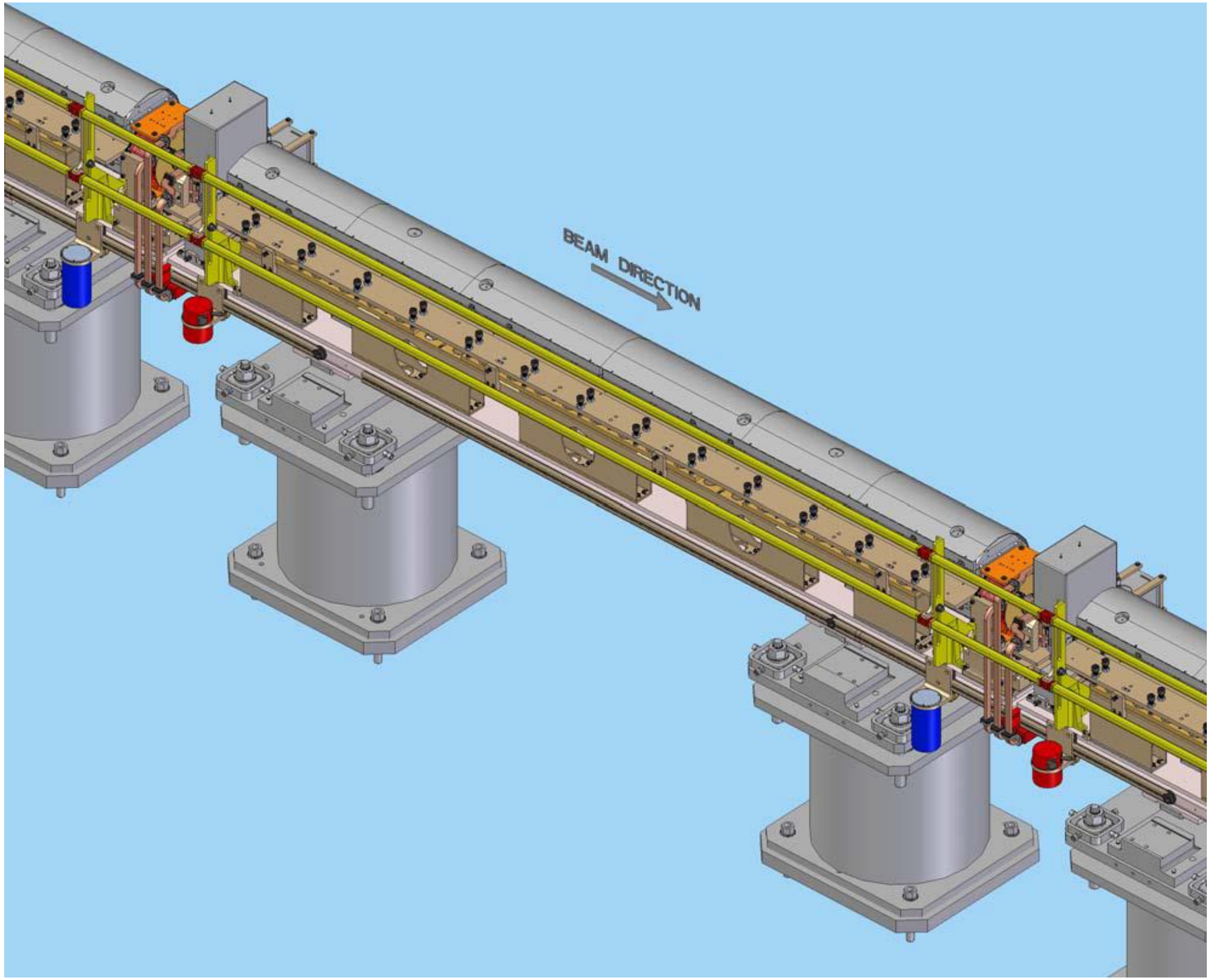


WPM

- *Wire*
  - *Stainless Steel Gold plated (0.5 mm diameter)*
- *Frequency*
  - *100KHz*
- *Weight*
  - *35 kg*
- *Tube*
  - *Brass 10 mm diameter*

[LeCocq]

LCLS case (SLAC)



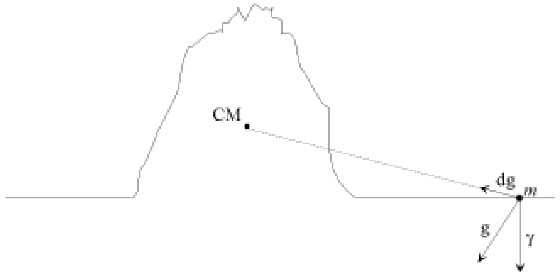
[LeCocq]

Alignment systems and gravity

Metrology networks must provide a straight alignment of accelerators linacs.

Reference frames (wire and water surface) are influenced by gravity:

- ✓ Earth curvature, height, latitude
- ✓ Distribution of masses in the neighborhood

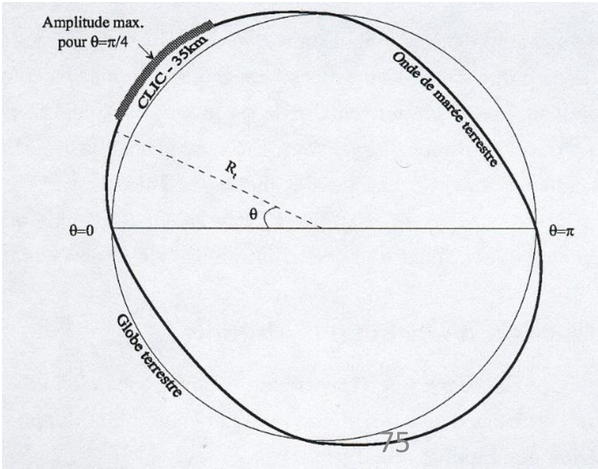


Maxi. deviation of the vertical: 15" at CERN

- ✓ Moon and sun attraction

  Moon and sun act as disturbing masses, modifying the gravitational field

  Their impact on a given point vary according their position w.r.t the point.



[CLIC Note]

Alignment systems and gravity

[CLIC Note]

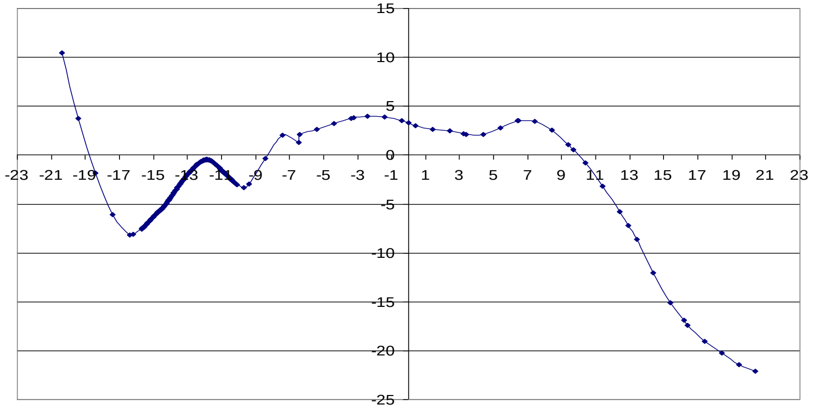
Impact on WPS system:

The non uniformity of gravitational field due to combined effects of latitude, height and deflection of vertical can deform the wire significantly (up to 15 µm) but can be corrected (theoretical result that needs to be cross-checked experimentally).

Impact of HLS system:

HLS is affected by ocean and Earth tides but corrections can be applied [Boerez]

Effect of neighborhood masses must be taken into account



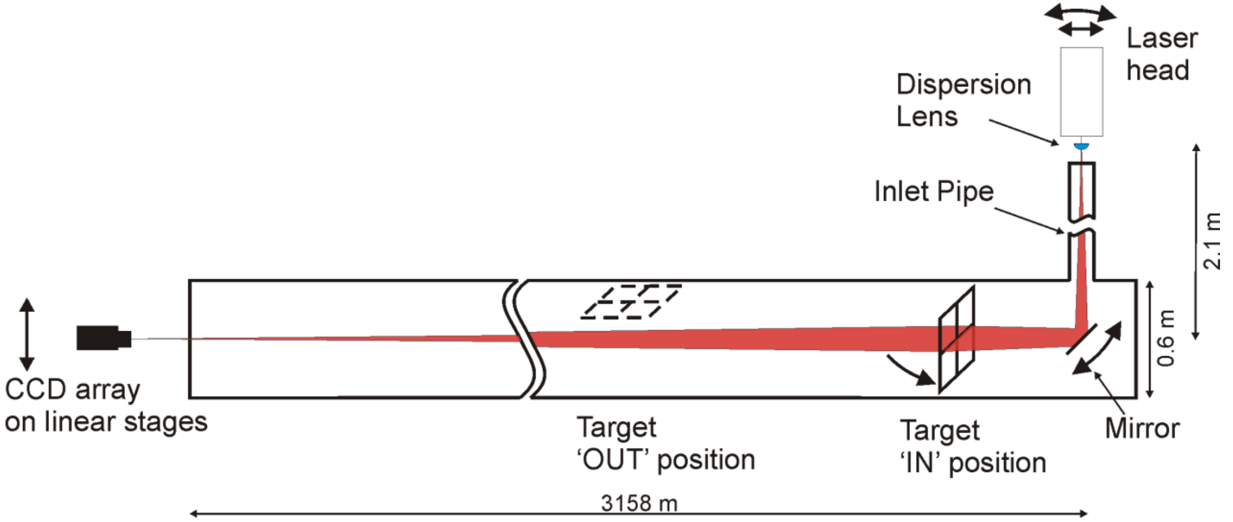
Geoid profile of 40 km

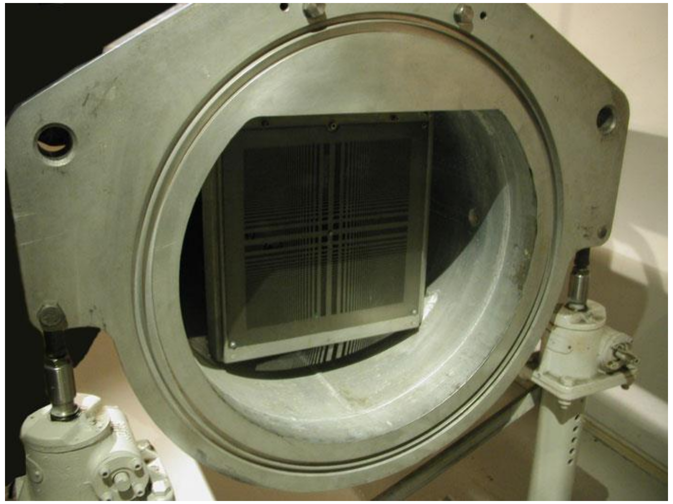
The uncertainty of the geoid determination must be strictly added to the uncertainty of vertical alignment. See [Guillaume].

Instrumentation toolkit

- Determination of the position
  - Standard instruments
  - Specific alignment systems
    - Wire offsets
    - Hydrostatic Levelling System (HLS) & applications
    - Wire Positioning System (WPS) & applications
    - Drawbacks of WPS & HLS
    - Laser based alignment systems
- Adjustment

Observing diffraction pattern of Fresnel zones plates (SLAC)





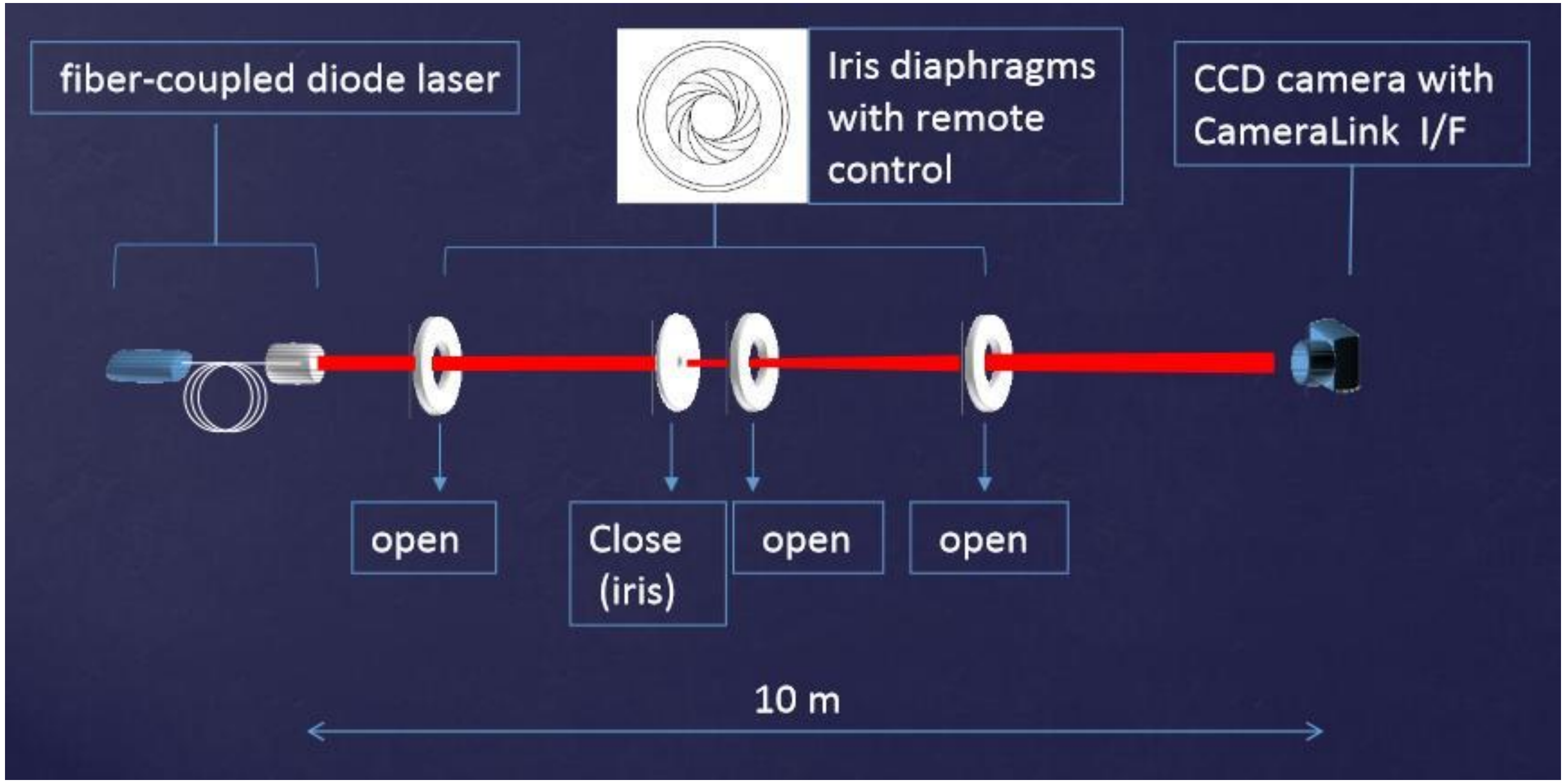
Advantages	Drawbacks
Large number of targets (~300)	Repositioning of targets
Rad-hard	Non compact targets

[Ruland2]

The Fresnel lens focuses the light on the detector forming an interference pattern

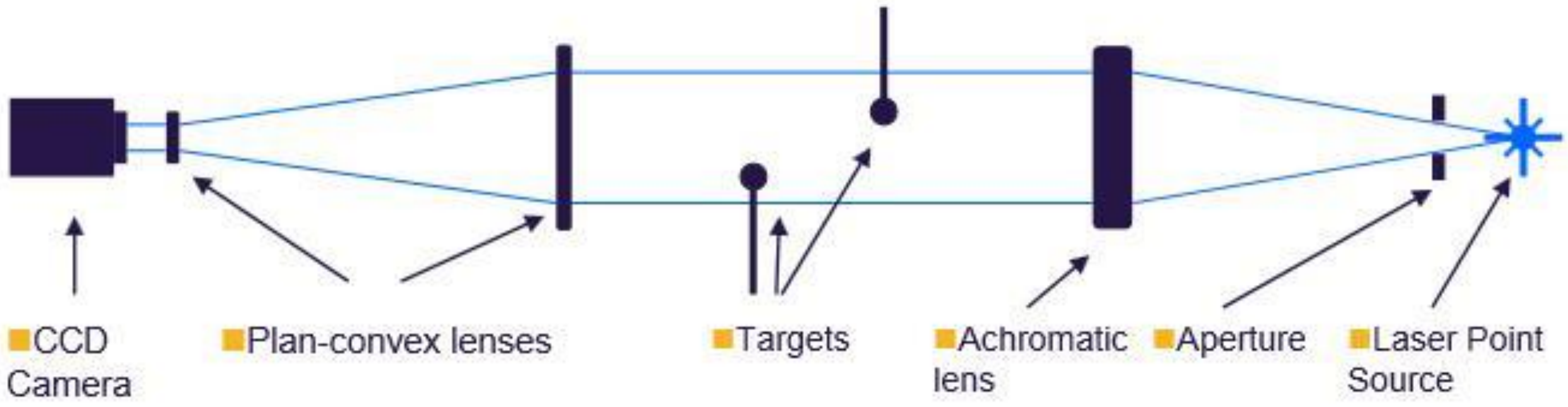
Observing diffraction pattern of an iris (Spring 8)

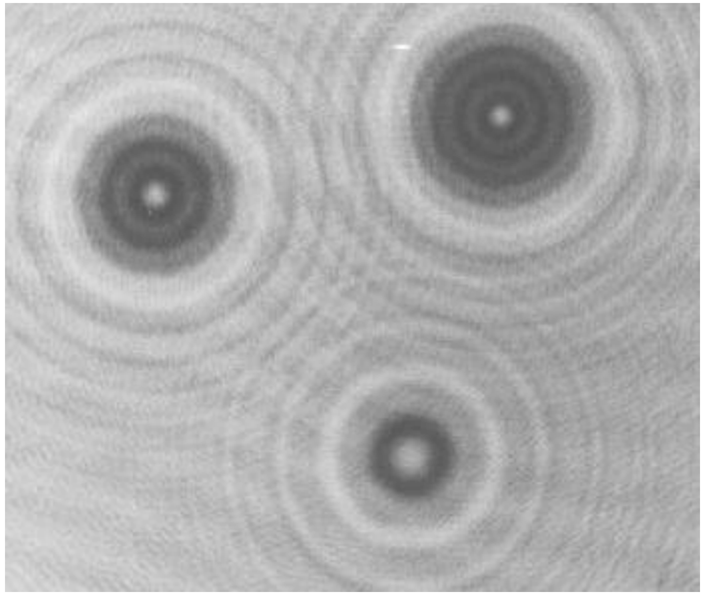
[Zhang]



Advantages	Drawbacks
Static targets	Measurement uncertainty depends on longitudinal position

Observing diffraction pattern of spheres (DESY)

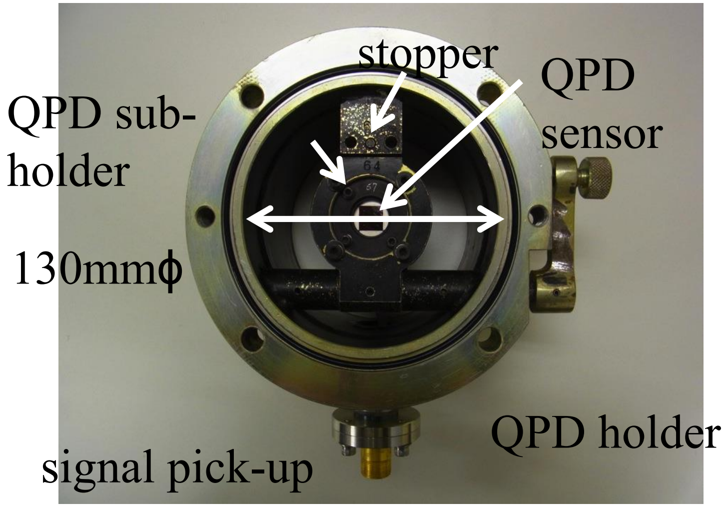




Advantages	Drawbacks
Static targets	Limited number of targets (~16)
	Measurement uncertainty depends on longitudinal position

[Prenting]

Observing laser spot with open / close QPD's (KEK)



QPD: quadrant photo-detectors

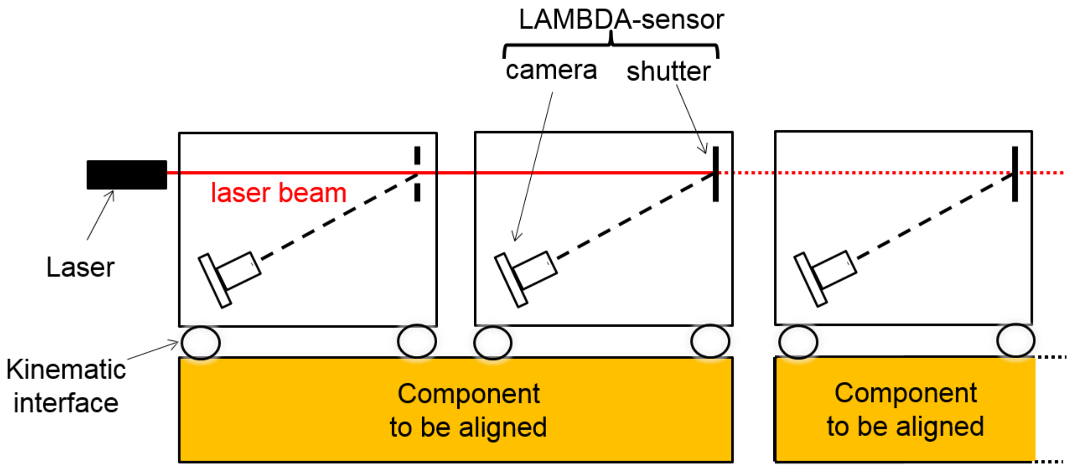
[Suwada]

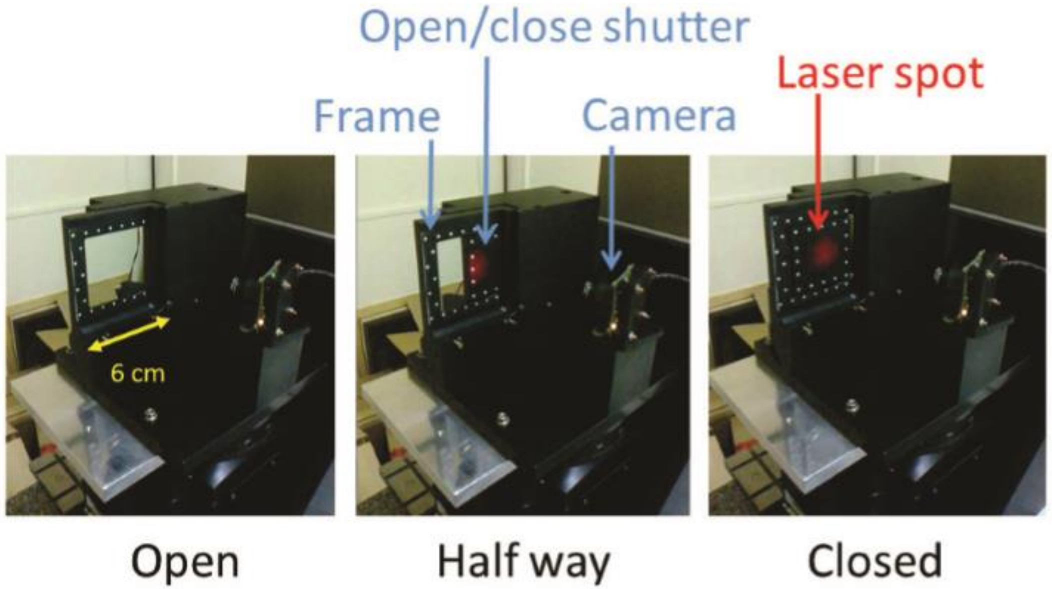
Advantages	Drawbacks
Large number of photo-detectors	Uncertainty due to open/close photo-detectors

The central position at the target can be estimated by measuring the intensity centroid of the laser based fiducial in the transverse detection of the QPD

Laser based system

LAMBDA project: principle





- Compact & compatible with its environment
- Measurement repeatability 1 µm, accuracy 5 µm
- Low cost

[Stern]

Comparison of several laser based alignment systems

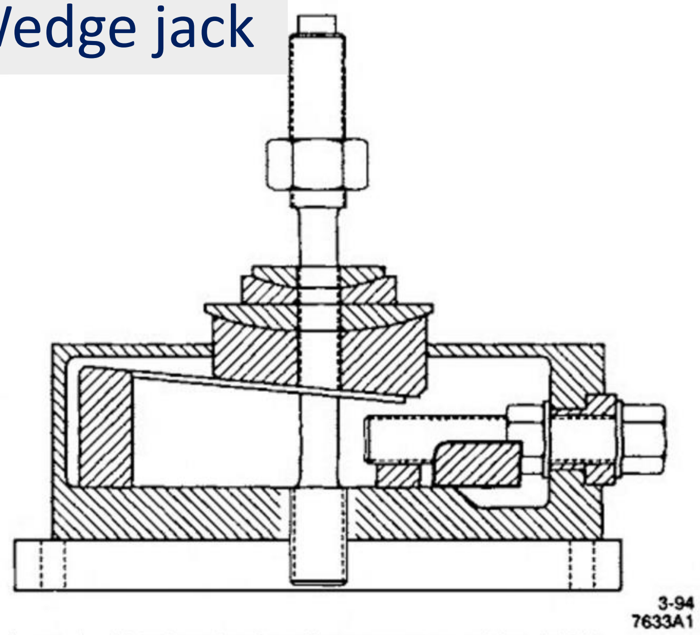
		Wanted accuracy	Already achieved
Observing diffraction pattern	…of Fresnel zone plates (SLAC)	500µm (1σ) over 3000m	Estimated accuracy: 500µm (1σ) over 3000m
	…of an iris (SPRING 8)	10µm (2σ) over 10m	Pointing stability: 10µm (2σ) over 10m
	…of spheres (DESY)	300µm (1σ) over 150m	Estimated achievable accuracy: 100/200 µm (1σ) over 150m
	… of diffraction plate (NIKHEF)	10µm (1σ) over 200m	Estimated achievable accuracy: 1µm (1σ) over 140m
Observing laser spot	…with open/close quadrant photo-detectors (KEK)	100µm (1σ) over 500m	Pointing stability: 40µm Estimated accuracy: 100µm (1σ) over 500m
	…with open/close shutters (CERN)	10µm (1σ) over 200m	Pointing stability: 5µm (1σ) over 35m

Instrumentation toolkit

- Determination of the position
  - Standard instruments
  - Specific alignment systems
    - Wire offsets
    - Hydrostatic Levelling System (HLS) & applications
    - Wire Positioning System (WPS) & applications
    - Drawbacks of WPS & HLS
    - Laser based alignment systems
- Adjustment

Standard means of adjustment

Wedge jack

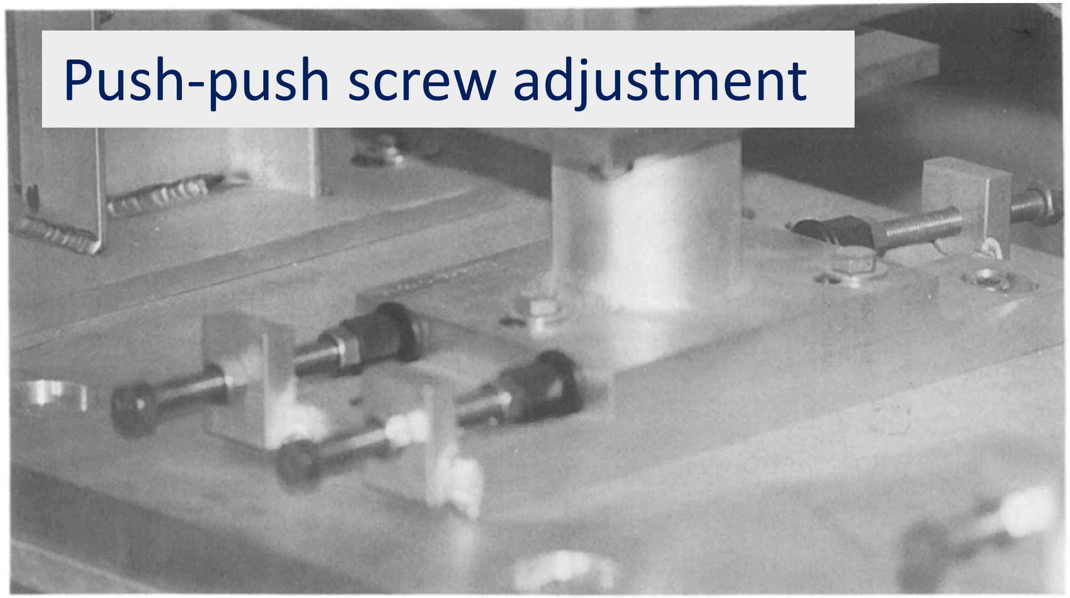


Wedge jack adjuster as used in APS.

The upper wedge is pushed up or down by displacing horizontally the lower wedge.

[Ruland2]

Push-push screw adjustment

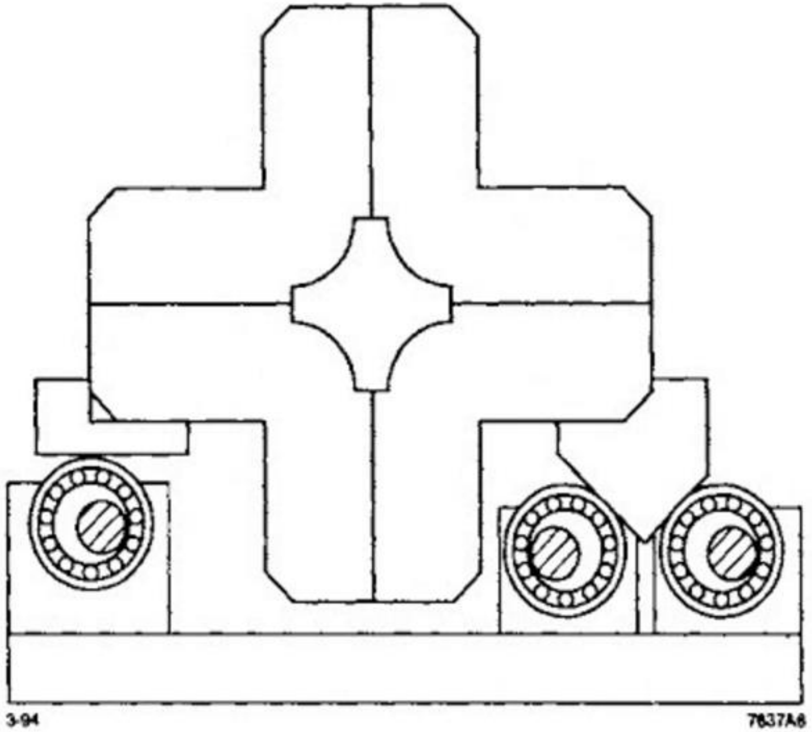


Push-push screw arrangement.

- Horizontal plane adjusted by the height of 3 vertical rods
- One or two sliding plates to adjust the horizontal
- Adjustment: pull/push the top plate sliding on the plate below.

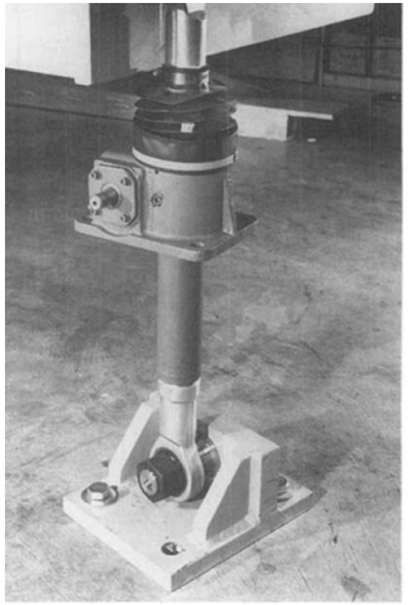
Standard means of adjustment

Roller cams

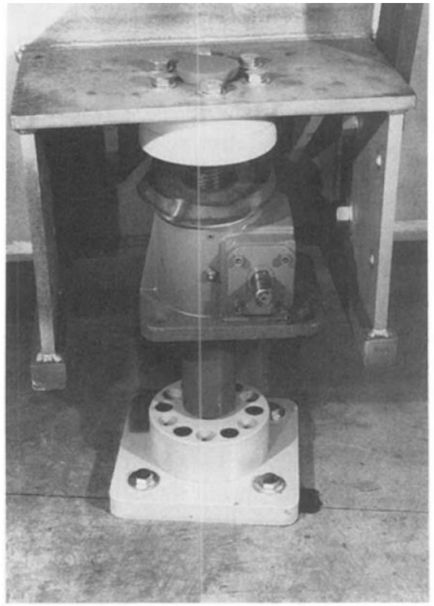


Magnet positioning mount with roller cams.

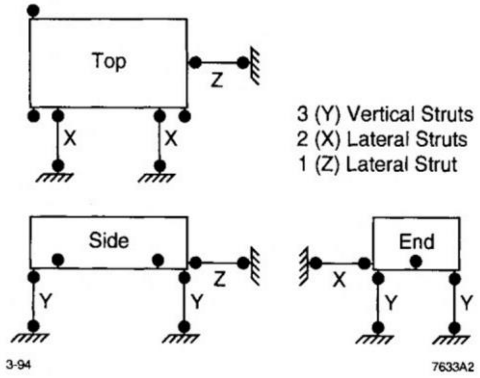
Struts



ALS 5-ton machine screw jack strut.



ALS 20-ton machine screw jack strut.



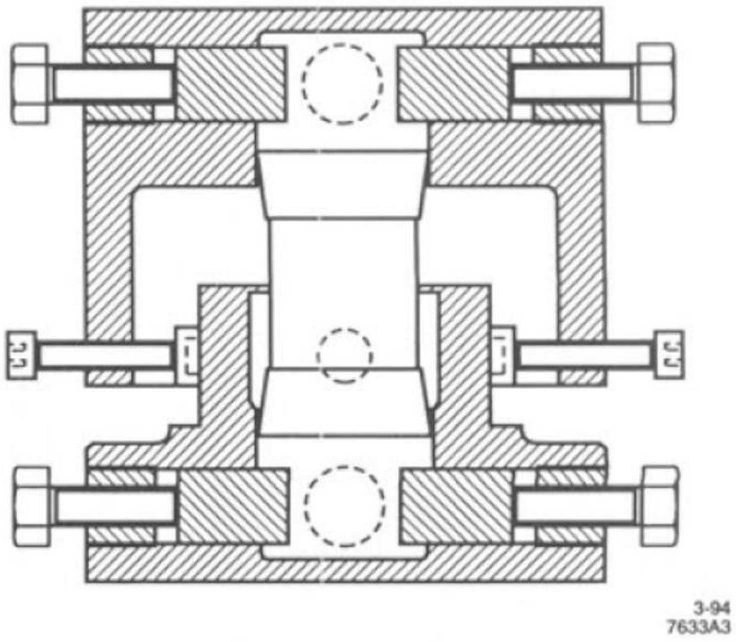
Kinematic suspension.

Struts are length-adjustable rigid members with spherical joints at each end.

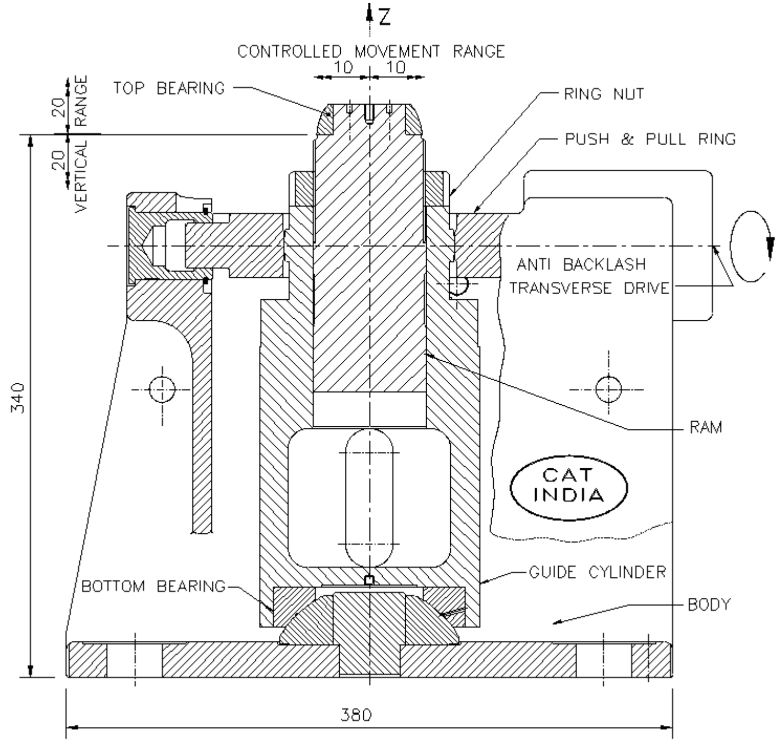
[Ruland2]

Standard means of adjustment

Polyurethane jack



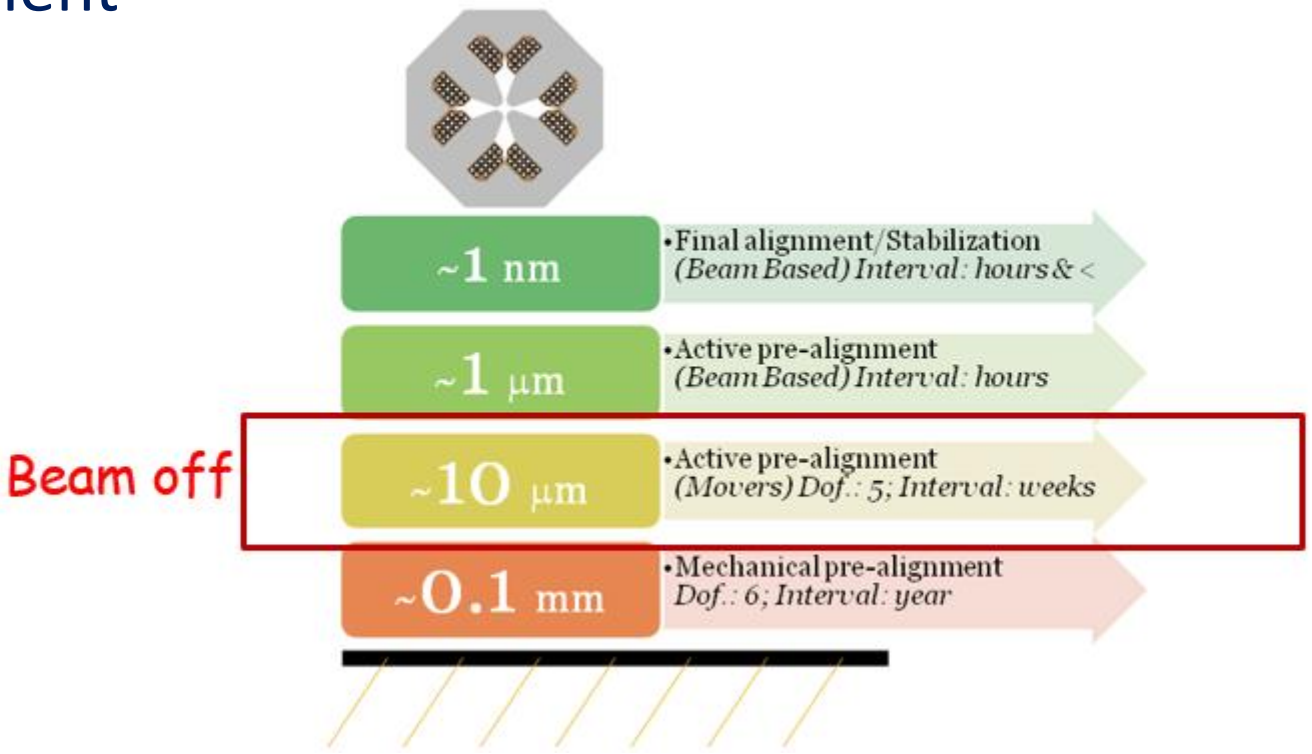
«Indian» LHC jack



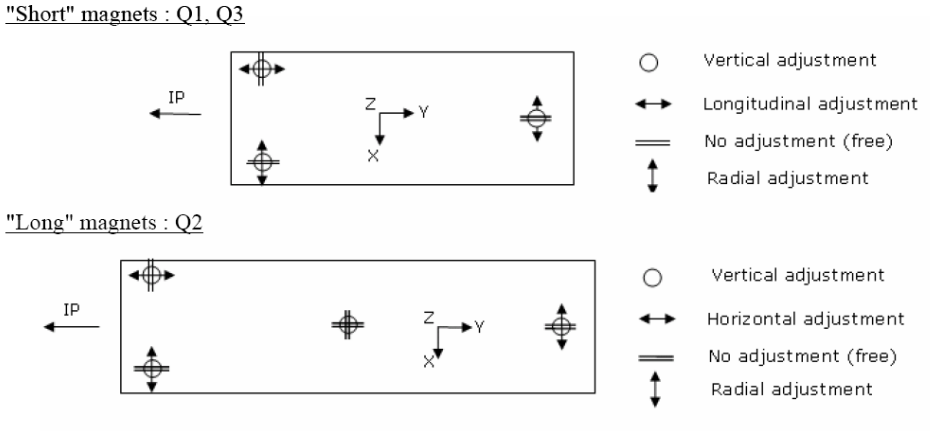
Motorized jacks

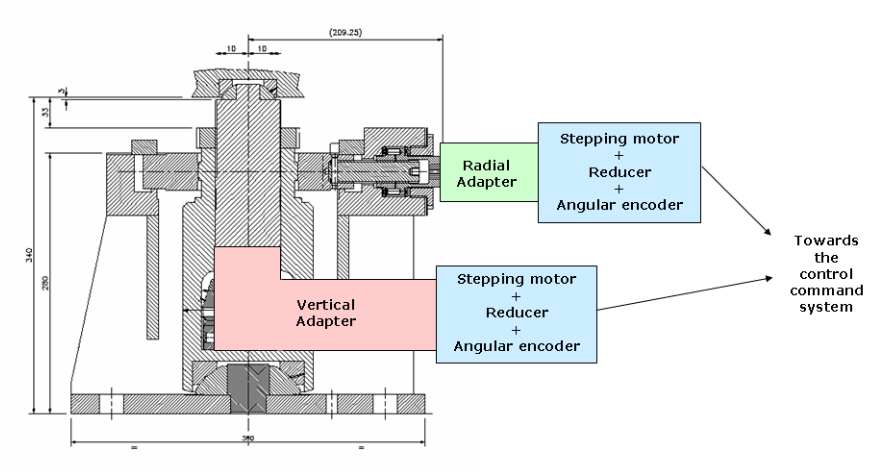
Different cases:

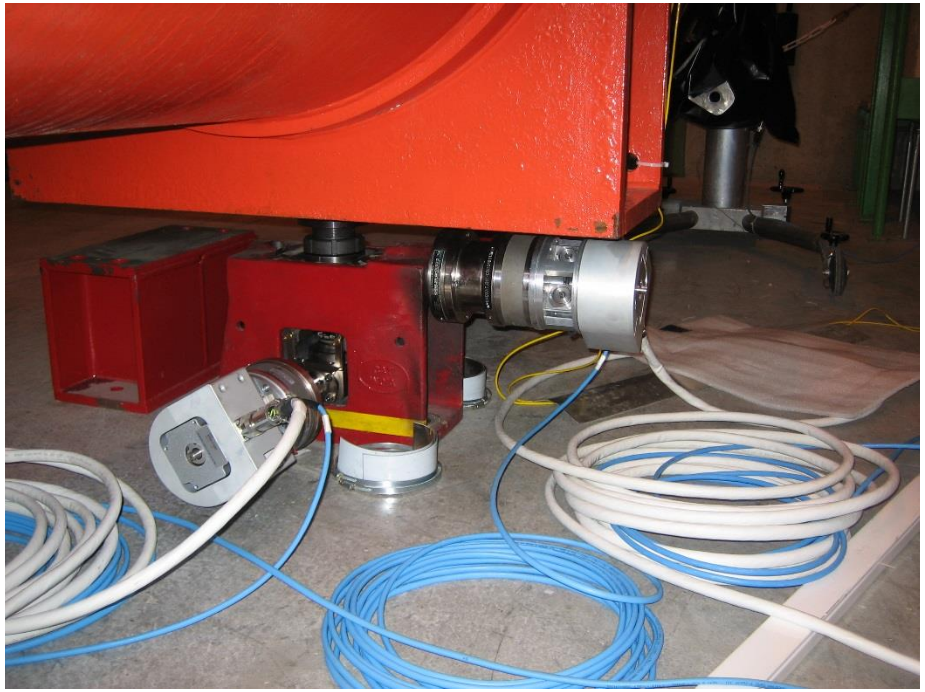
- Remote alignment in severe environment
- Active pre-alignment



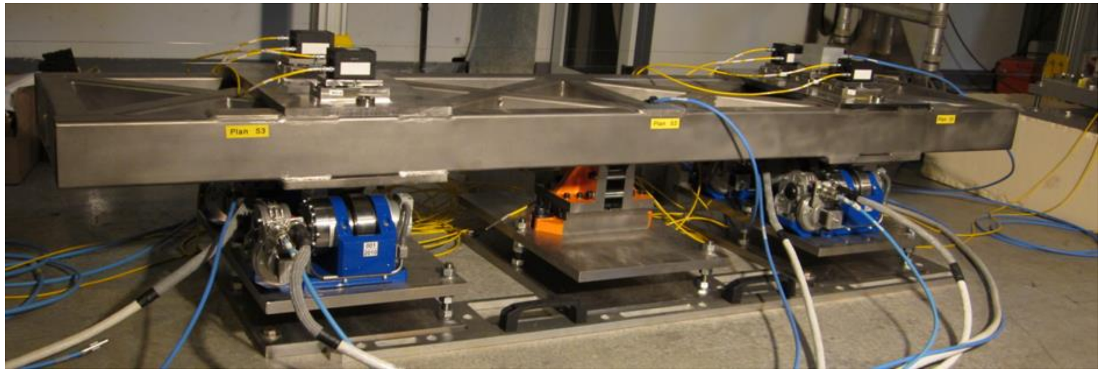
LHC motorized jacks

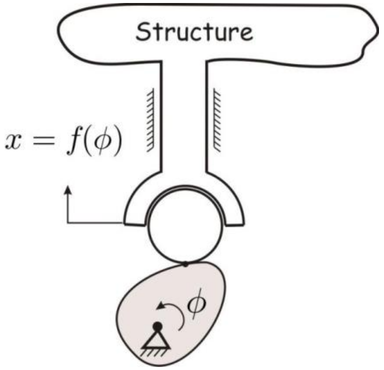


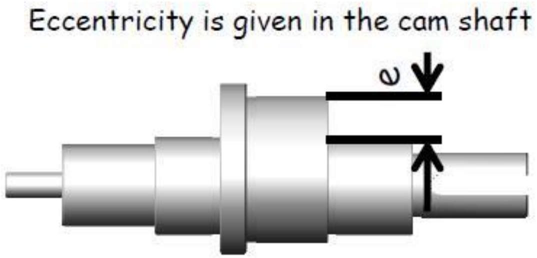


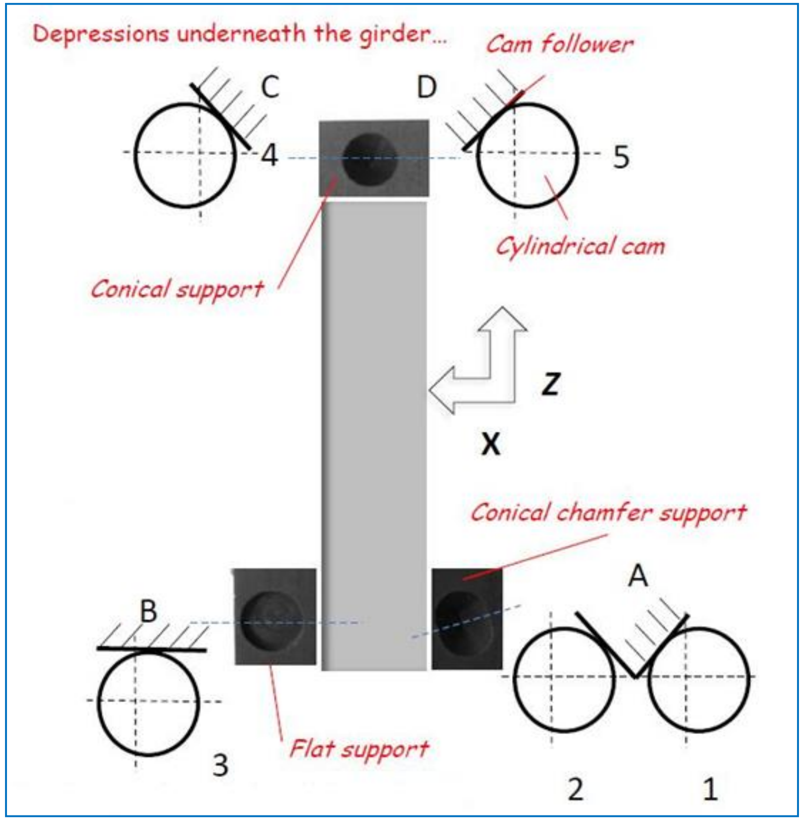


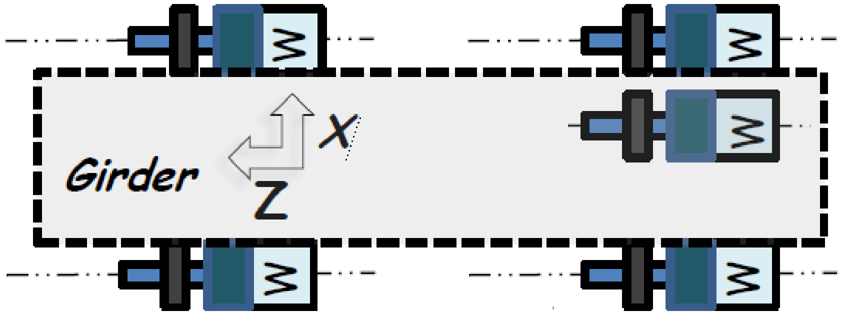
Cam movers







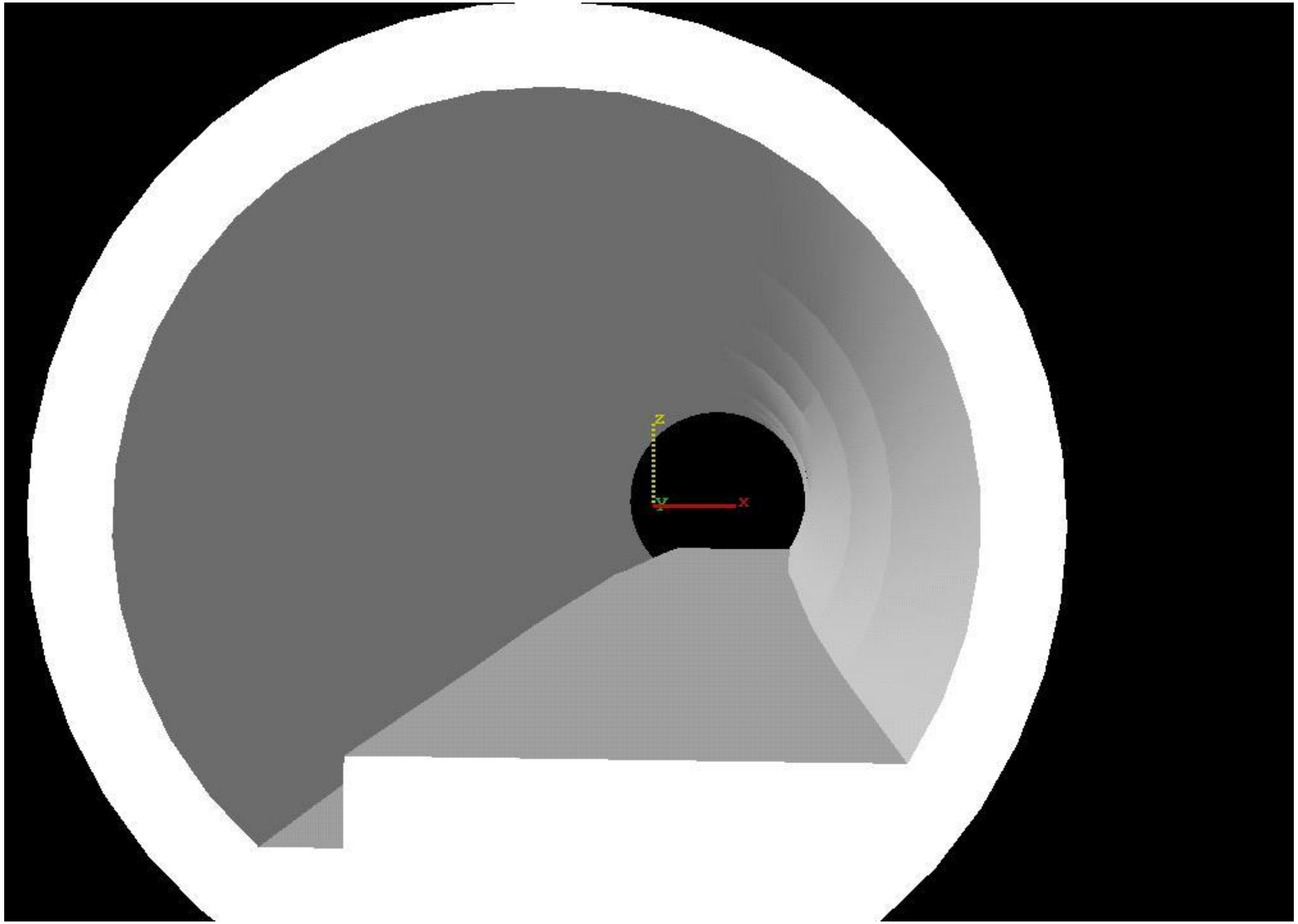




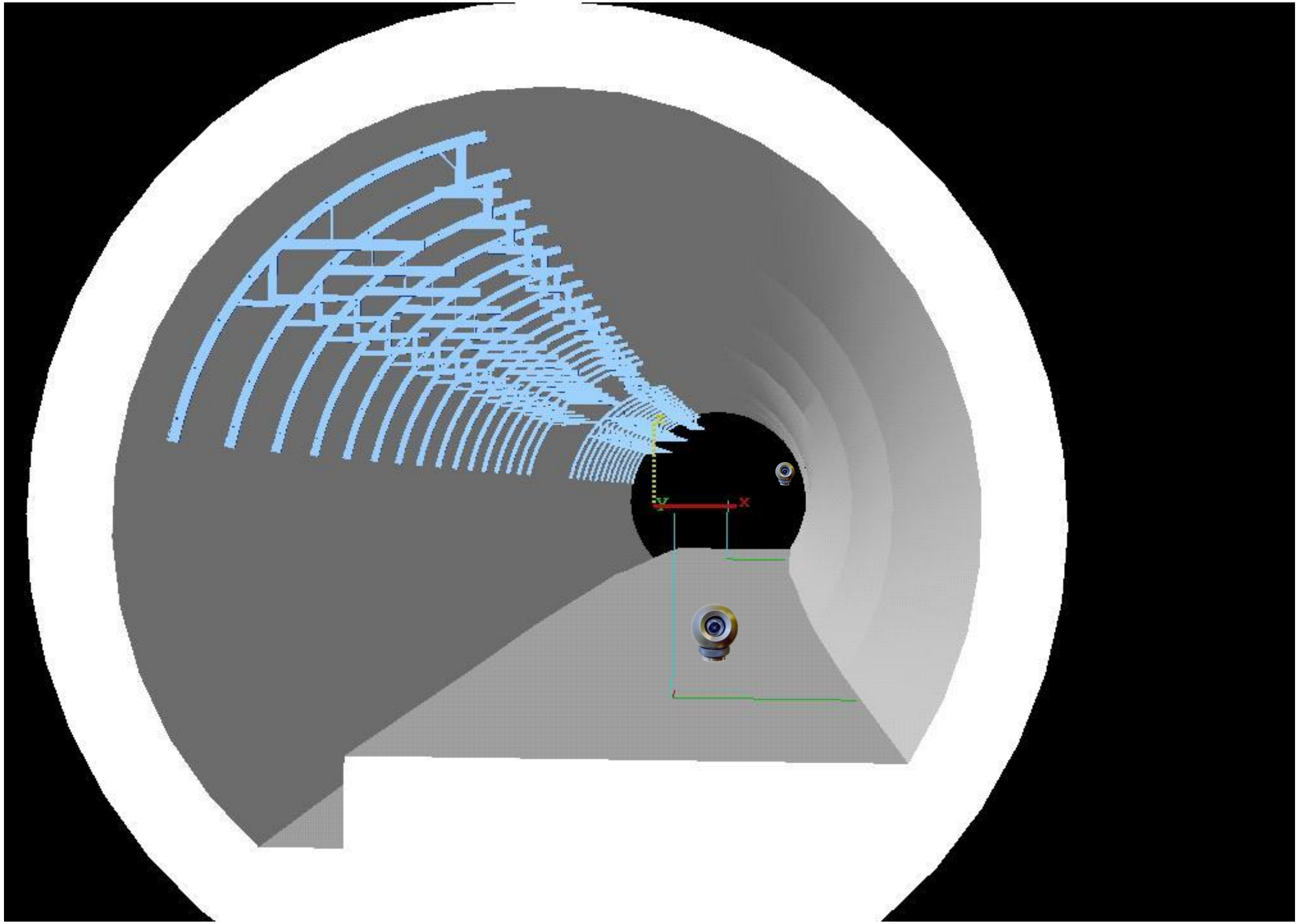
(Base View)

Case of the LHC

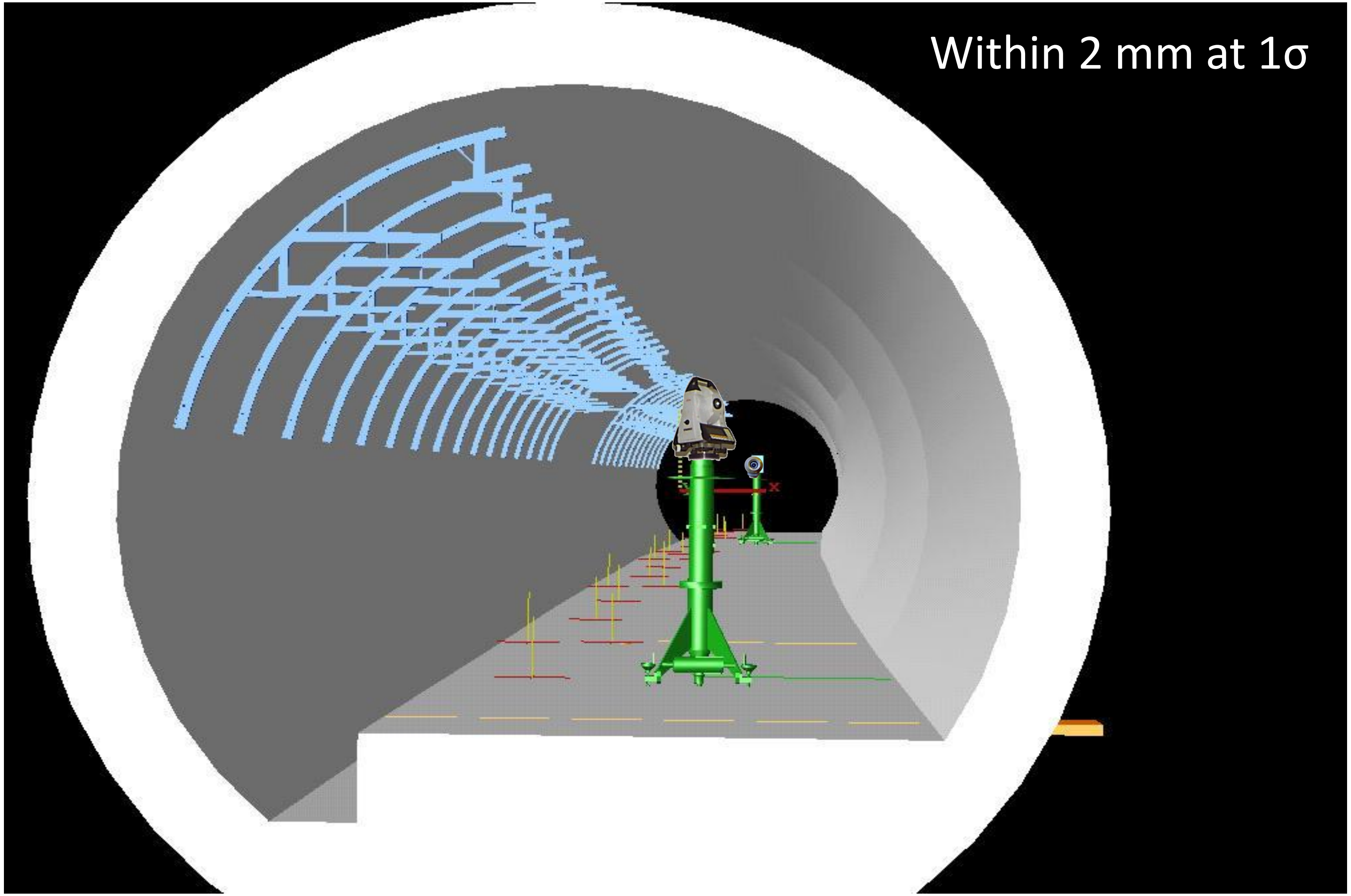
Tunnel empty



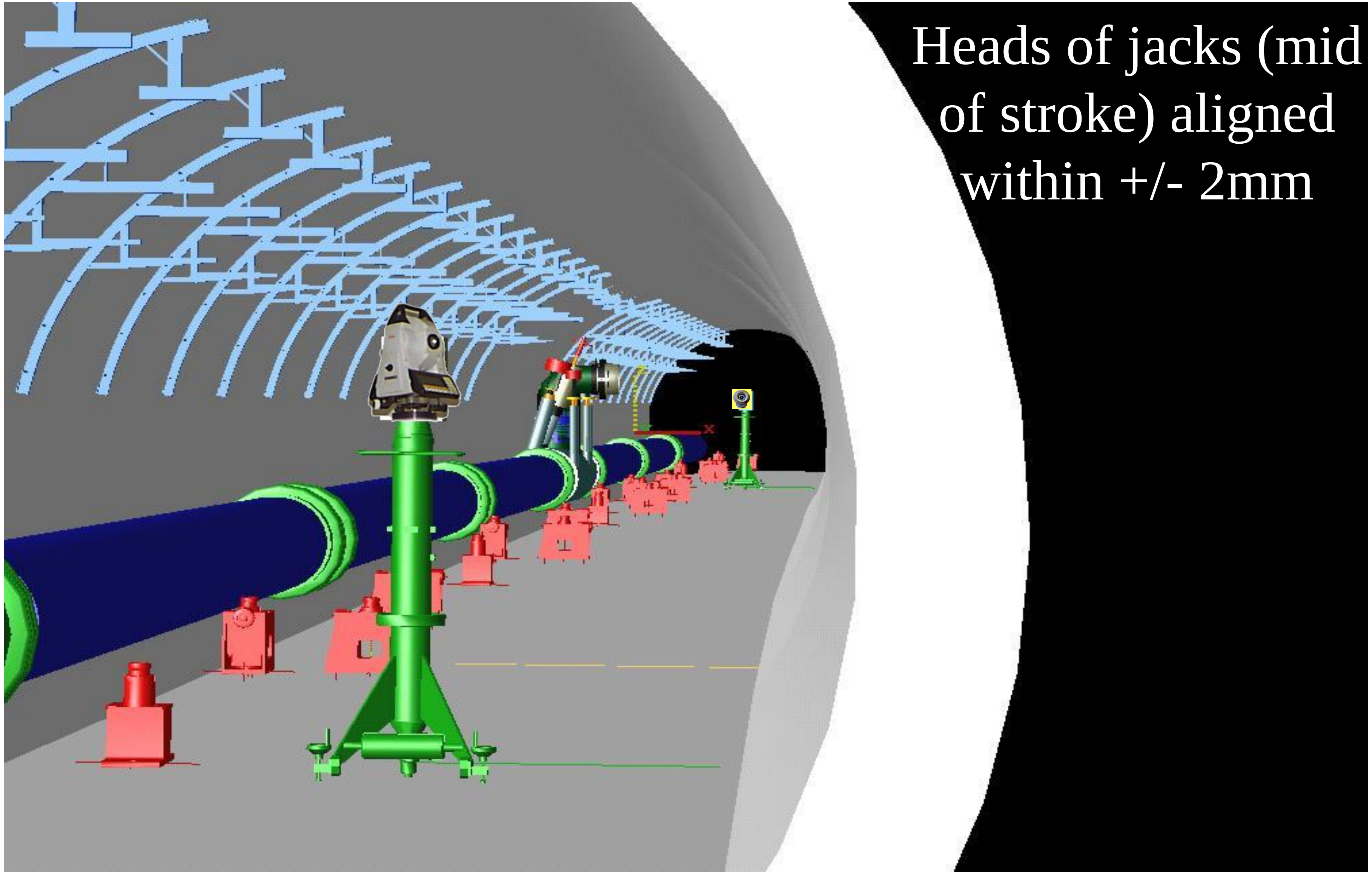
Determination of underground geodetic network



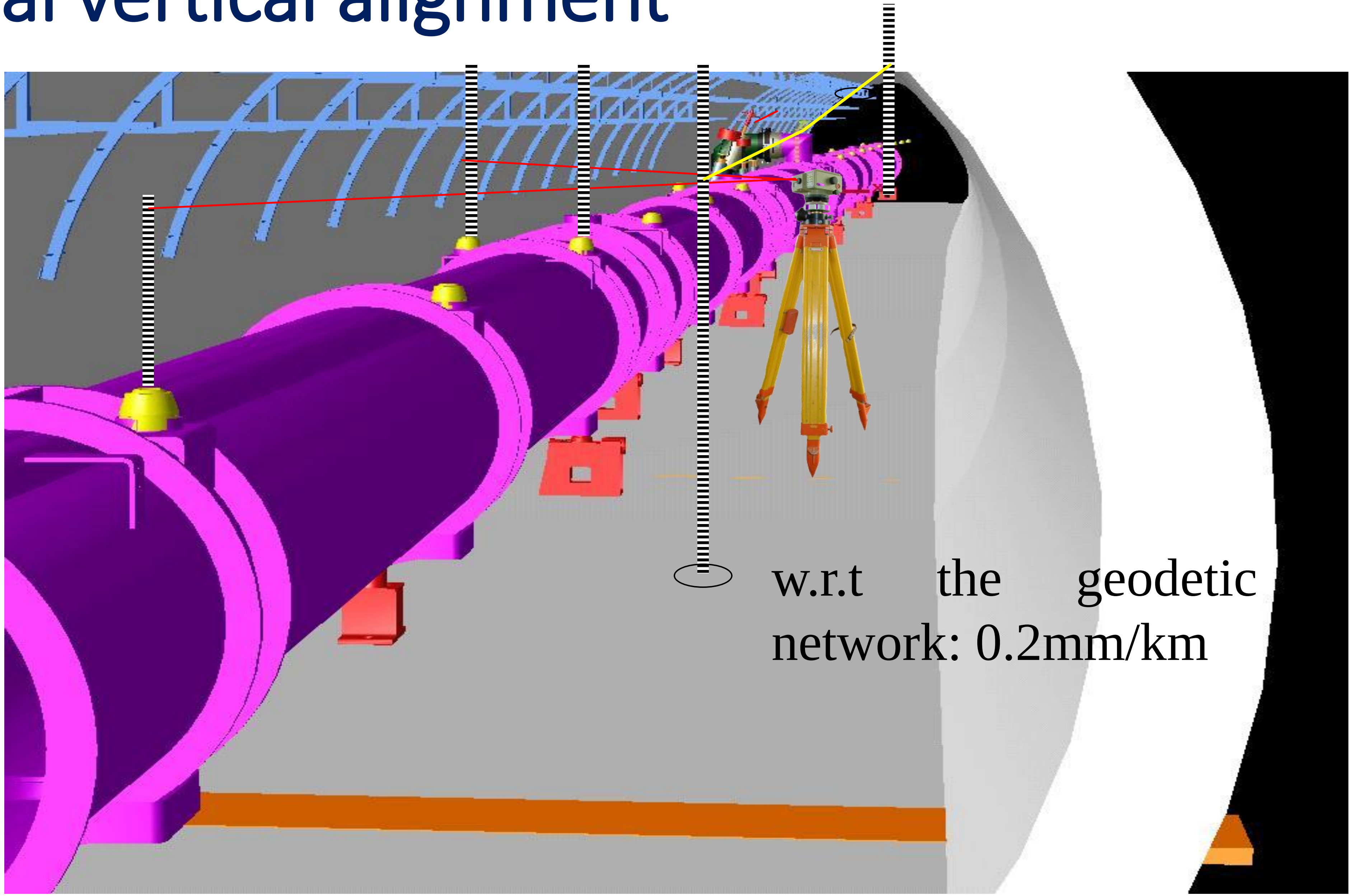
Marking on the floor



Positioning of jacks

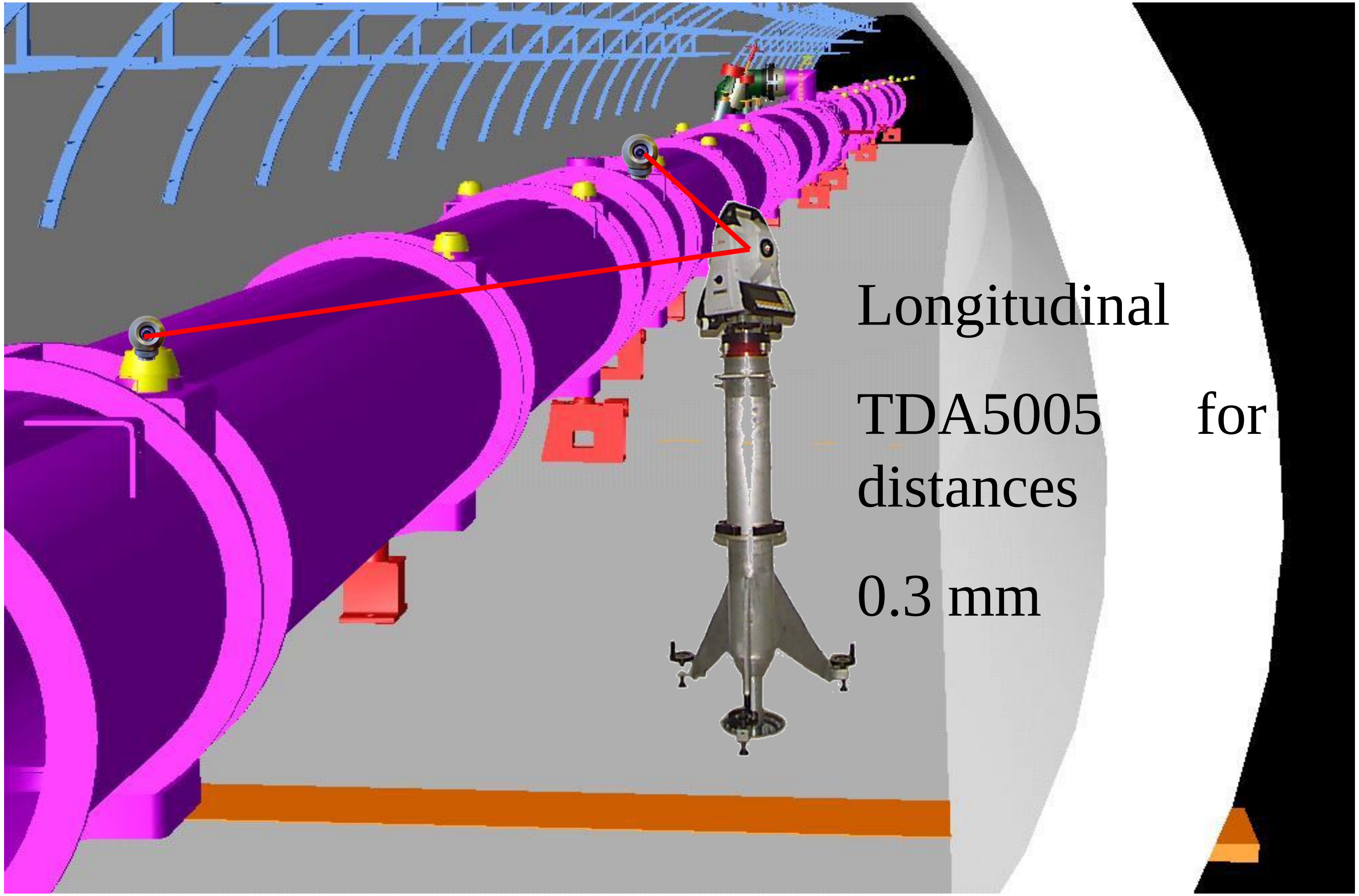


Initial vertical alignment



w.r.t the geodetic network: 0.2mm/km

Initial longitudinal alignment

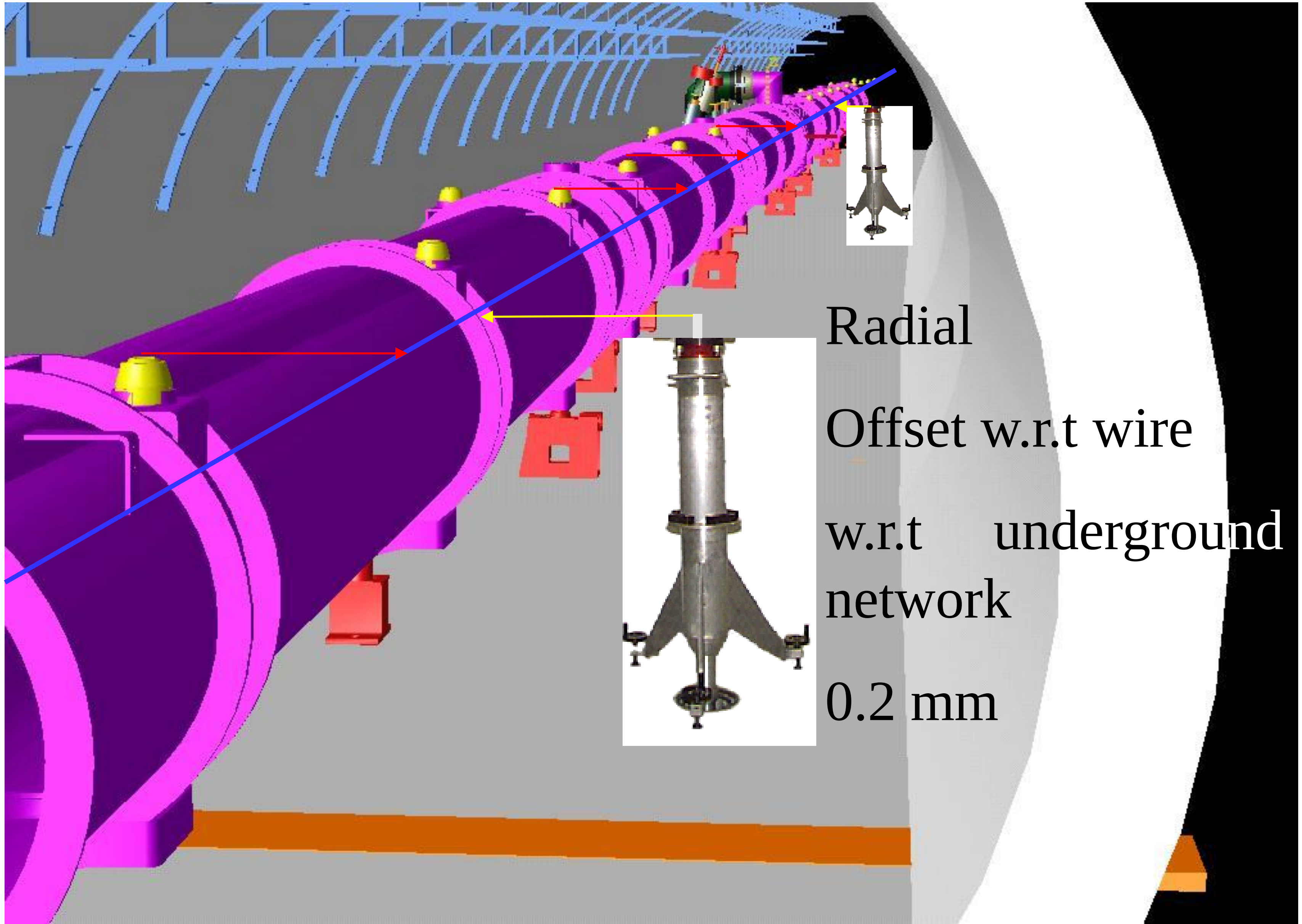


Longitudinal

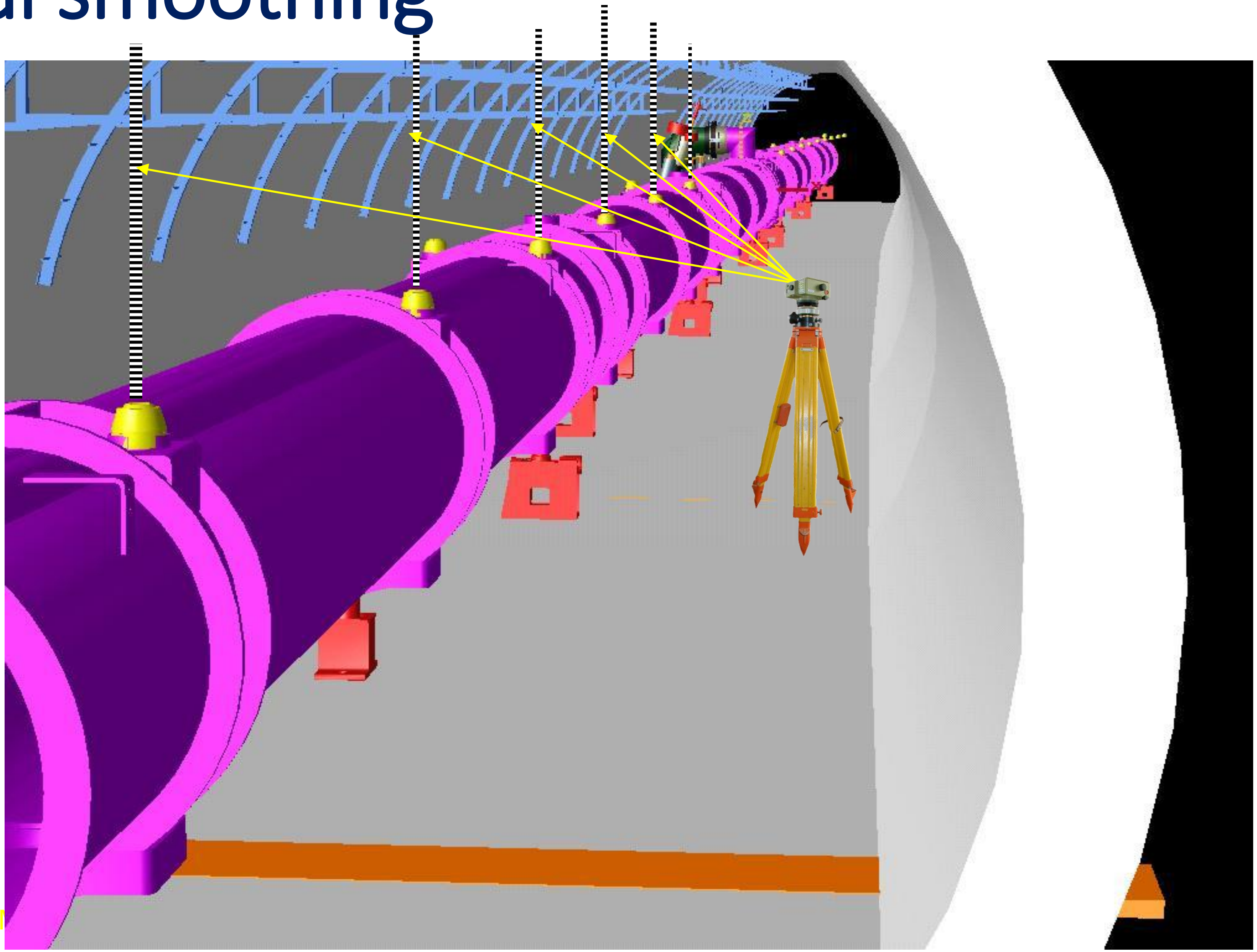
TDA5005 for distances

0.3 mm

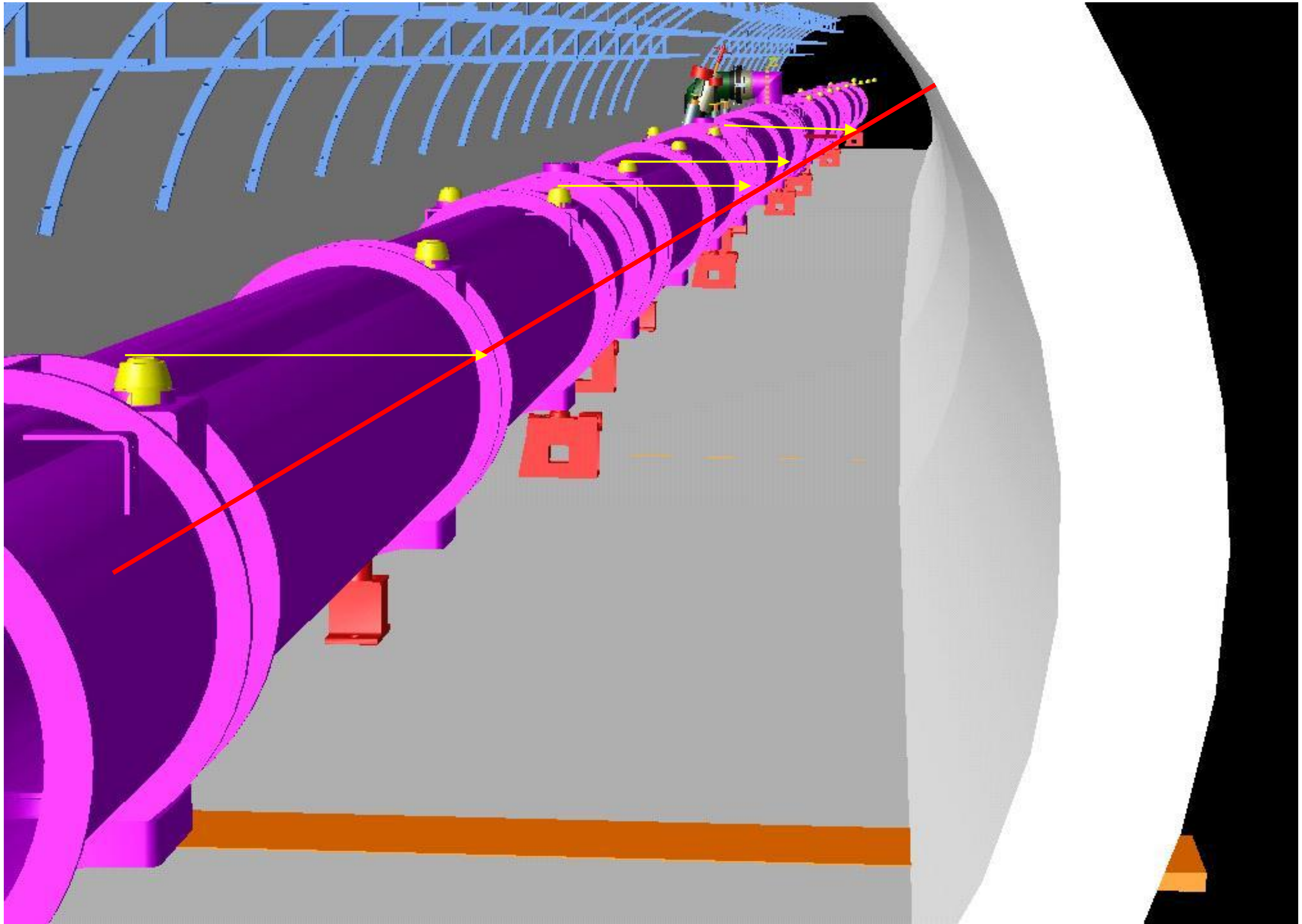
Initial radial alignment



Vertical smoothing



Radial smoothing



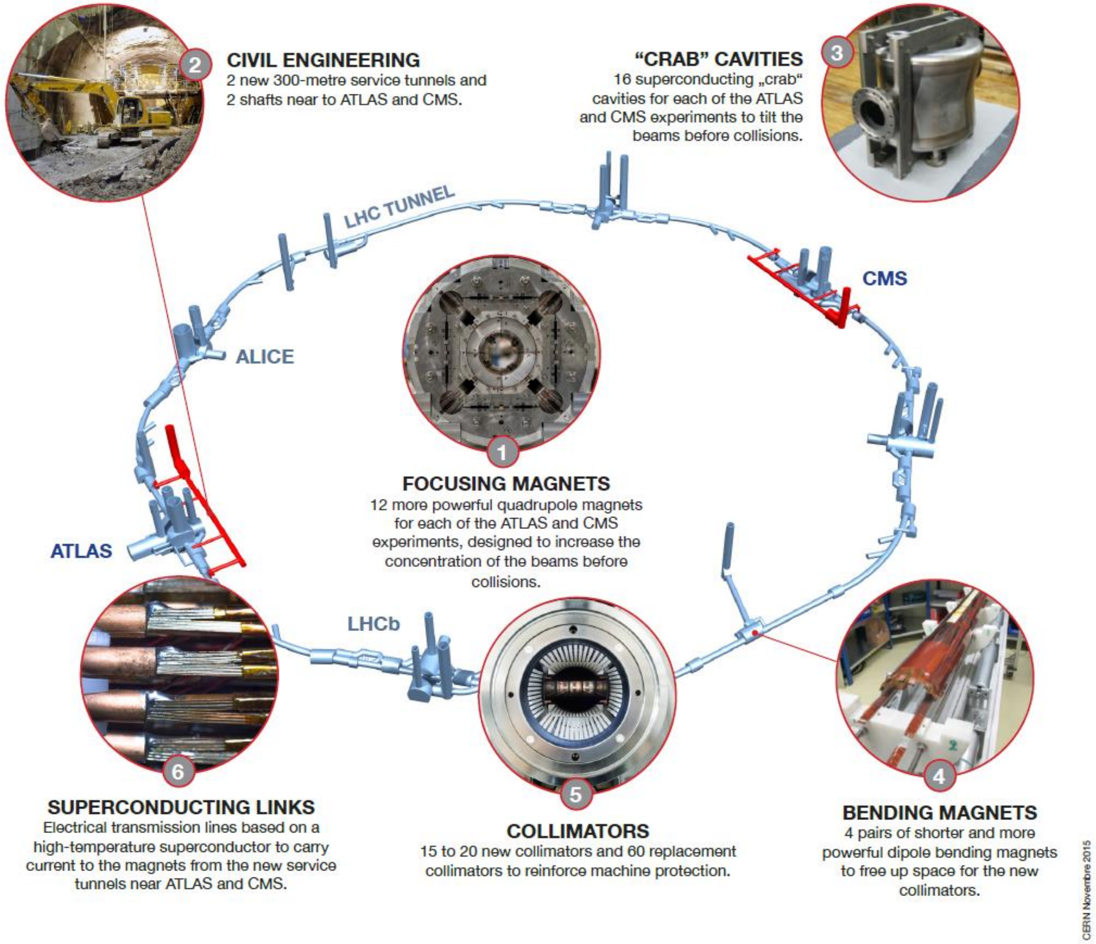

RS-1000 n.15
sylvac
-81.69

10

Current challenges on HL-LHC

- Internal monitoring of cold masses
- Full Remote Alignment

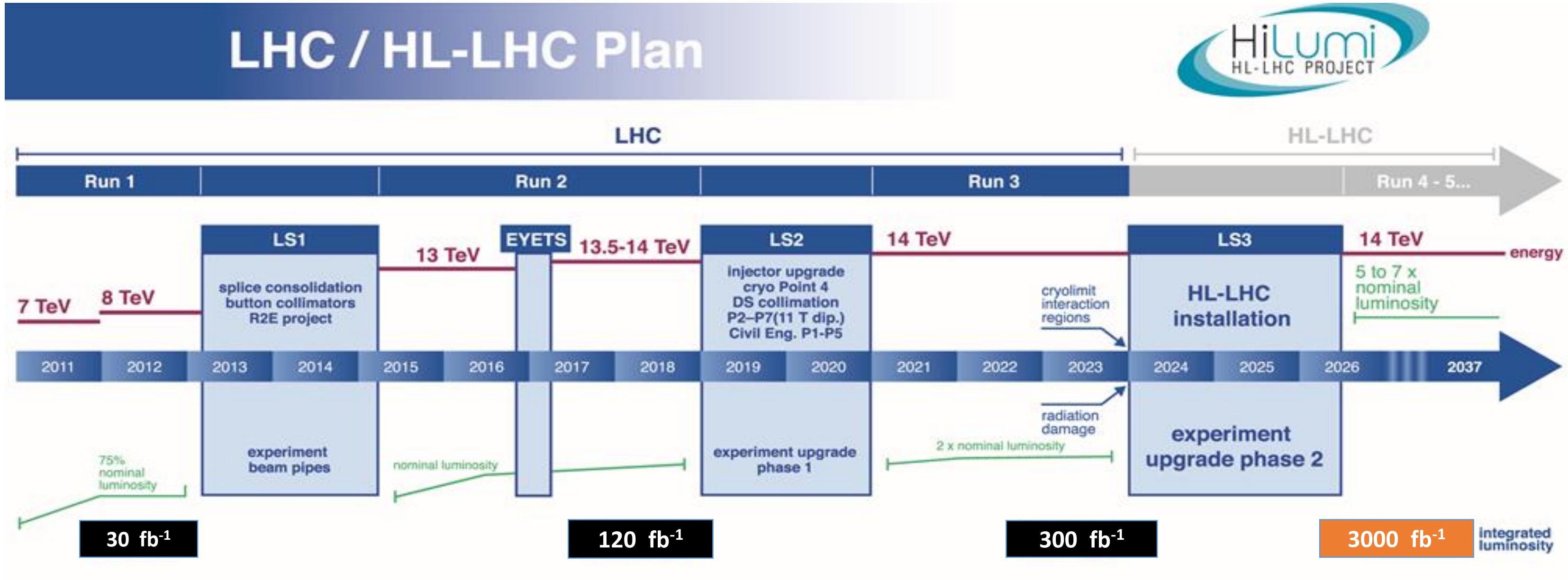
HL-LHC: introduction

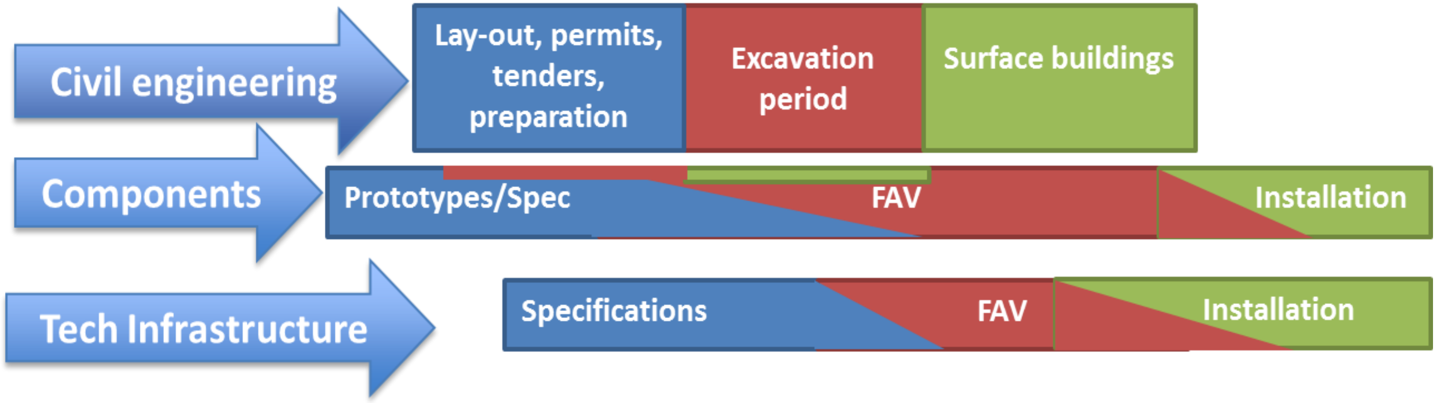


- ✓ New IR-quads Nb3Sn (inner triplets)
- ✓ New 11 T Nb3Sn (short) dipoles
- ✓ Collimation upgrade
- ✓ Cryogenics upgrade
- ✓ Crab Cavities
- ✓ Cold powering
- ✓ Machine protection
- ✓ …

Major intervention on more than 1.2 km of the LHC

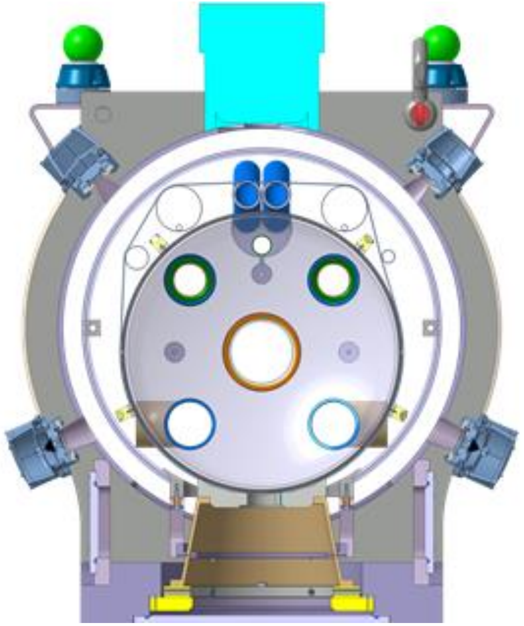
HL-LHC: introduction

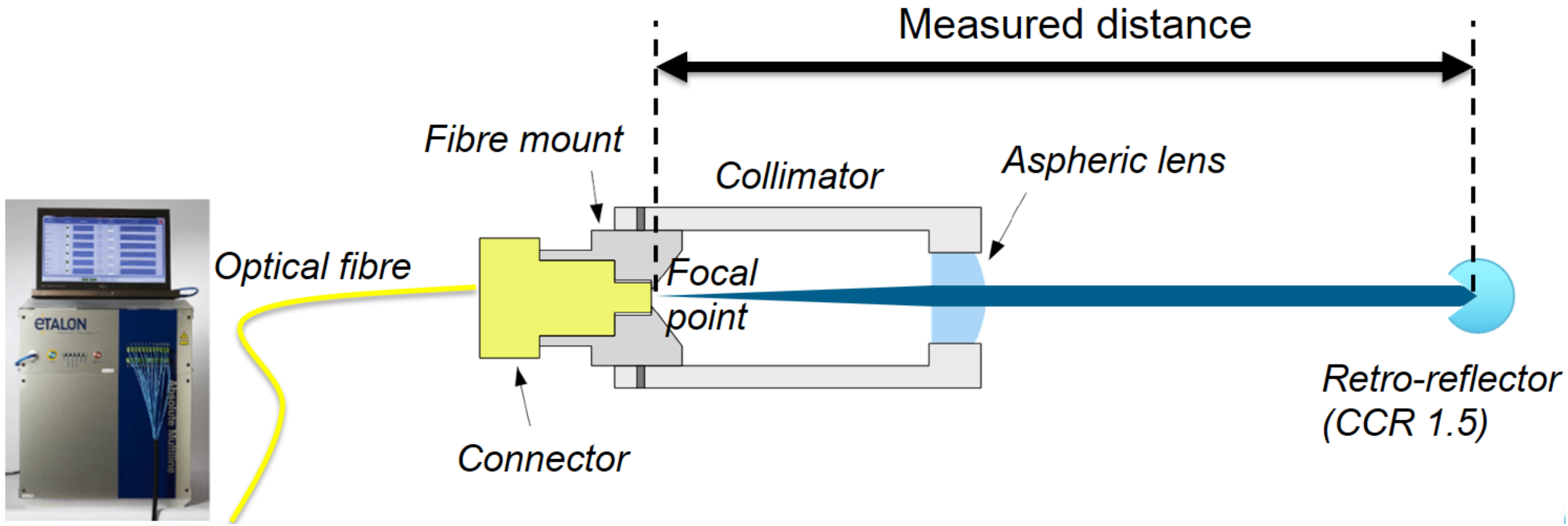




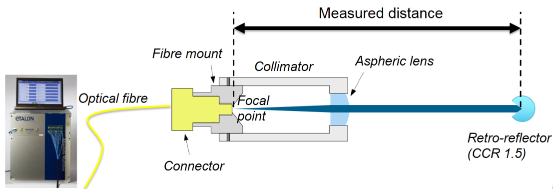
HL-LHC: internal monitoring system

- From the LHC experience: we know at the micron level the position of the cryostat, but not what happens inside → difficult to correlate with beam.
- Displacements up to ± 0.5 mm (3σ) seen on the LHC dipoles after transport
- Strong interest from physicists to know more accurately than in the LHC the longitudinal position of the cold mass





HL-LHC: internal monitoring system



- Decision to include in the baseline the internal monitoring of the inner triplet cold masses using laser interferometer (less «invasive» solution)
- Validation of the commercial solution based on Frequency Scanning Interferometry (FSI), providing absolute distance measurements

- $\Delta Phase\ (meas.) = \frac{2\pi}{c} * L_M * \Delta\nu$
- $\Delta Phase\ (\ ref.\ ) = \frac{2\pi}{c} * L_R * \Delta\nu$

$$\frac{\Delta Phase\ (meas.)}{\Delta Phase\ (\ ref.\ )} = \frac{L_M}{L_R}$$

The FSI distance measurement is deduced from the ratio of the phase change induced in an interferometer reference (stable reference in the form of absorption peaks of an integrated gas cell) and the interferometer measurement (to the reflective target) by frequency scanning

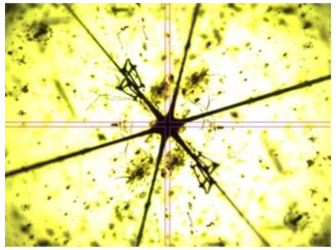
HL-LHC: internal monitoring system

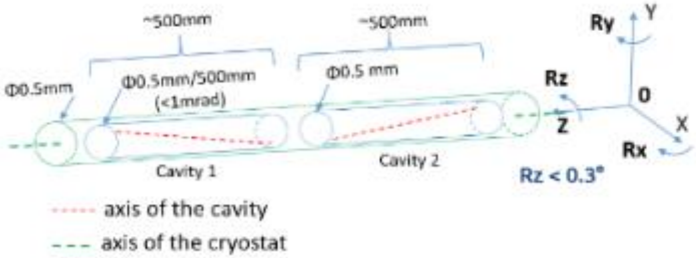
Validation on independent benches
Performance of one line FSI & study of an alternative
- Irradiation tests
- Thermal tests
- Precision, accuracy,…

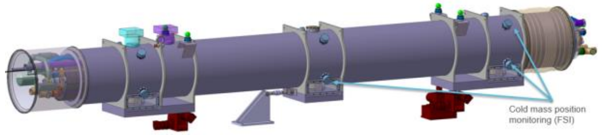
Validation on Crab cavities in SM18 & SPS
Performance target at warm, vacuum, cold, and cross-comparison with other systems

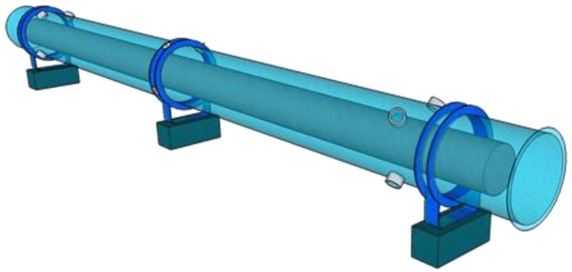
Validation on a test magnet (Dipole)
Validation of performance
- Accuracy and precision
- Long term stability
- Cryo-condensation issues

10 MGy





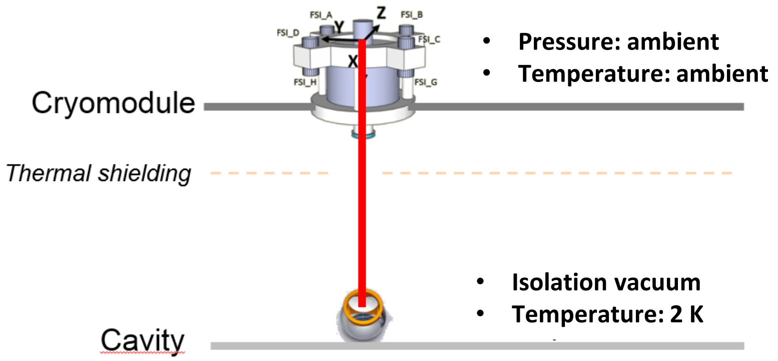


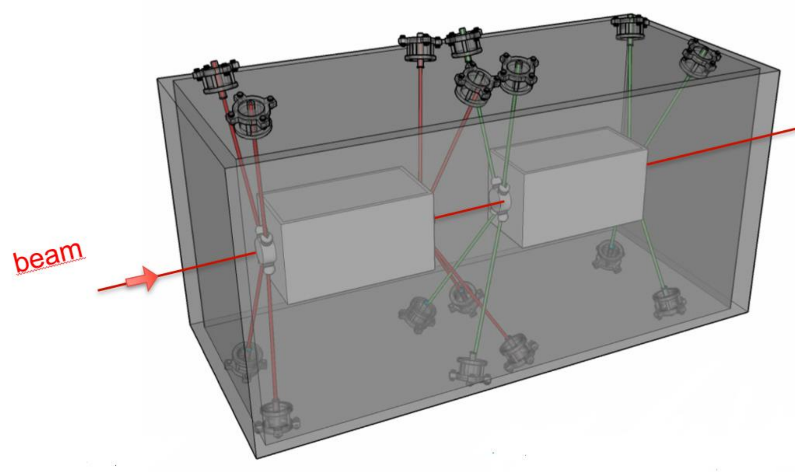


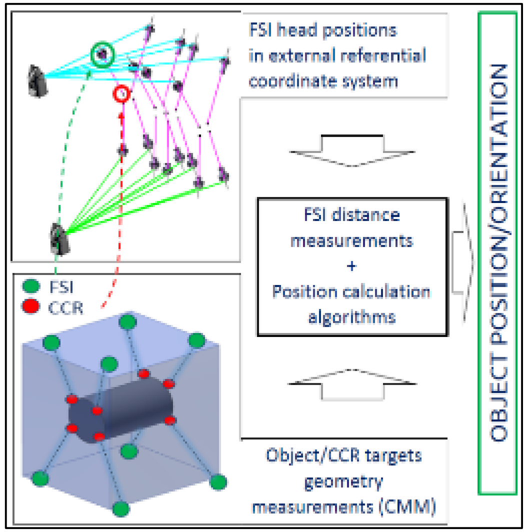
[Mainaud Durand2]

HL-LHC: internal monitoring system

From the LHC experience



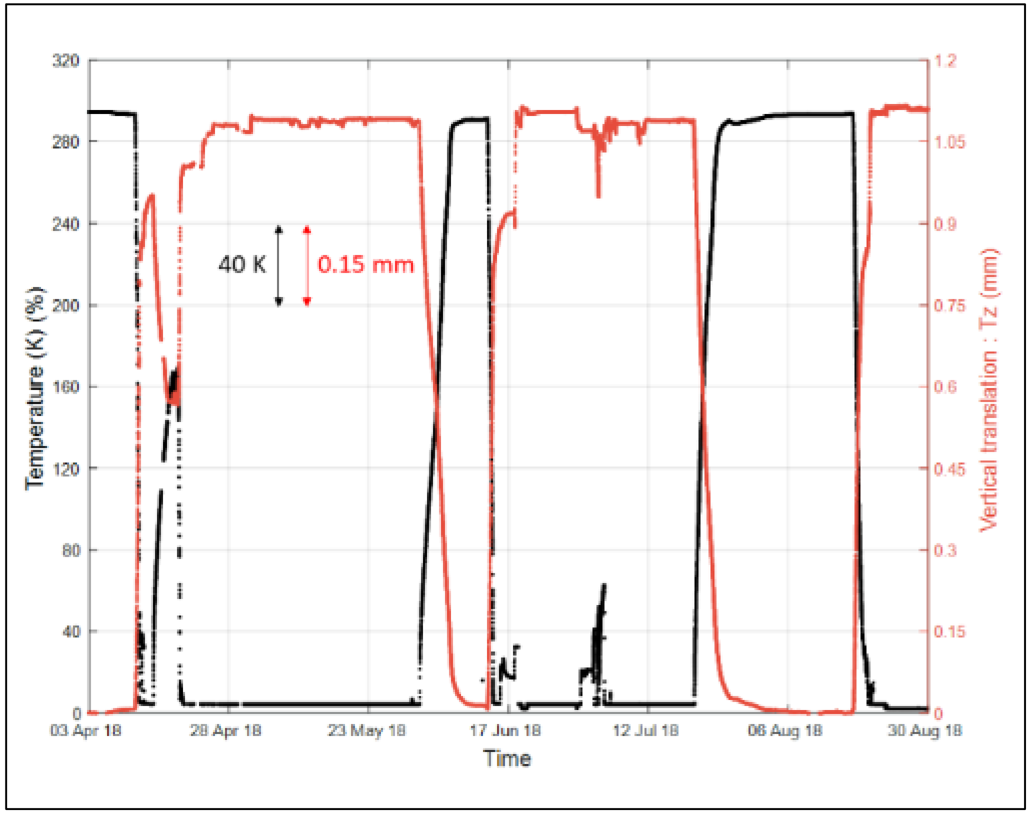




[Rude]

HL-LHC: internal monitoring system

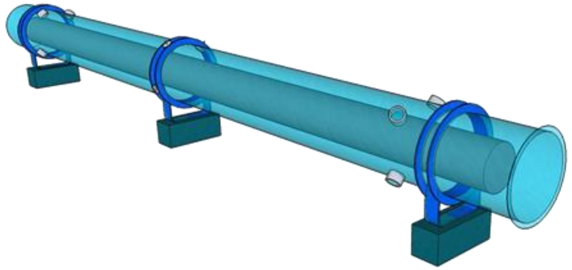
Crab cavities monitoring with FSI

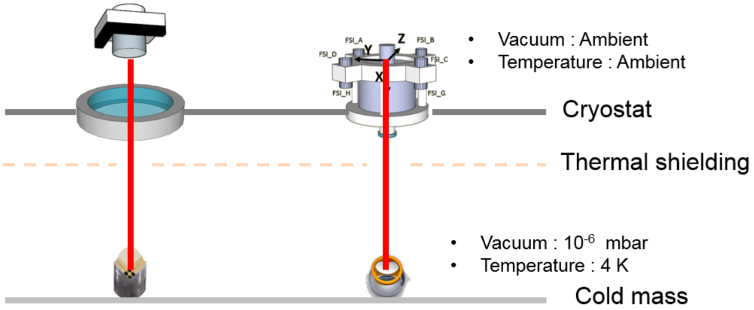


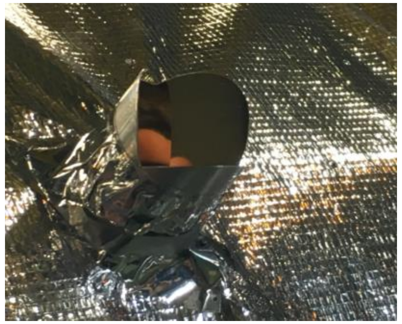
- Successful cross-comparison with other systems at warm, at cold, under vacuum
- Accuracy of the absolute position of crab cavities using FSI : ±0.05 mm
- Relative position: a few micrometers

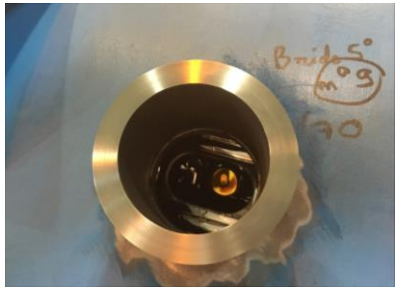
HL-LHC: internal monitoring system [Mainaud Durand3]

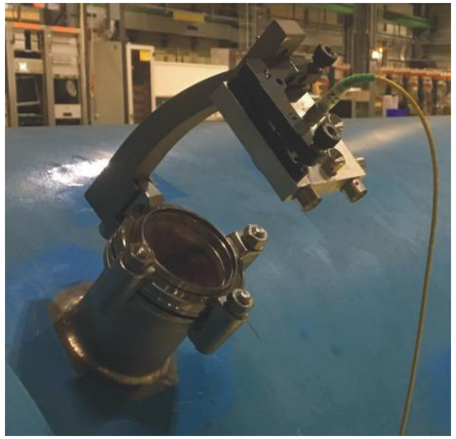
IT quadrupole monitoring with FSI



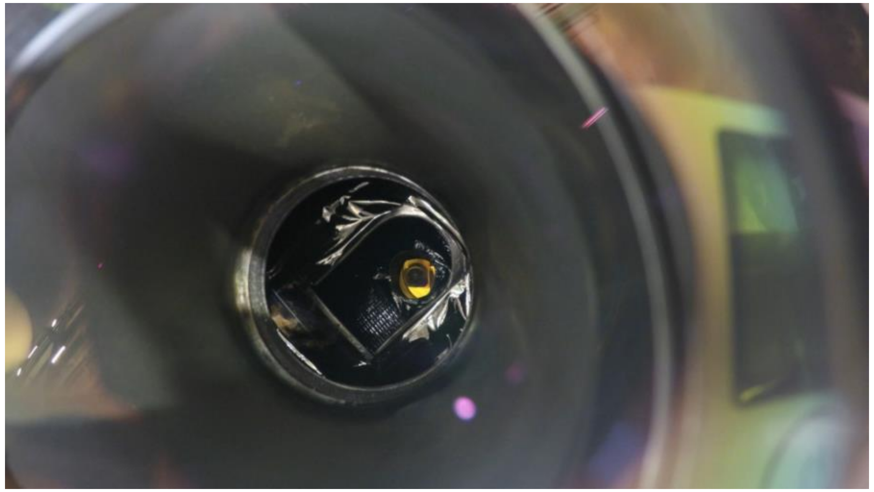






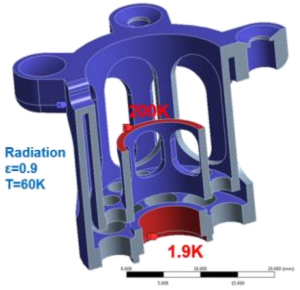


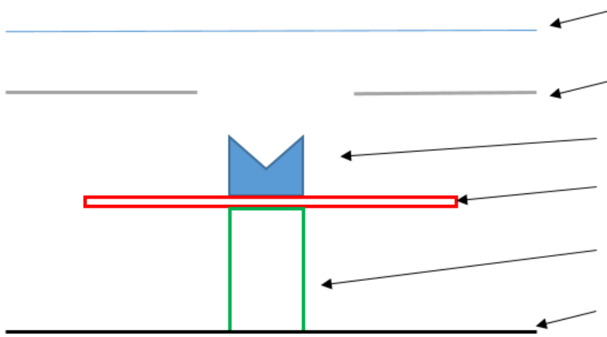
HL-LHC: internal monitoring system

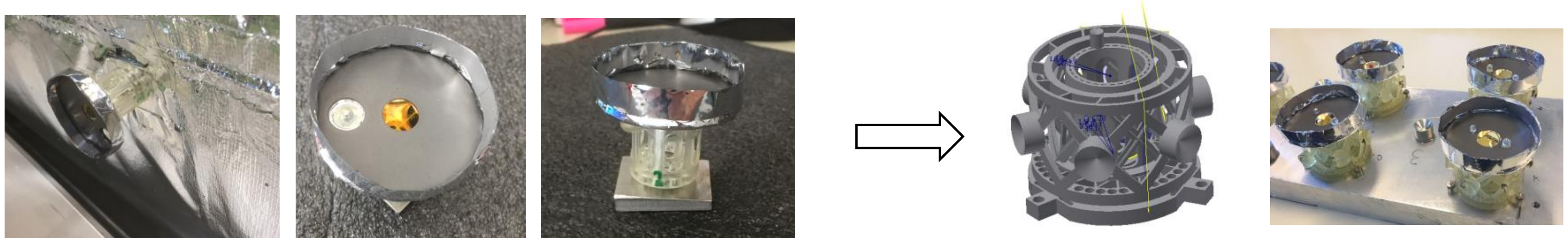


How can we achieve a "heating" of the probes up to ~200K ?

Permanent heating – by making sure that the probe stays at >=200K, no cryo-condensation should ever take place in principle. This could be achieved using the power radiated from the vacuum vessel (which is 300K "hot").

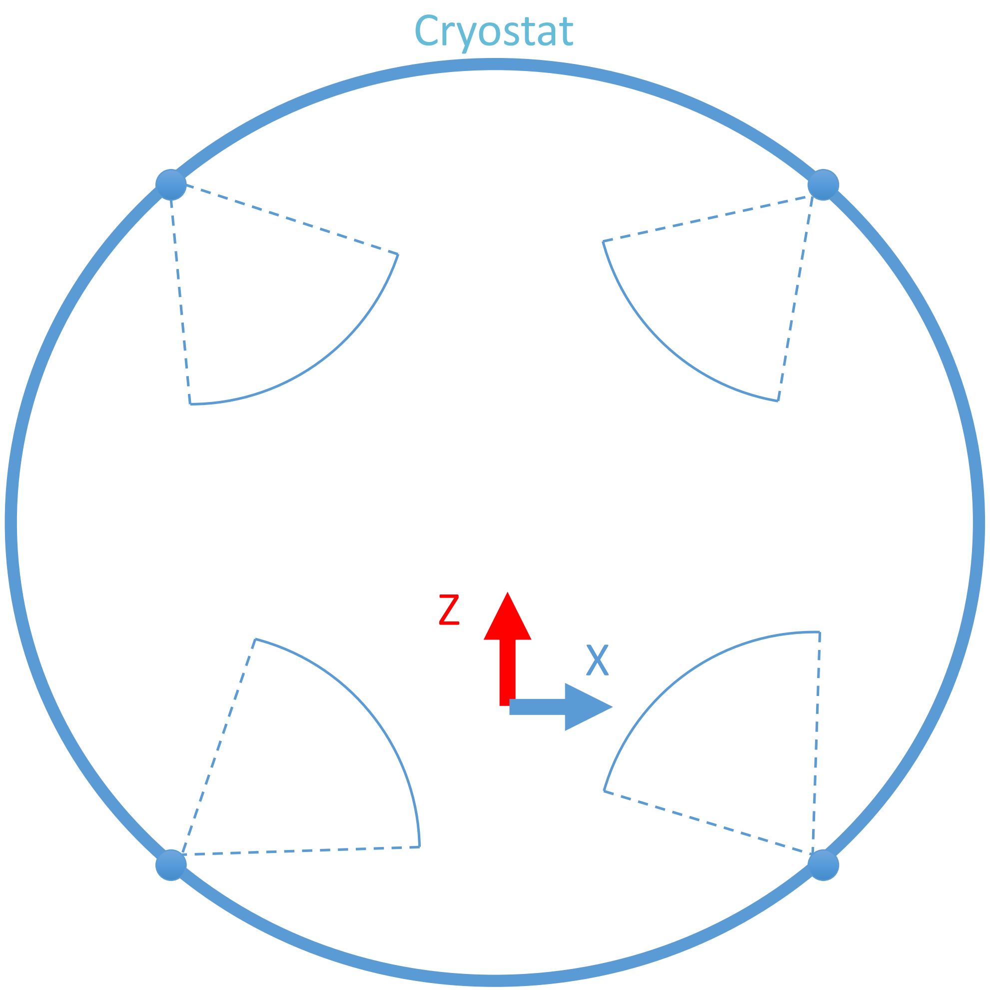


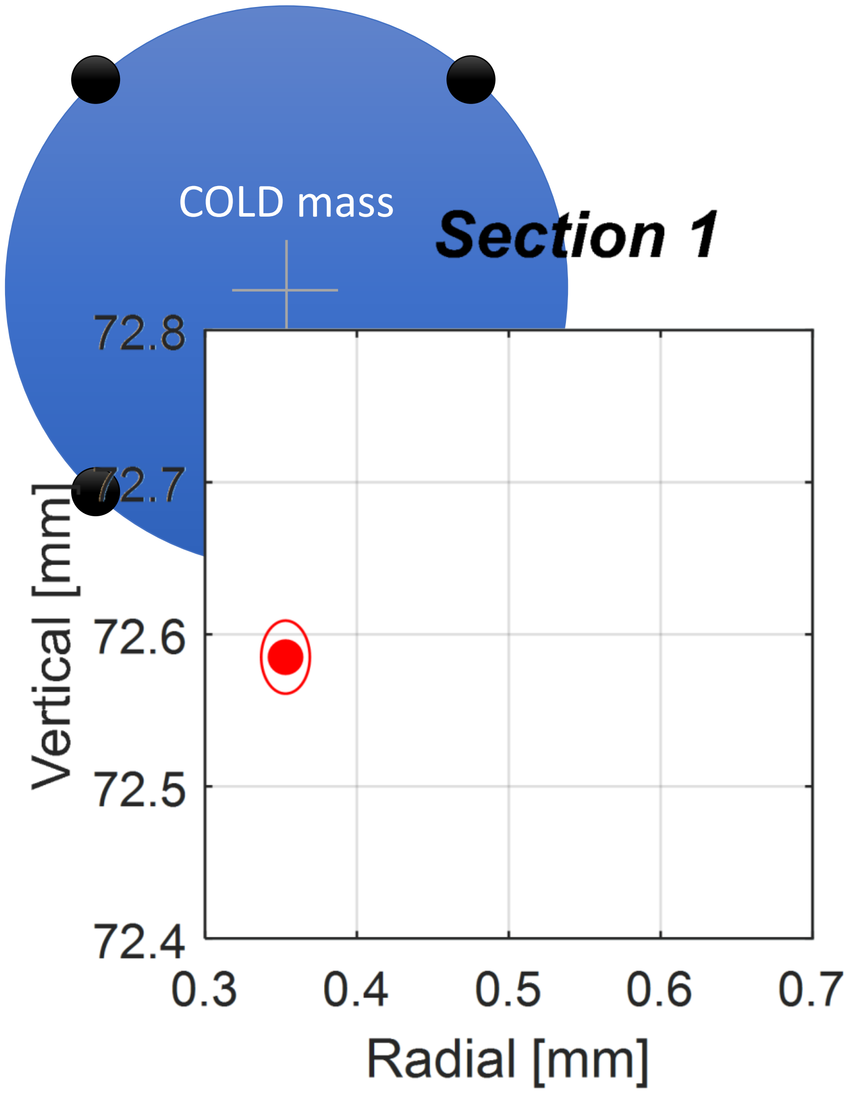




[Rude]

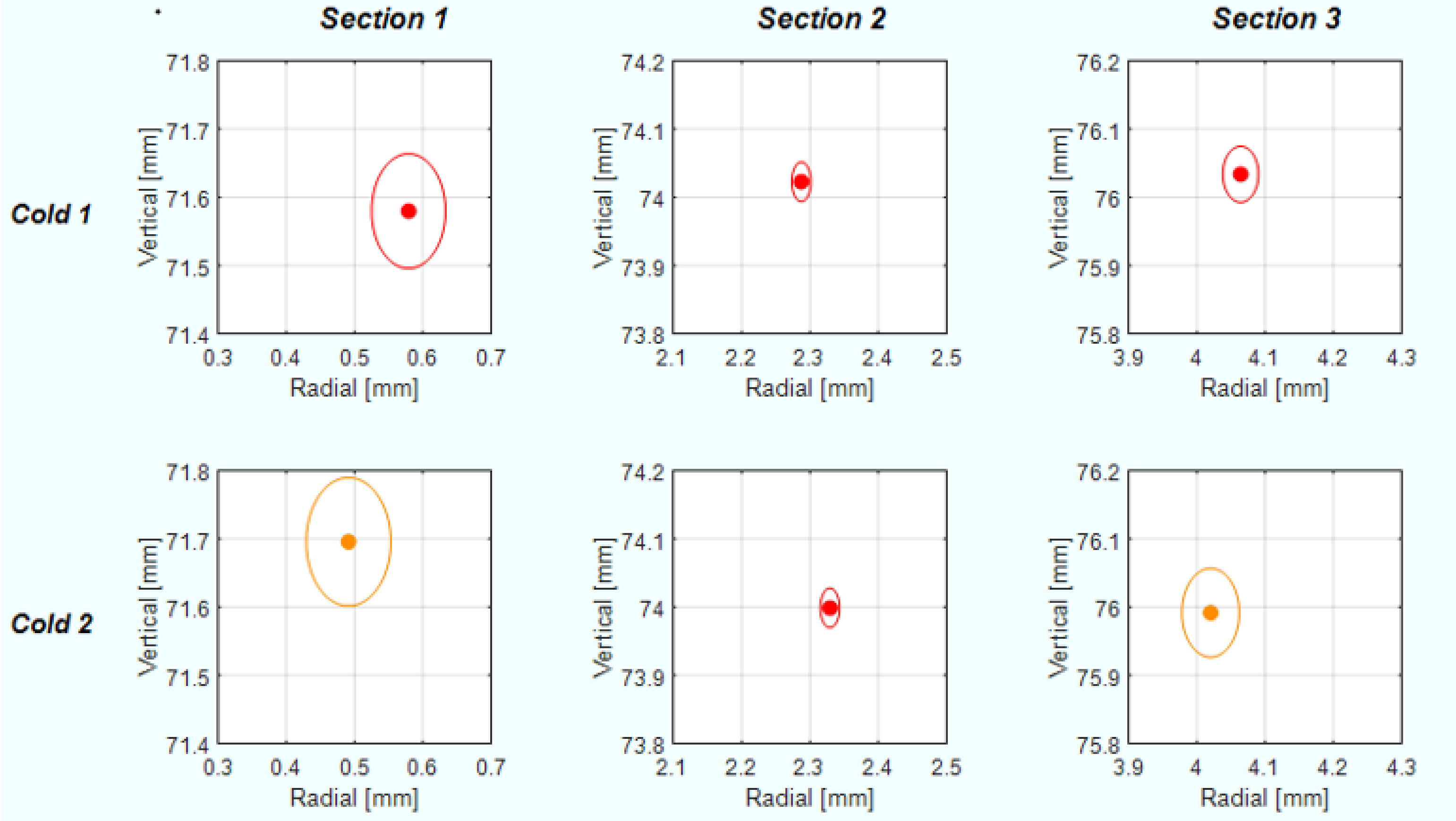
HL-LHC: internal monitoring system





Position calculation

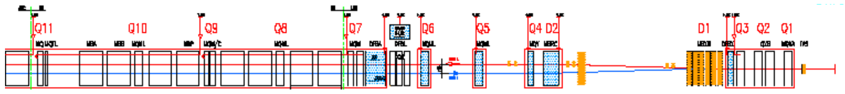
HL-LHC: internal monitoring system



Etalon (convergent beam) + Window + Newport reflector

Etalon (convergent beam)+ Window + Glass sphere with coating

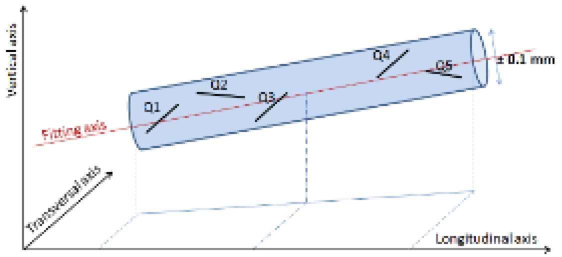
Towards Full Remote Alignment

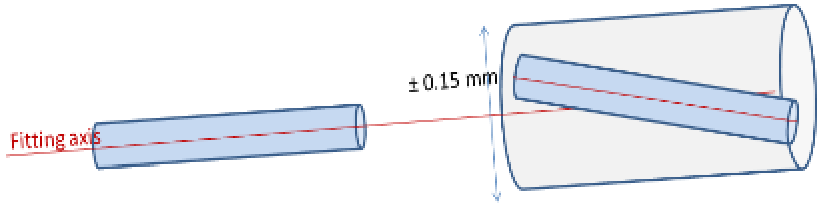


HL-LHC alignment requirements:

Estimation of the deviation of the magnets from a laser straight line, with a quadratic sum of the following independent contributions: ± 0.27 mm:

- Fiducialisation: mechanical axis vs external fiducials: ± 0.1 mm
- Smoothing :
  - Mechanical axis of quadrupoles included in a cylinder with a radius of 0.1mm
  - Left / right mechanical axis included in a cylinder with a radius of 0.15 mm.
- Misalignment between alignment campaigns: ± 0.17 mm (integrating ground motion, mechanical stress encountered during vacuum and cool-down phases)



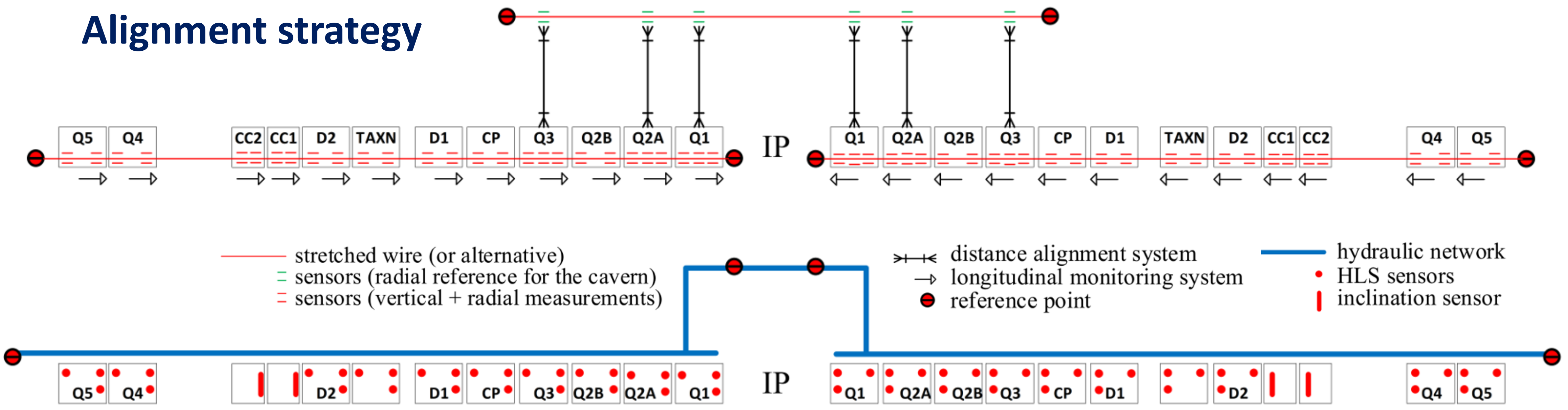


Remote adjustment of the position of the main components from Q1 to Q5 (5DOF)

[Mainaud Durand4]

Towards Full Remote Alignment

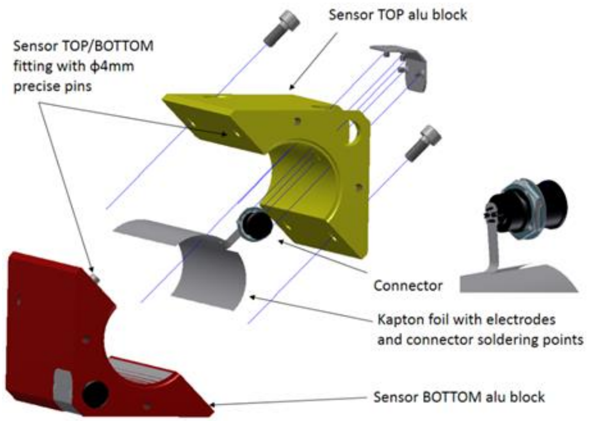
Alignment strategy

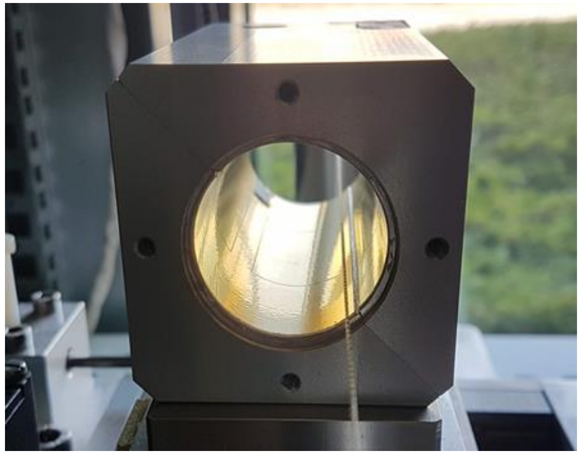


- Combined with an internal monitoring of the position of cold masses in the Inner Triplet cryostats using FSI system
- Motorized jacks supporting all main components.

Towards Full Remote Alignment

Development of low cost sensors





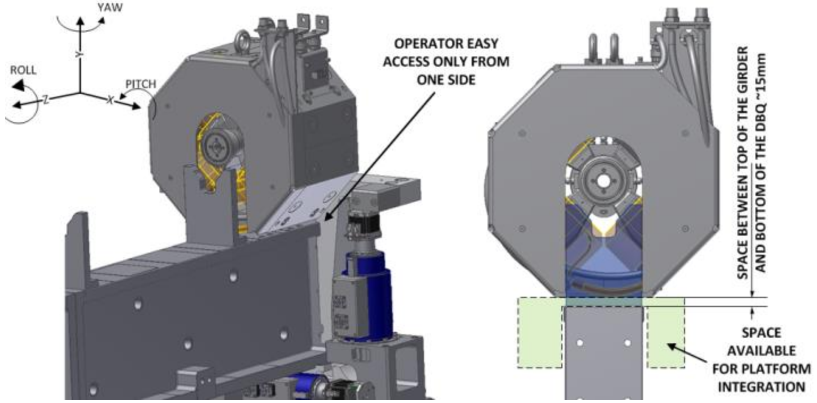
Kapton WPS (kWPS)

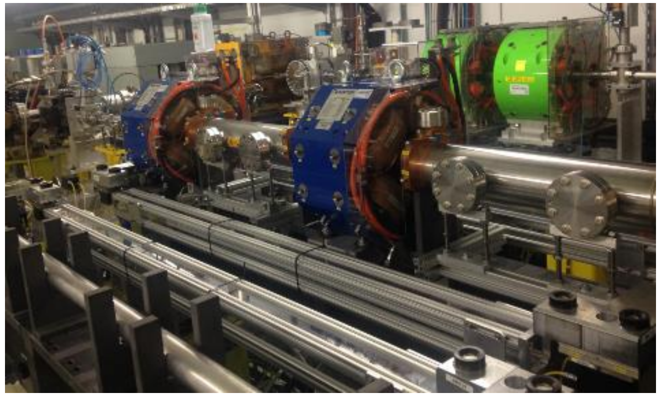
- Based on flexible Kapton polyamide PCB with electrodes printed on the surface and covered with a layer of gold
- Sensor assembly consists of:
  - 2 aluminium blocks including connectors & screws
  - A Kapton foil glued during a simple assembly process

- First tests performed on the prototype show a micrometric repeatability of measurements over ± 5 mm of range
- Irradiation tests under way
- Next steps: accuracy and long term stability of the sensor.

Towards Full Remote Alignment

«Standardized» adjustment platform





Why a 5 DOF adjustment platform?

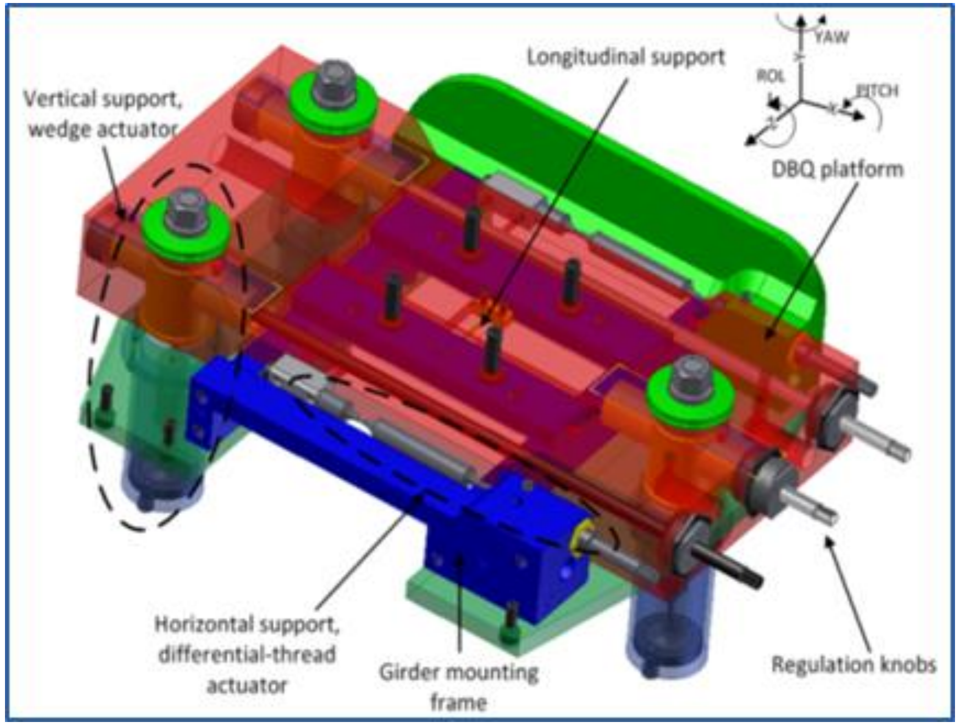
- More than 40 000 DB quadrupoles to be aligned 2 per 2 on a common support within a budget of error < 20 µm
- First tests used shims for the adjustment: the alignment took more than 1 day per quadrupole!
- Decision to develop a specific platform, with all adjustment knobs on the same side, in a limited volume.

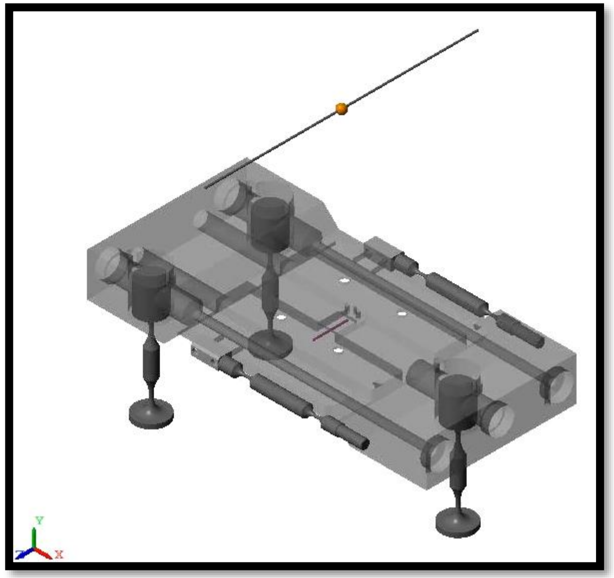
Requirements:

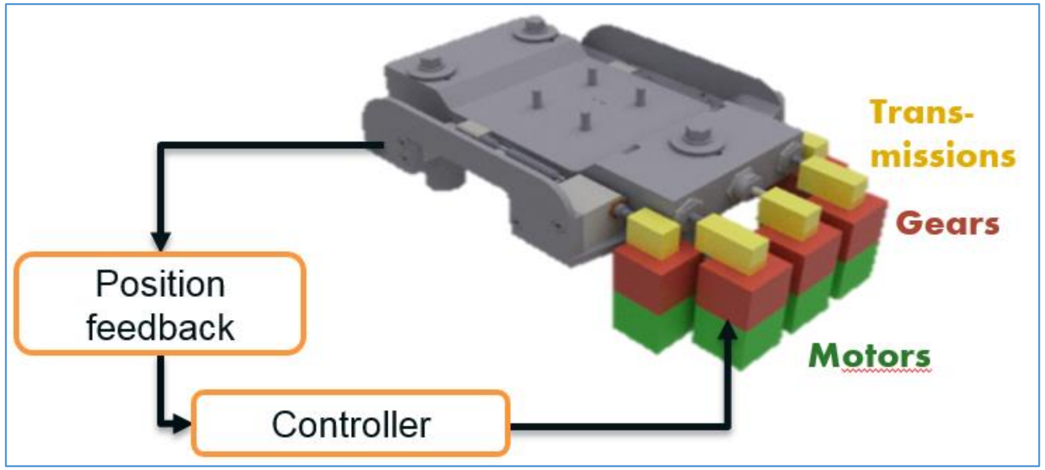
- Stroke: ± 1 mm in translations, rotations adjustment within ± 4 mrad
- Micrometric adjustment for X and Y translations, 20 µrad for angular adjustment

Towards Full Remote Alignment

«Standardized» adjustment platform





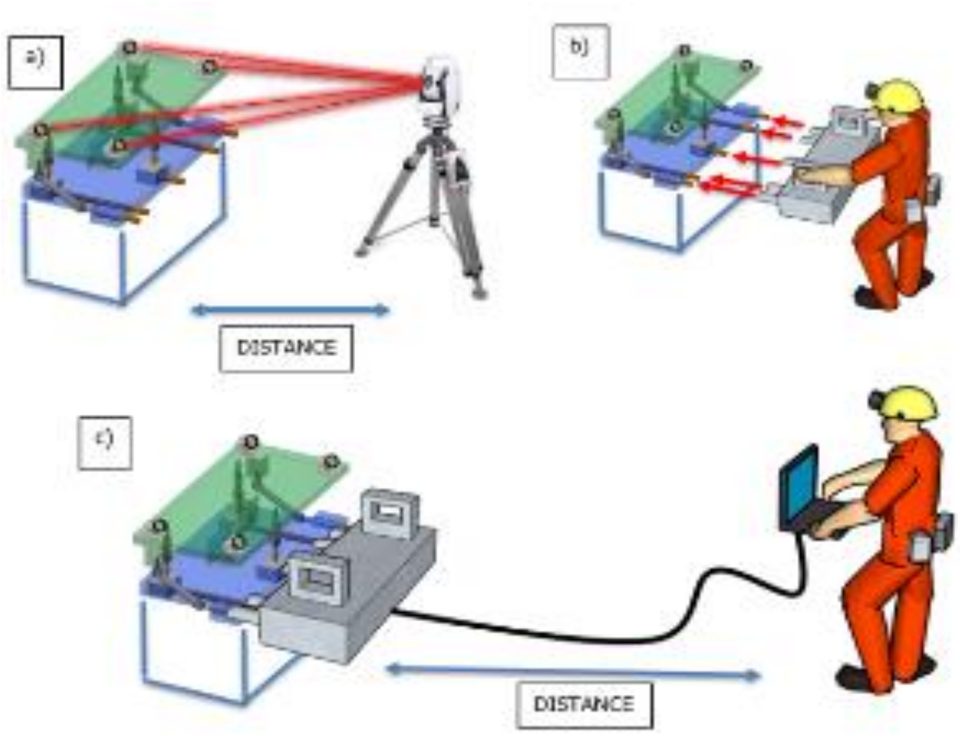


Towards Full Remote Alignment

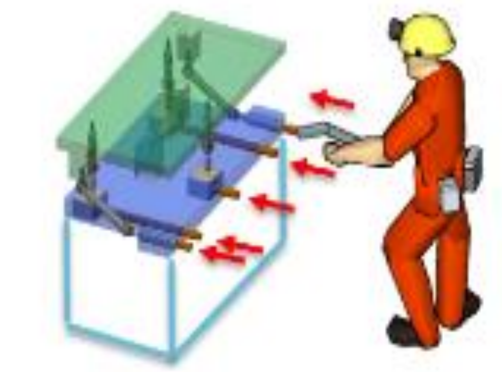
«Standardized» adjustment platform

Towards Full Remote Alignment

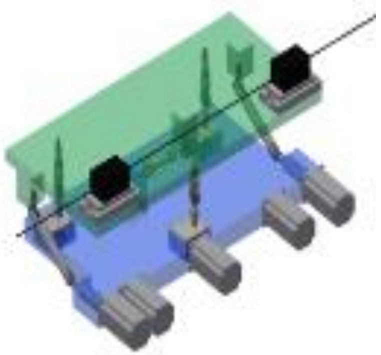
«Standardized» adjustment platform



Universal adjustment solution – concept of use plug-in motors:
a) Platform measurement from distance using a laser tracker;
b) Installation of plug-in motors in less than one minute;
c) Remote adjustment from distance.



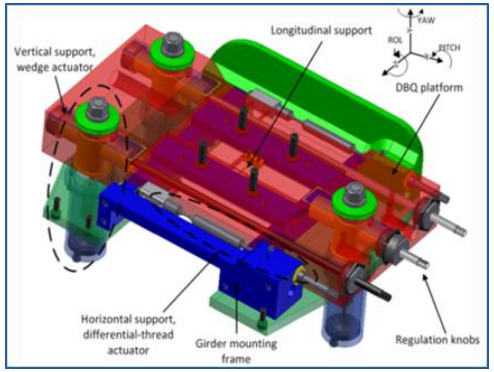
Universal adjustment platform – manual operation concept

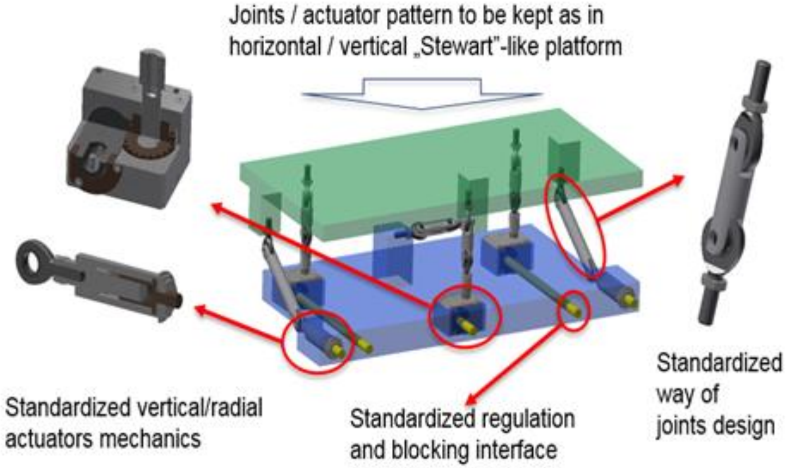


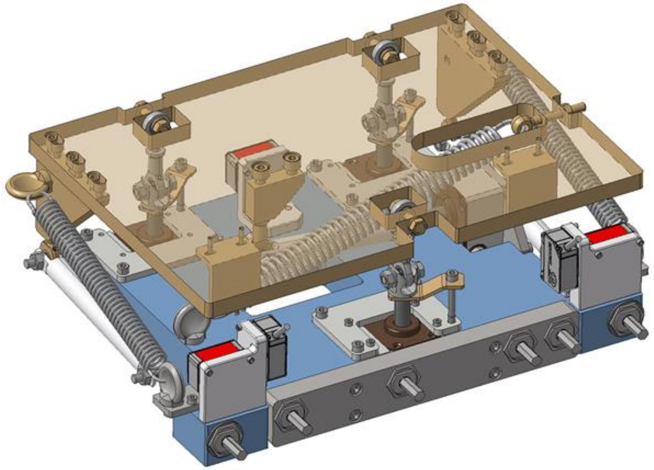
Universal adjustment solution - permanent motors version concept

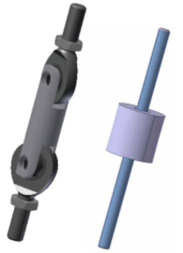
Towards Full Remote Alignment

«Standardized» adjustment platform

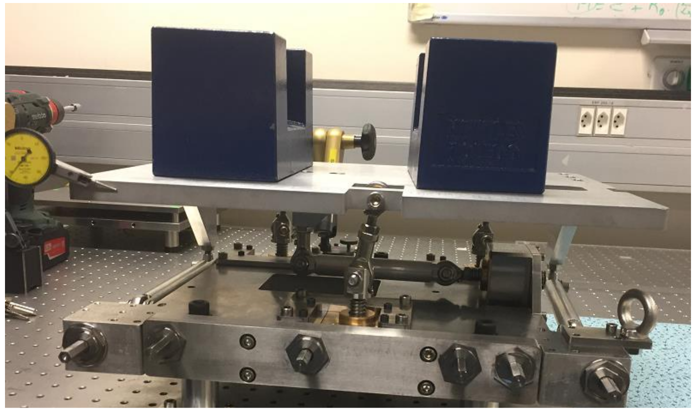






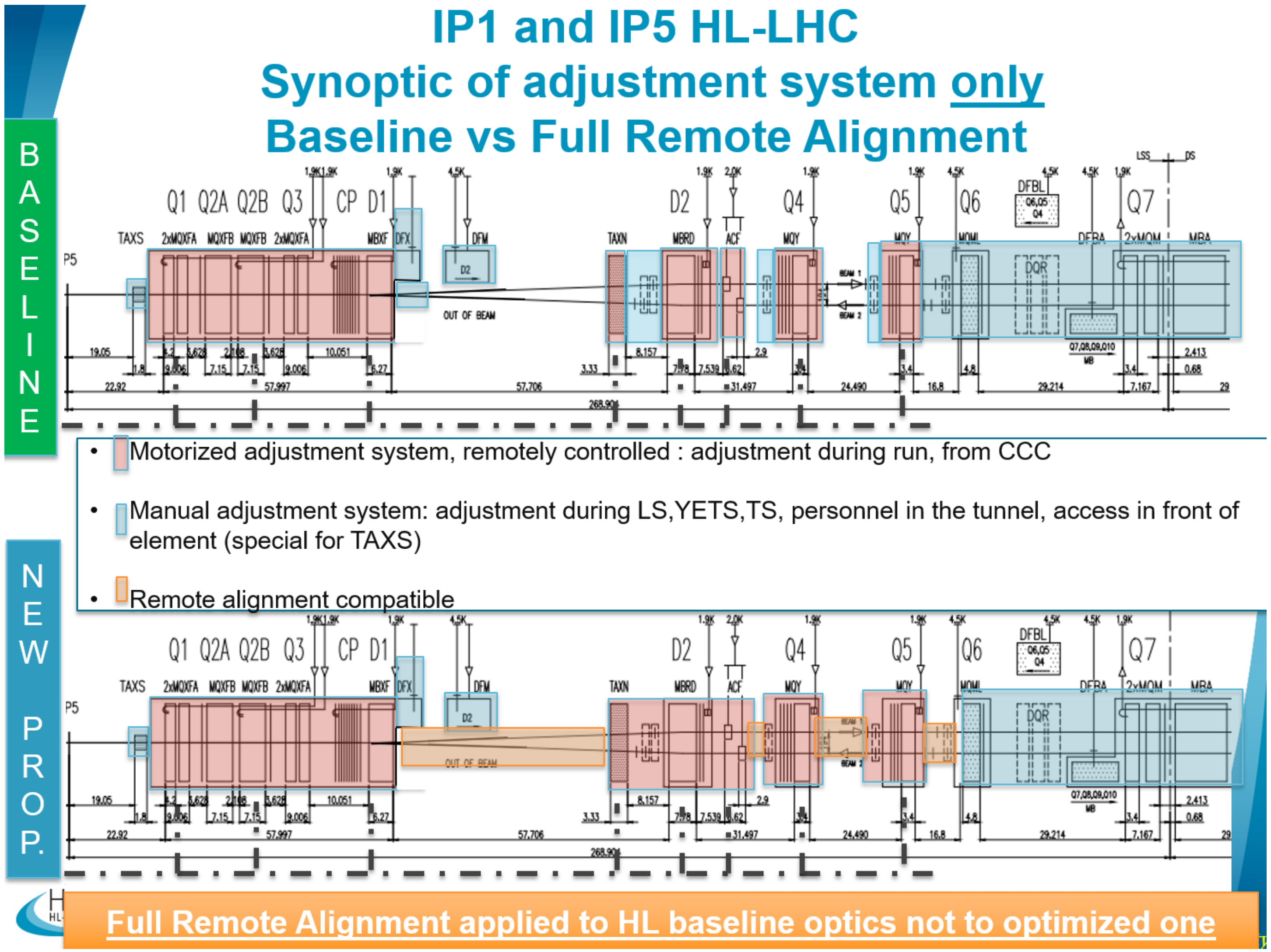


(1) (2)



(1) Spherical joints
(2) Flexural joints: Nitinol joints and flexible shaft

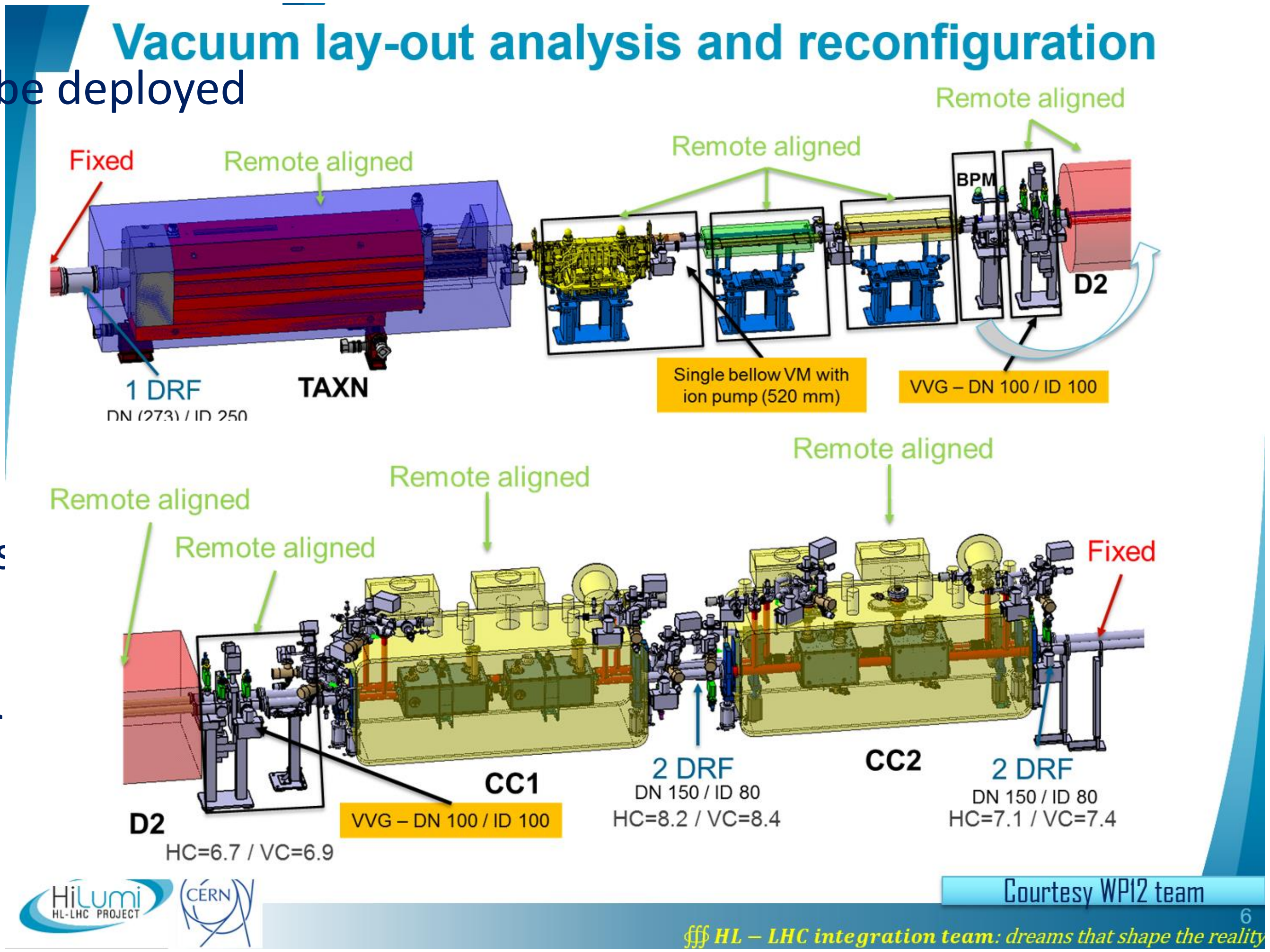
Towards Full Remote Alignment



Courtesy P. Fessia

Towards Full Remote Alignment

After study: the full remote alignment can be deployed



Main advantages:

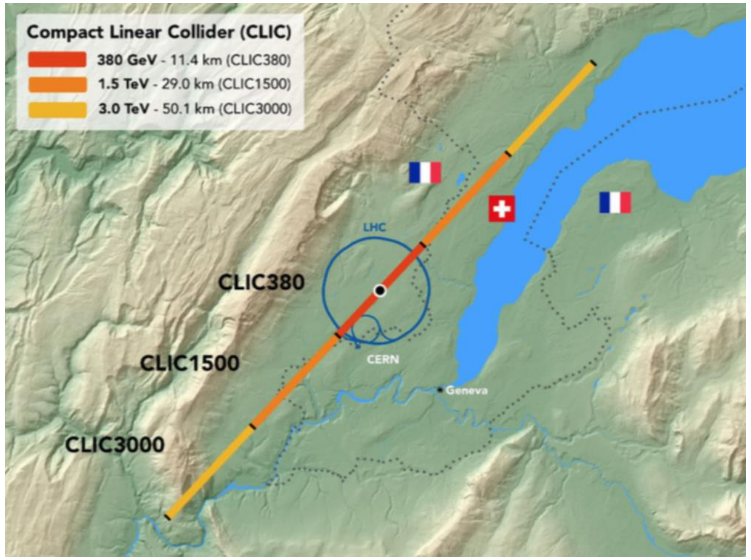
- It will allow the reduction of radiation dos
- It will increase the window for machine o
- It will put less pressure on orbit corrector
- It will provide a higher machine flexibility
- It opens the possibility to re-optimize the

Courtesy P. Fessia

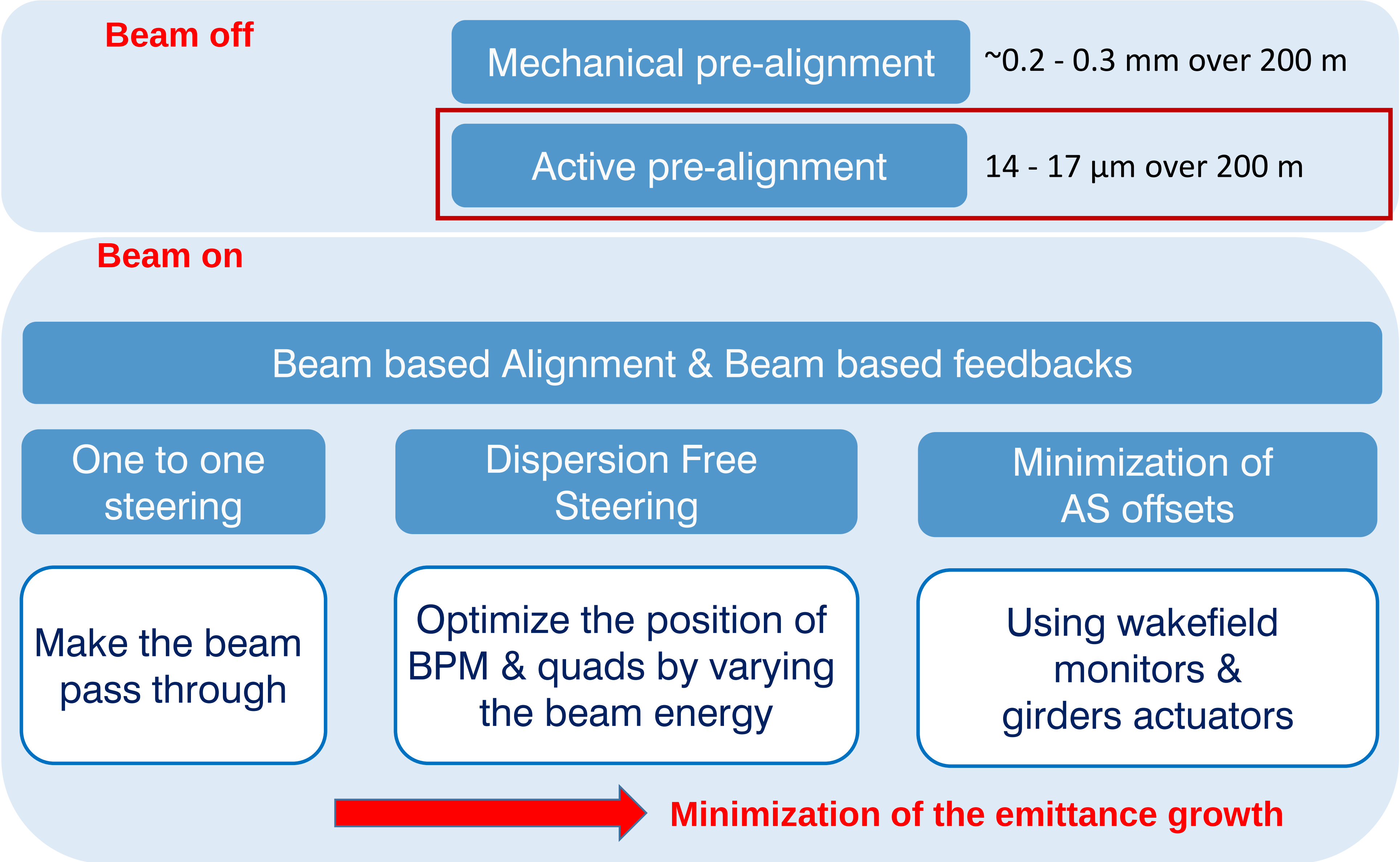
R&D: case of CLIC project

CLIC: introduction

- CLIC= Compact LInear Collider
- Project Implementation Plan under preparation for consideration by the European Strategy Update Process in 2020.



CLIC: introduction



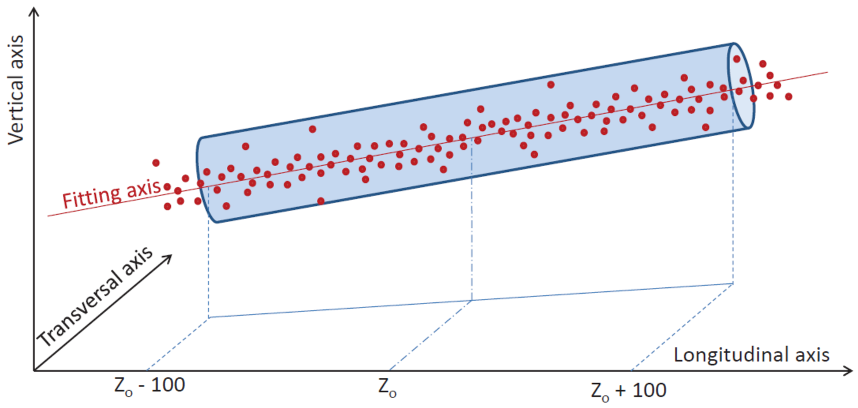
CLIC: introduction

- Considering the number of components to be aligned, ground motion, such tight tolerances can not be obtained by a static on-time alignment system.
- Active pre-alignment: we associate movers and sensors to the components to maintain them in place.

Total budget error allocated to the associate positioning of the reference axes of the major accelerator components can be represented by points inside a cylinder over a sliding window of 200m.

Along BDS:

Radius equals to 10 µm over sliding windows of 500 m

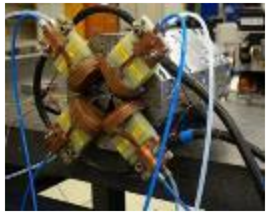


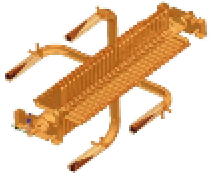
Along Main Linac: over sliding windows of 200 m

Component type	AS	BPM	MB Quad	DB quad
Radius (µm)	14	14	17	20

CLIC: introduction

Components to be aligned:





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

Strategy:

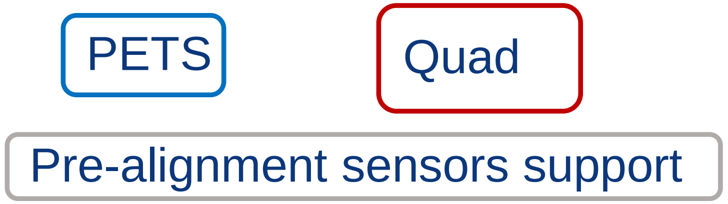
BPM | Quad

AS | AS | AS | AS

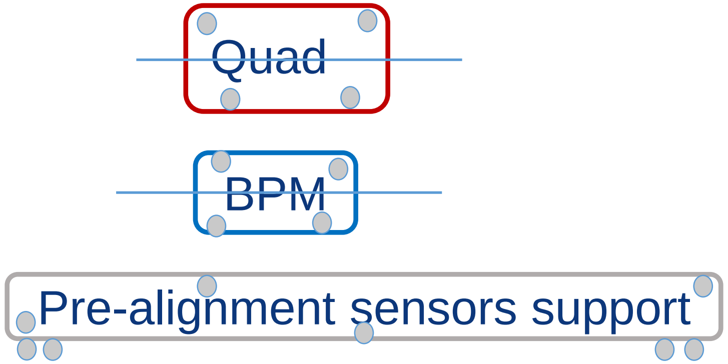
2 steps:

- Fiducialisation & initial alignment of the components and their support
- Transfer in tunnel and alignment in tunnel

CLIC: alignment strategy

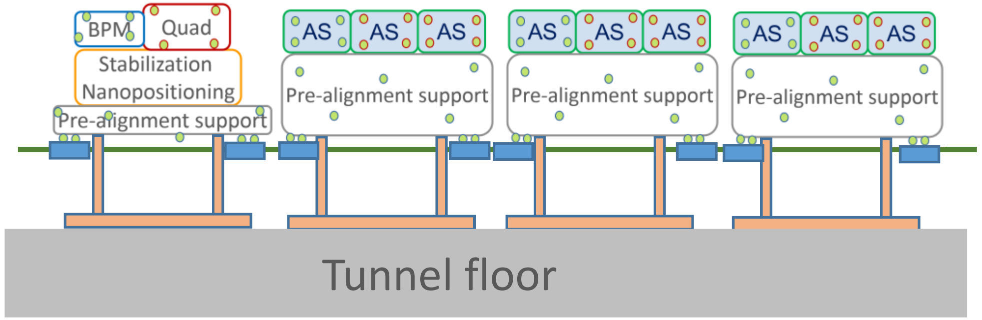


Fiducialisation:



Initial alignment:

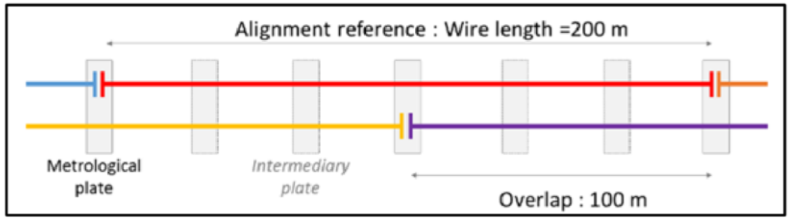
Transfer in the tunnel:

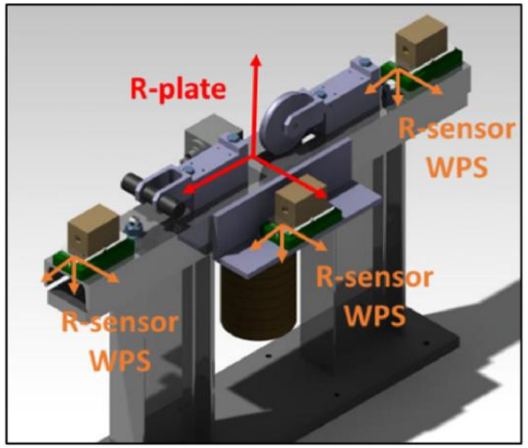


[Mainaud Durand5]

CLIC: alignment strategy

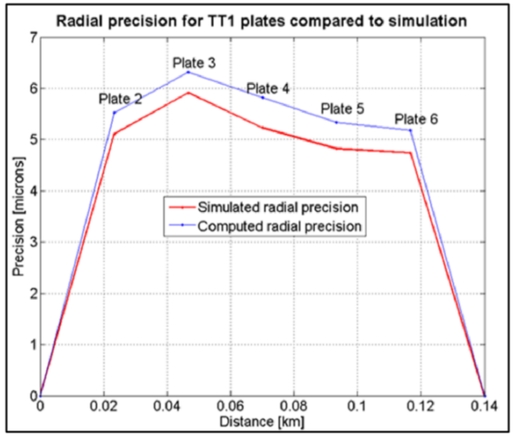
Absolute alignment using overlapping reference lines

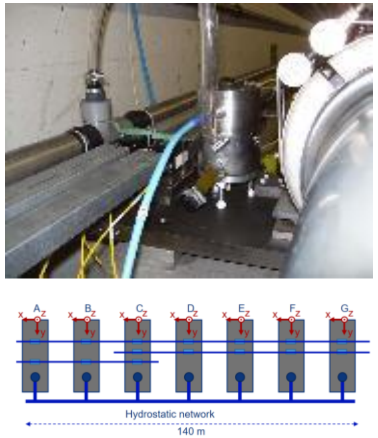




MRN = Metrological Reference Network

Very good correlation between simulated data and TT1 results





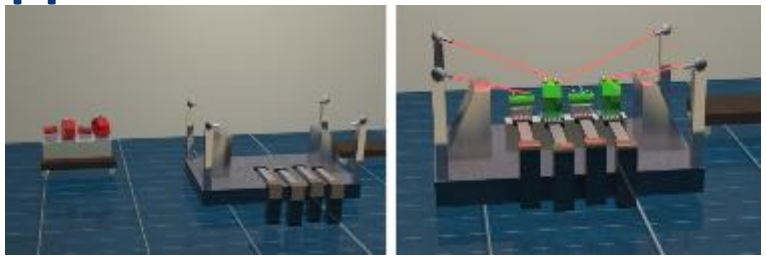
Propagation error over the CLIC collider simulated using the variance-covariance matrix as estimator of parameters:

- For a sliding window of 200m, the standard deviation of the transverse position of each component w.r.t. a straight line is included in a cylinder with a radius below 7 µm
- Maximum standard deviation of 1.1 mm computed along the 25 km of linacs

[Mainaud Durand6]

CLIC: alignment strategy

Fiducialisation & alignment on common support



✓ Results achieved in the PACMAN project:

- Sub-micrometric repeatability to determine the magnetic axis of quadrupole, the electro-magnetic center of the middle cell of AS, the electrical center of BPM
- Relative position of BPM versus quadrupole determined within an uncertainty of measurement below 5 µm.
- Fiducialisation (determination of the position of the reference axis w.r.t. external targets) for the 3 types of components < 5 µm.
- Referential frame of the pre-alignment sensors determined w.r.t. references axes within an accuracy of 2.5 µm

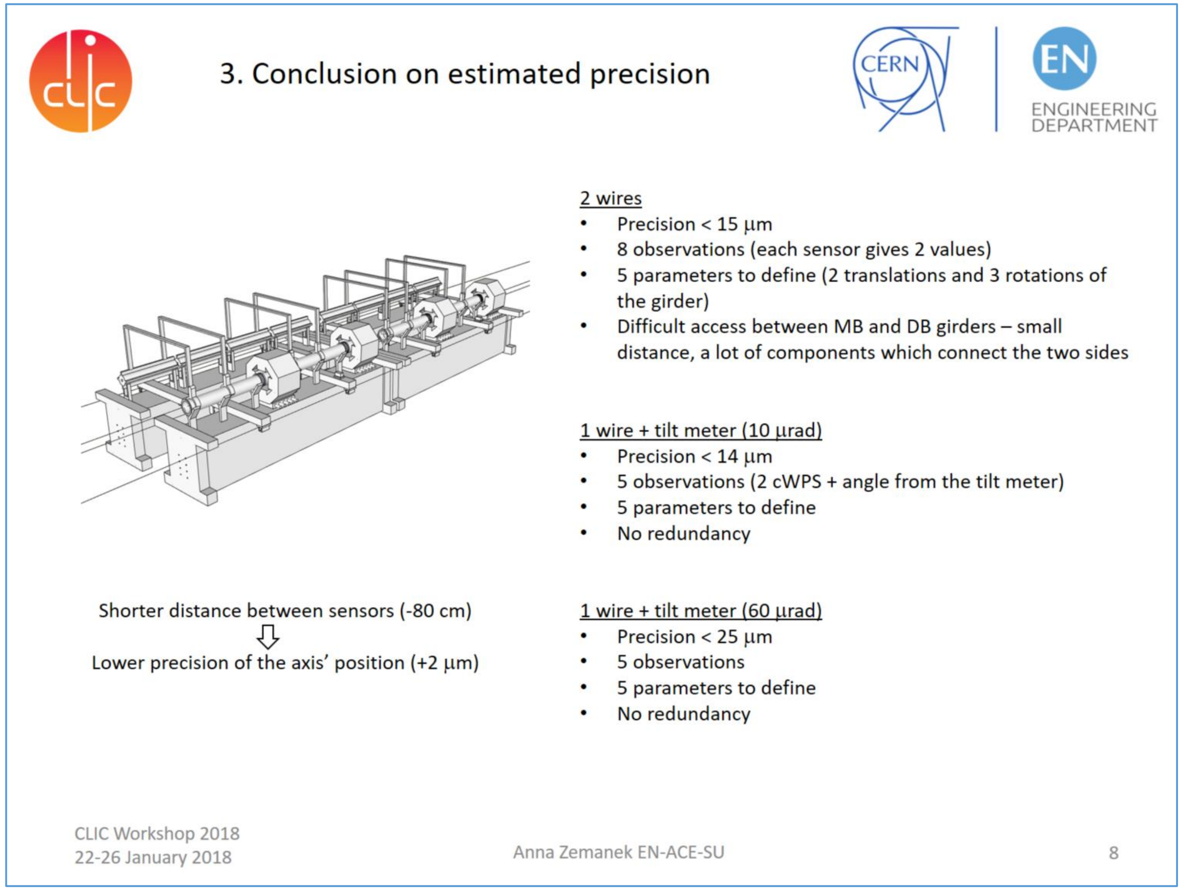
[Caiazza]

CLIC: alignment strategy

SPN = Support Pre-alignment Network

Relative alignment of the components

✓ Determination of the position: sensors associated to each



3. Conclusion on estimated precision

CERN | EN ENGINEERING DEPARTMENT

Shorter distance between sensors (-80 cm)
⇩
Lower precision of the axis' position (+2 μm)

<u>2 wires</u>
- Precision < 15 μm
- 8 observations (each sensor gives 2 values)
- 5 parameters to define (2 translations and 3 rotations of the girder)
- Difficult access between MB and DB girders – small distance, a lot of components which connect the two sides

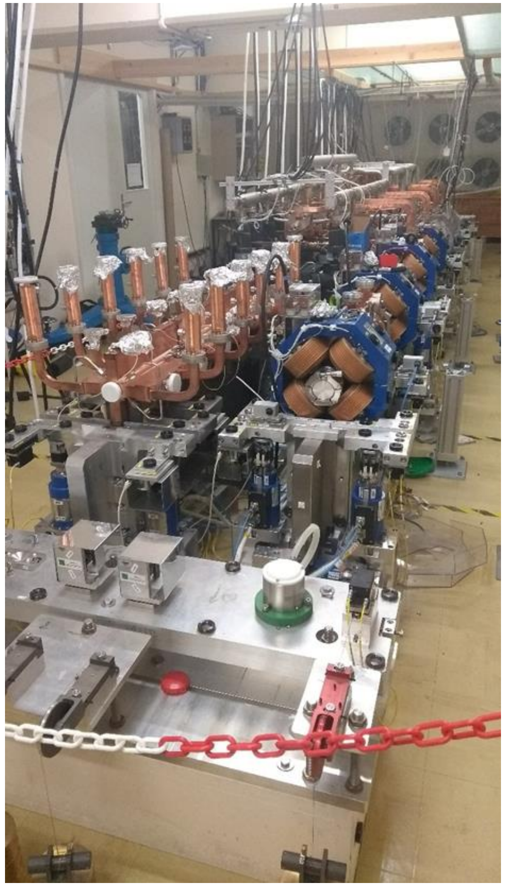
<u>1 wire + tilt meter (10 μrad)</u>
- Precision < 14 μm
- 5 observations (2 cWPS + angle from the tilt meter)
- 5 parameters to define
- No redundancy

<u>1 wire + tilt meter (60 μrad)</u>
- Precision < 25 μm
- 5 observations
- 5 parameters to define
- No redundancy

CLIC Workshop 2018
22-26 January 2018

Anna Zemanek EN-ACE-SU

8



CLIC: alignment strategy

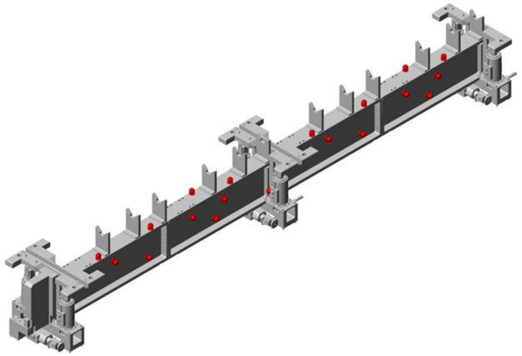
Relative alignment of the components: adjustment ➔ 2 cases

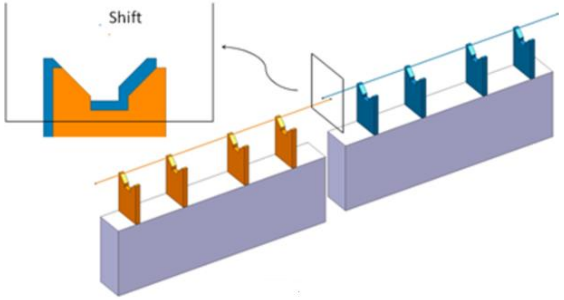
Articulation point + linear actuators (3DOF):

- Snake configuration kept for the DB side, allowing a natural smoothing
- Adjustable articulation point, controlled by FSI measurements within an accuracy of 5 µm
- 3 linear actuators supporting the master cradle will perform the alignment
- Ves replaced by adjustable platforms

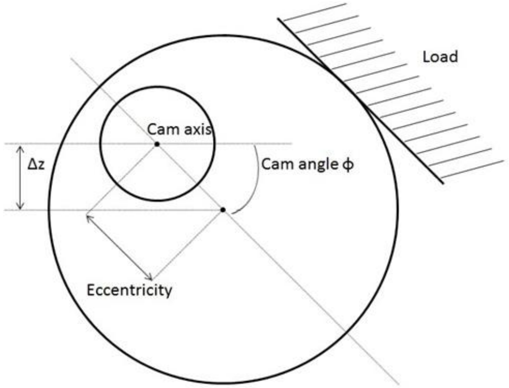
Cam movers (5 to 6 DOF):

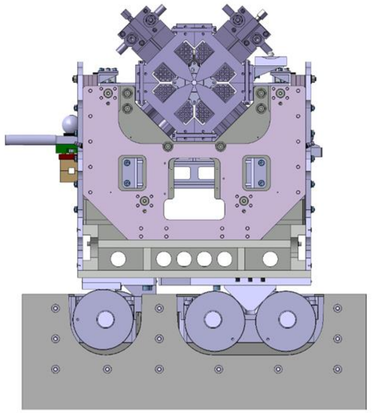
- 5 DOF configuration validated for 2 lengths of quadrupoles: 0.5m and 2m (sensors offsets below 1 µm and roll below 5 µrad), met in one movement using feedback from alignment sensors.
- Proposition to add a 6th cam mover





[Sosin]

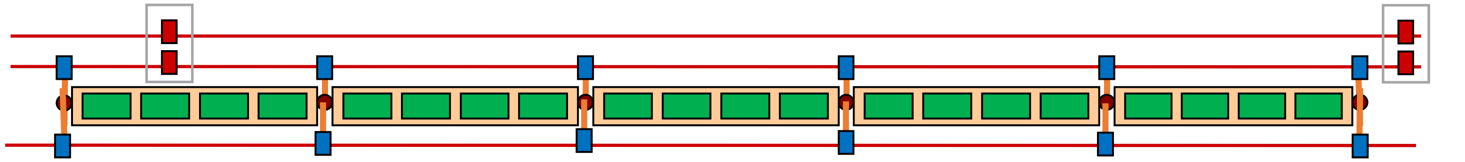




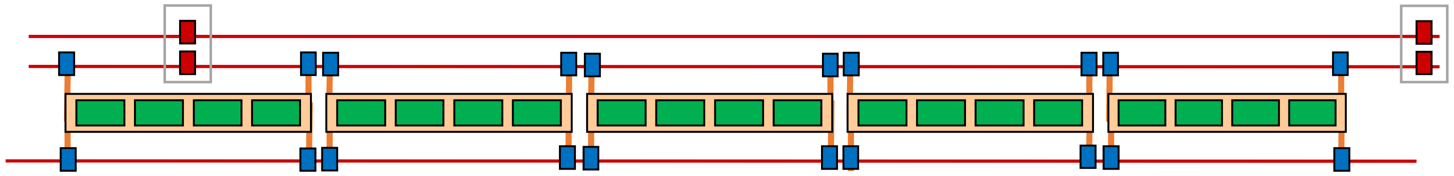
[Kemppinen]

CLIC: alignment strategy

If you combine long & short systems

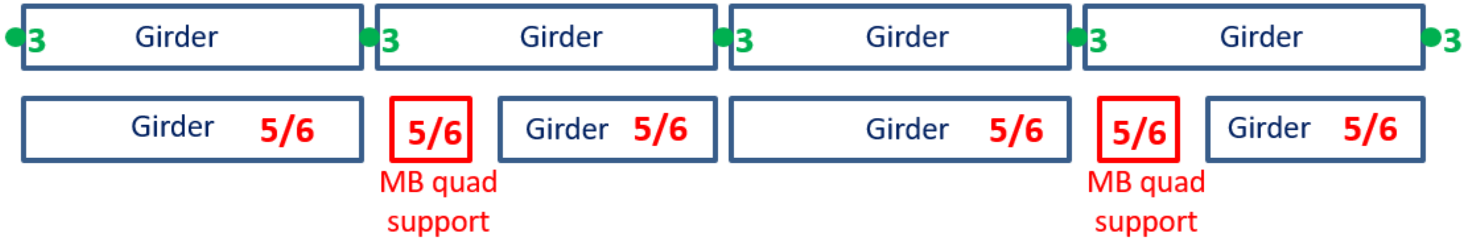


or



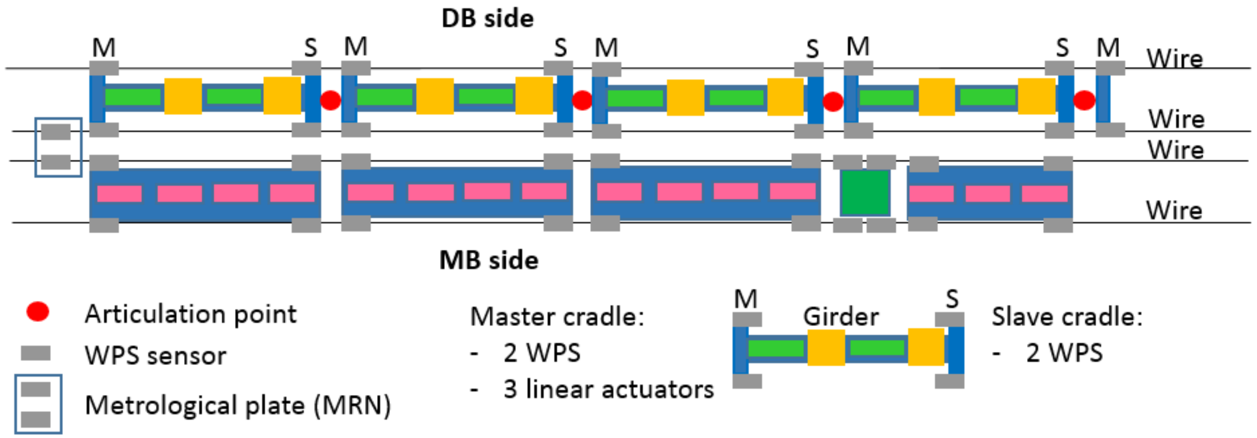
Adjustment configuration

Degrees of freedom: 3 / 5 to 6

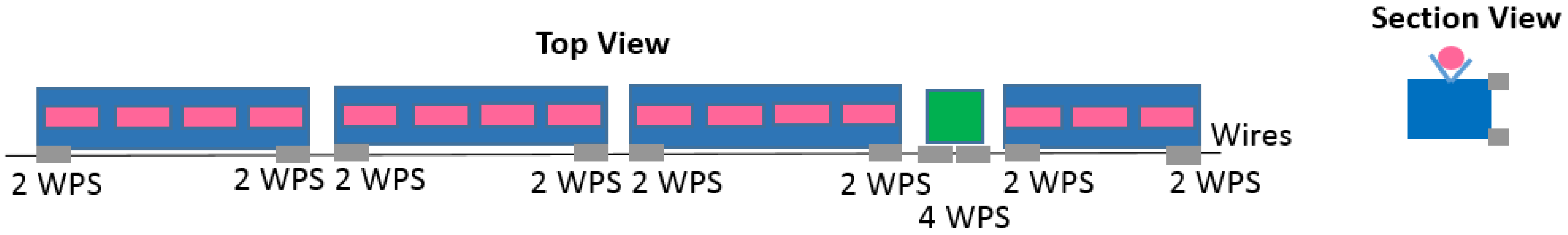


CLIC: alignment strategy

Sensors configuration for 380 GeV DB option



Sensors configuration for 380 GeV Klystrons option



PACMAN project

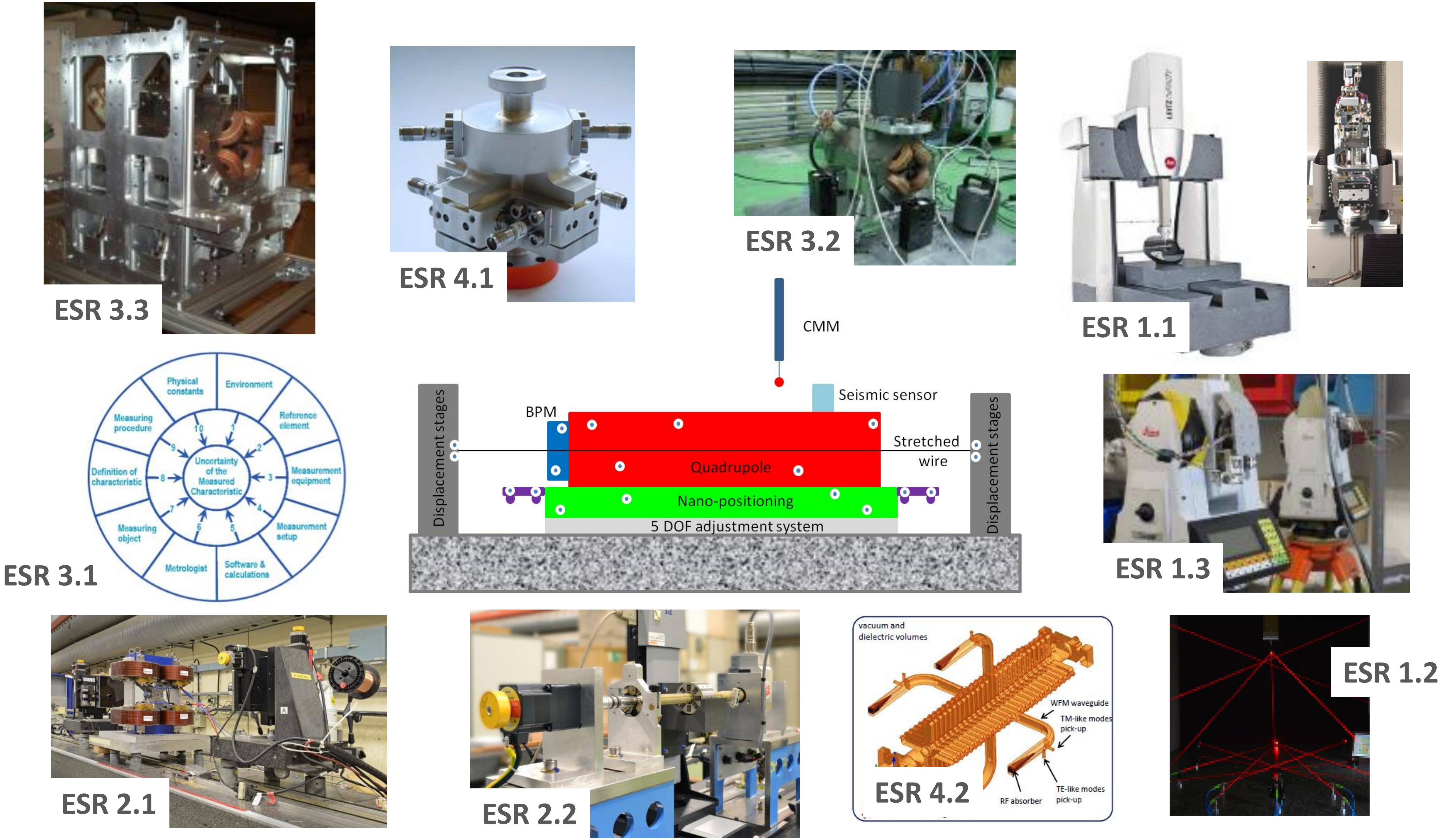
Web site: http://pacman.web.cern.ch/

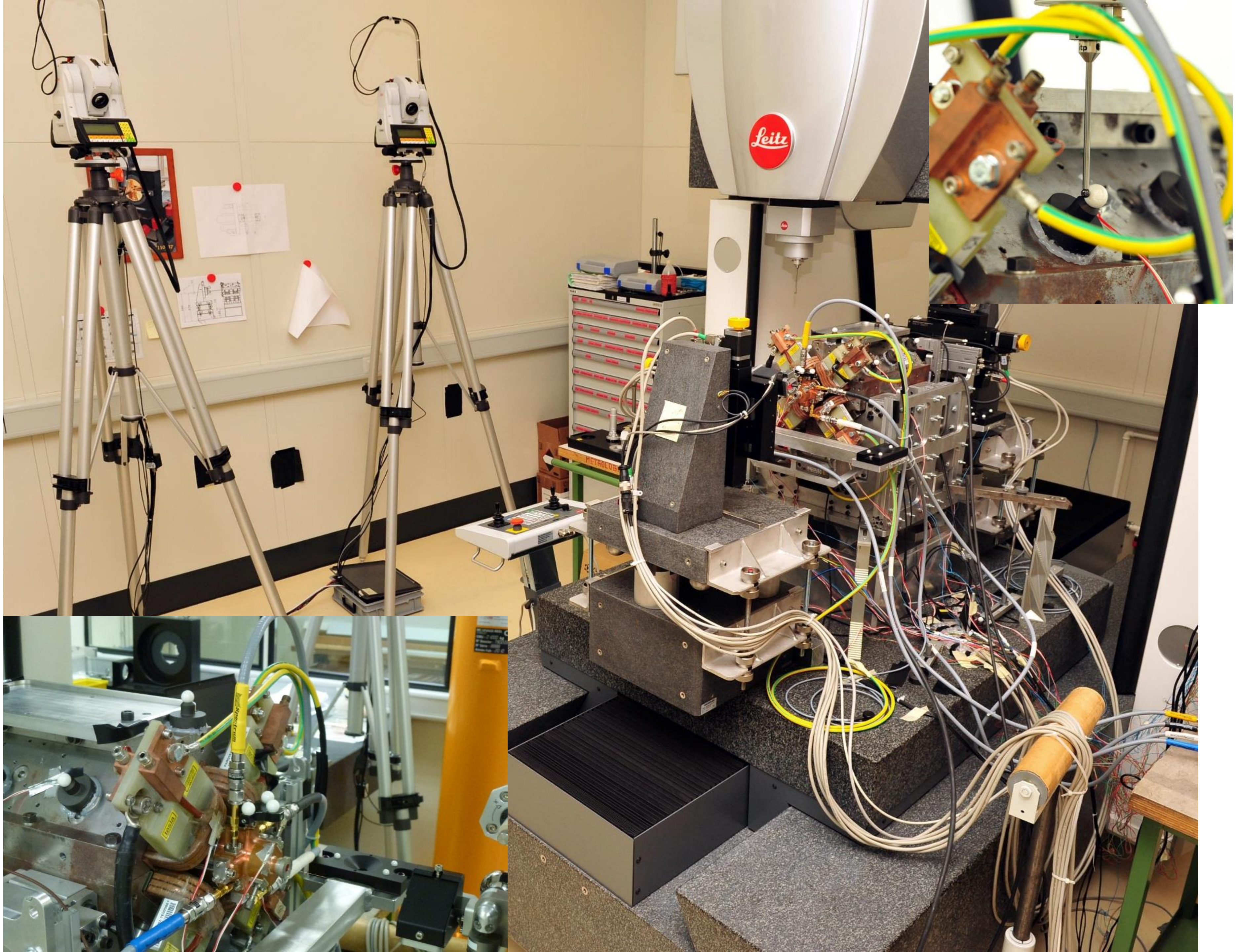
9 academic partners
8 industrial partners
4 years project: 1/09/2013 - 31/08/2017

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

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.


ESR 3.3
ESR 4.1
ESR 3.2
ESR 1.1
CMM
Physical constants
Environment
Measuring procedure
Reference element
Definition of characteristic
Uncertainty of the Measured Characteristic
Measurement equipment
Measuring object
Measurement setup
Metrologist
Software & calculations
ESR 3.1
Displacement stages
BPM
Seismic sensor
Stretched wire
Quadrupole
Nano-positioning
5 DOF adjustment system
Displacement stages
ESR 1.3
ESR 2.1
ESR 2.2
vacuum and dielectric volumes
WFM waveguide
TM-like modes pick-up
TE-like modes pick-up
RF absorber
ESR 4.2
ESR 1.2


Leitz

PACMAN: a few interesting results

Even if your BPM and quadrupole quadrants were manufactured at a micrometric accuracy, the electric / magnetic axes are not so close from the mechanical axes.

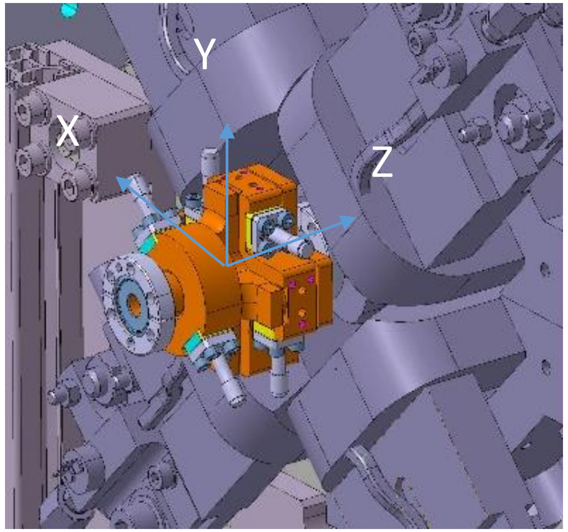


TABLE V. Mechanical, magnetic, and electric axes center offset.

	X [μm]	Y [μm]	Uncertainty [μm]
MBQ (magnetic vs mechanical)	−21.6	40.9	±10
BPM (electric vs mechanical)	17.3	40.6	±4
BPM/MBQ (electric vs magnetic)	−2.3	−7.5	±1.2

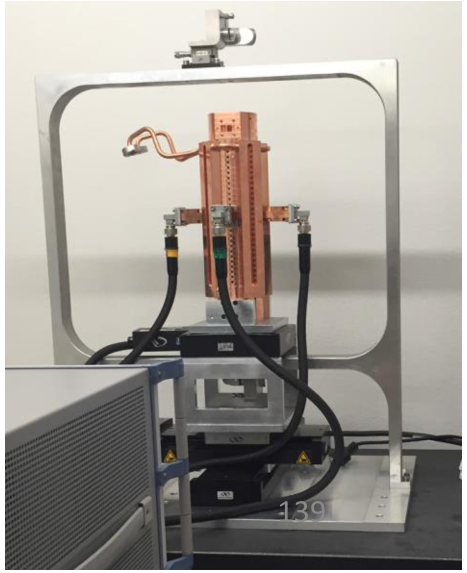
TABLE III. Offset between the mechanical axis and the magnetic axis at 126 A.

Horiz. center	Vert. center	Yaw	Pitch
32.2 μm	20.2 μm	−75.9 μrad	−57.4 μrad

TABLE II. Offset between the magnetic axis at 4 and 126 A.

Horiz. center	Vert. center	Yaw	Pitch
2.9 μm	3.1 μm	−2.3 μrad	−5.1 μrad

[Caiazza]

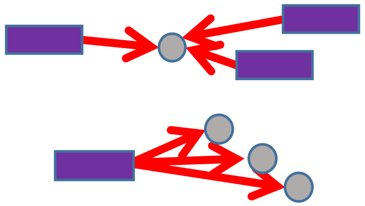


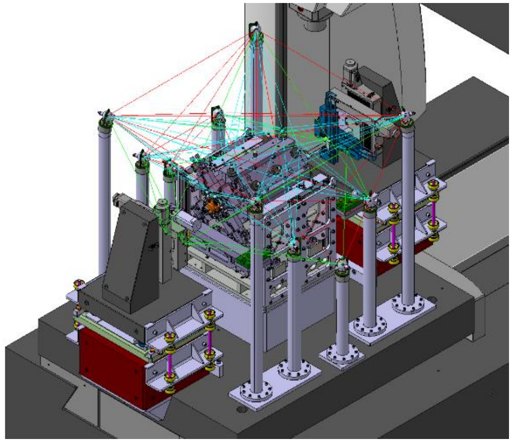
PACMAN: a few interesting results

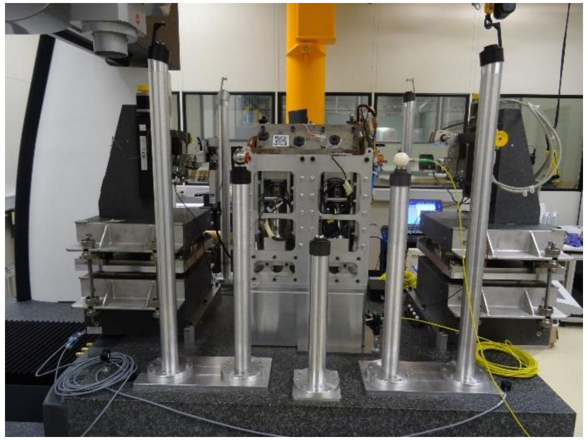
Determination of the position of the stretched wire, w.r.t. external targets:
3 methods:

- Coordinate Measuring Machine measurements (+wire measured using confocal sensor plugged on the CMM head): uncertainty ~ 2 µm
- Frequency Scanning Interferometry (absolute distance measurements)
- Micro-triangulation (angle measurements)

FSI demonstrated a very high accuracy: difference between FSI & CMM measurement on coordinates < 2.5 µm. Portable & self calibrating





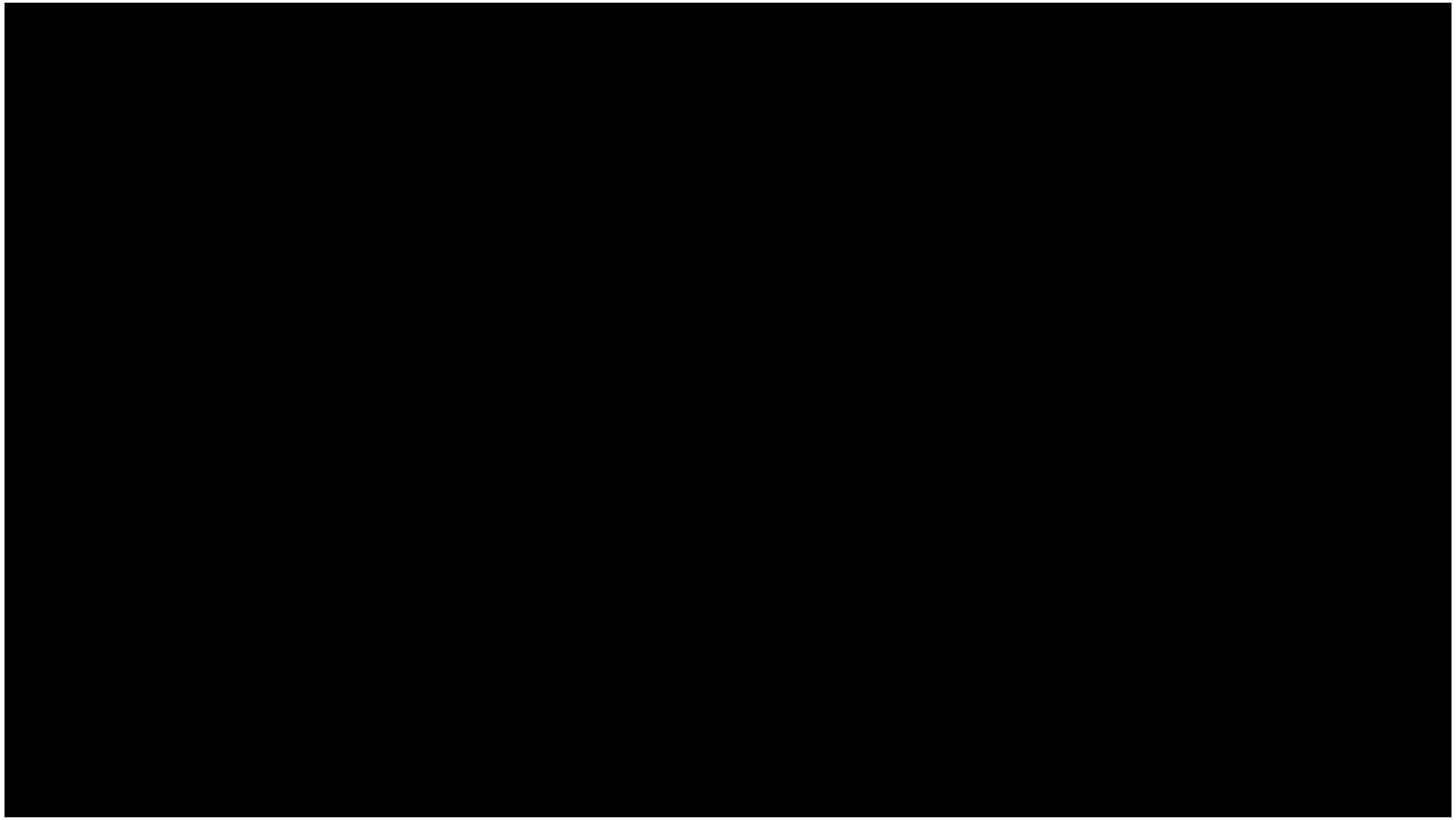


Micro-triangulation: after comparison with CMM measurements, 85% of the measured coordinates < 15 µm, 75% < 10 µm, 42 % < 5 µm, in a not optimal configuration.

PACMAN: scenario 1

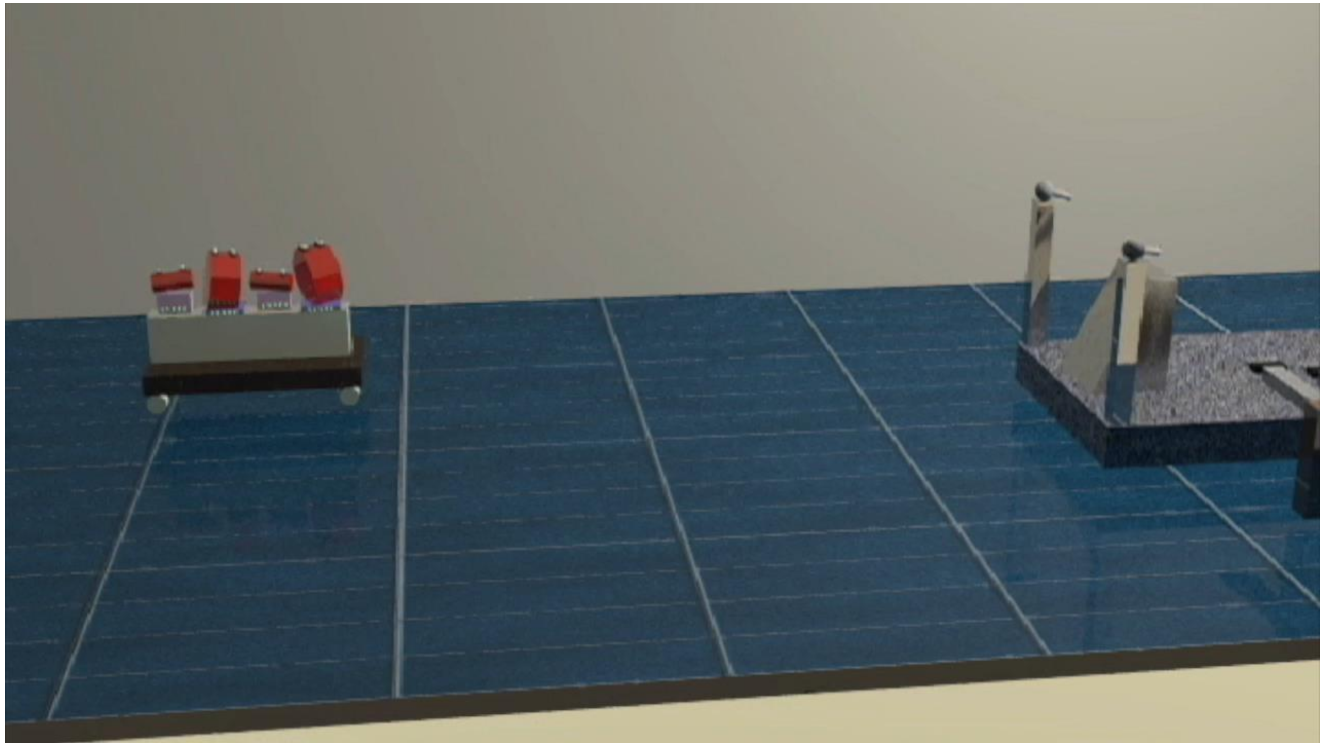
Strategy also applicable in the tunnel, after transport

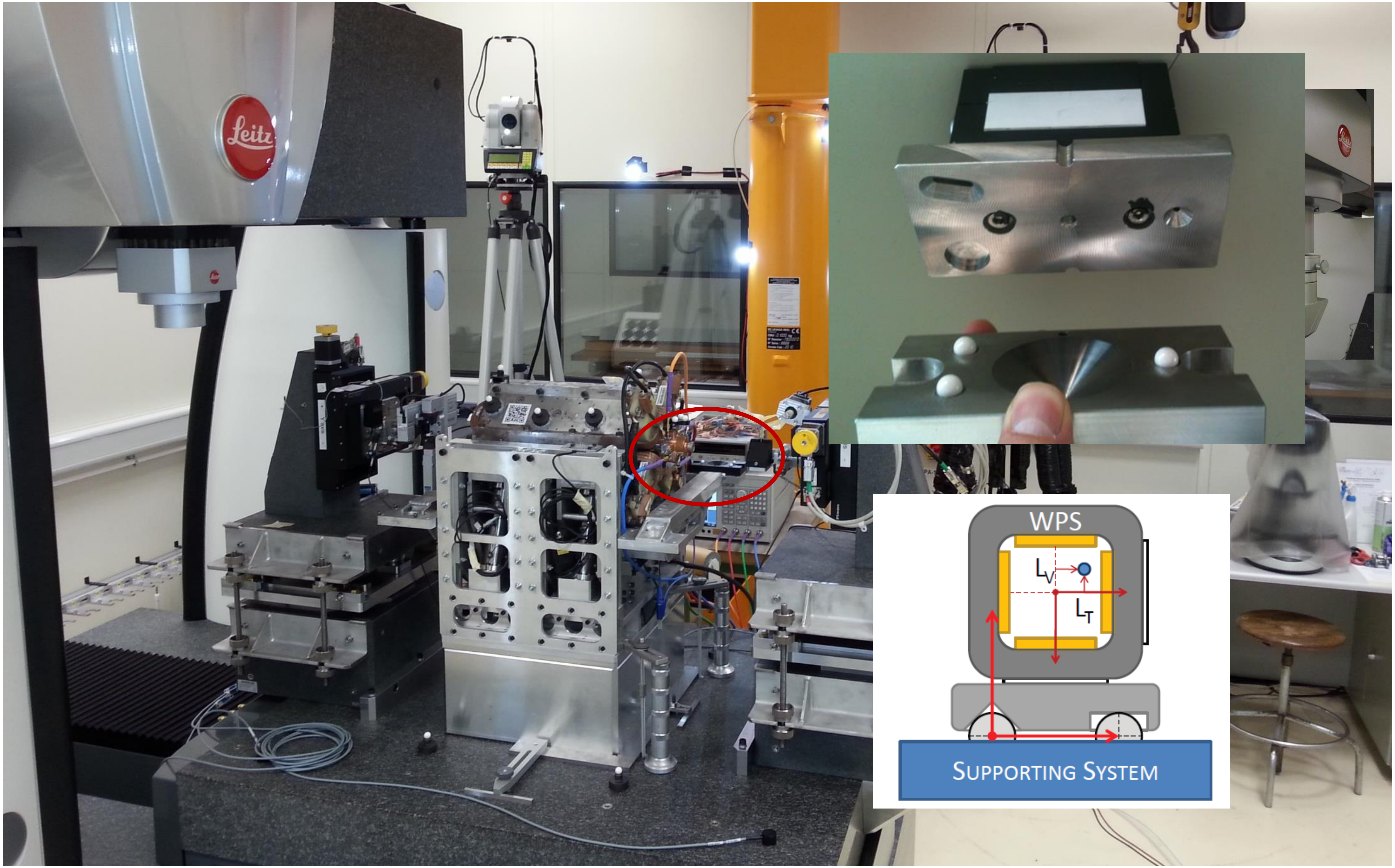
- All components individually fiducialised (PACMAN process using stretched wire)
- Alignment on a common support using plug-in system, knowing the position of the targets.



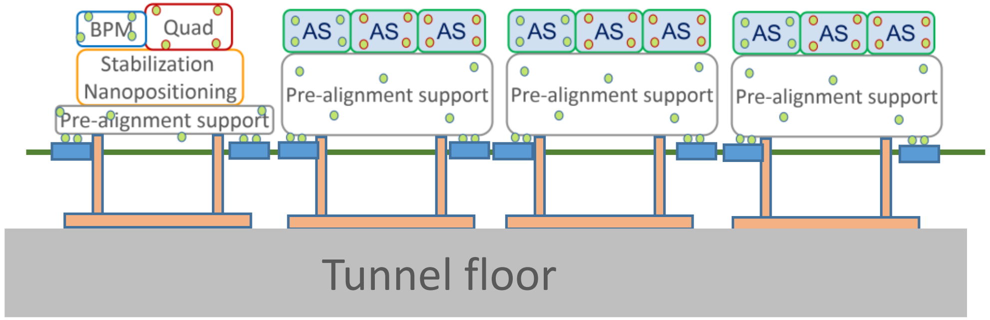
PACMAN: scenario 2

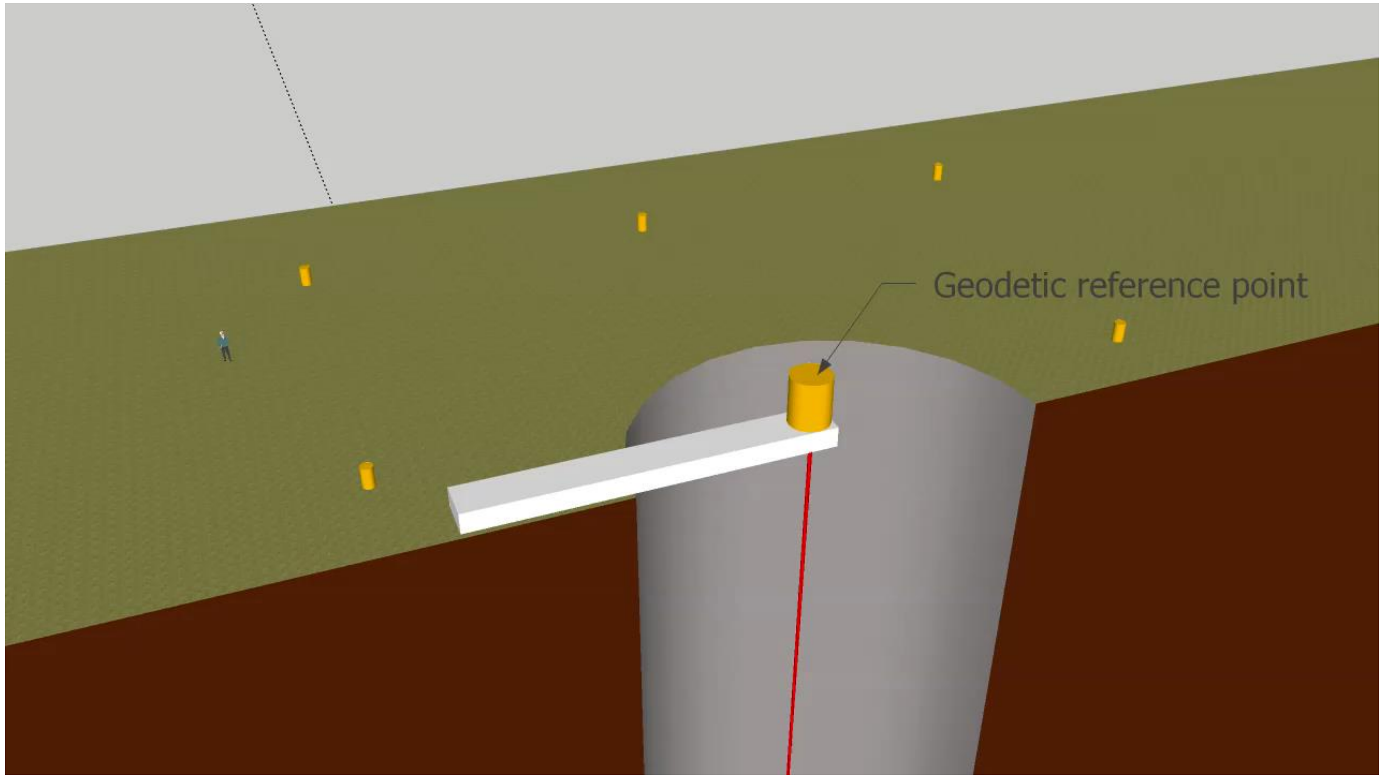
- All components installed roughly on a common support
- Installation of a stretched wire to align all the components reference axes at a theoretical position on the common support (PACMAN process + 5 DOF adjustment system)
- Determination of the position of the alignment targets once all the components are at the theoretical position




Leitz
WPS
L_V
L_T
SUPPORTING SYSTEM

PACMAN & summary





CLIC: alignment strategy

Summary of the results achieved

Components type	AS, BPM (µm)		MB quad (µm)		DB quad (µm)	
YEAR	2012	2018	2012	2018	2012	2018
Fiducialisation	5 (TBC)		10 (TBC)		10 (TBC)	
Fiducials to pre-alignment sensor interface	5	5	5	5	5	5
Pre-alignment sensor accuracy	5	5	5	5	5	5
Sensor linearity	5	5	5	5	5	5
Straight reference	10 (TBC)	7 (in radial, TBC in vert.)	10 (TBC)	7 (in radial, TBC in vert.)	10 (TBC)	7 (in radial, TBC in vert.)
Total error budget	14	11	17	11	20	11

BUT… Active pre-alignment strategy validated only at 20°C, not at 30°C!

CLIC: alignment strategy

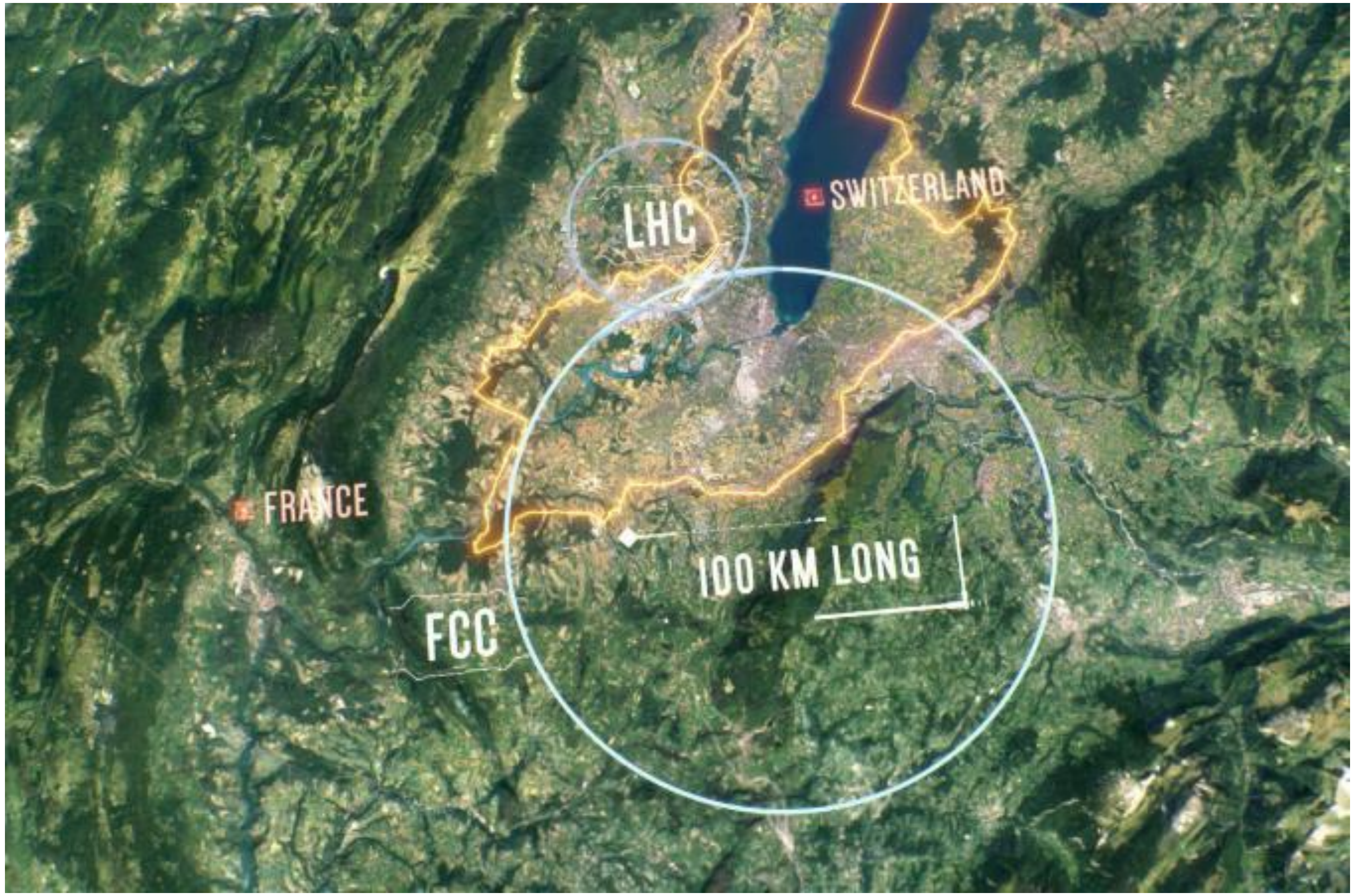
common with HL-LHC

common with FCC

Geodesy	Study of MRN	Study of SPN	Fiducialisation
Relative determination of vertical deflection	Modelisation of a wire using Eigenfrequencies	Study of low cost sensors and industrialization	PACMAN studies on AS structures
New methods for vertical deflection measurements in pits	Development of corresponding least squares algorithms	Development of low cost linear actuators and industrialization	Development of a FSI bench for in-situ fiducialisation
Impact of gravitational fields on wires	Sensors configuration optimization, simulations over long distances	Impact of an operation at 30°C on alignment systems	Development of low cost adjustment platforms and industrialization
	Development of a new wire	FSI R&D on sensors	Improve adjustment solution for the BPM on the quadrupole
	Development of a laser based solution	Development of a WPS with 2 wires	
		Development of 6 DOF cam movers	

FCC alignment

Future Circular Collider (FCC)



FCC alignment

- Absolute tolerance
  - As no real values obtained, we are going to do the best we can (few mm)
- Relative tolerance

* All errors included

Accelerator collider	Radius/ Circumference	Vertical (mm) @1σ	Transversal (mm) @1σ	Roll angle (mrad)
LEP(e+e-)	5km/27km	0.2-0.3	0.2-0.3	0.1
LHC (hh)	5km/27km	0.15	0.15	0.1
CLIC (e+e-)	2*25 km	17 microns radially*		
FCC-hh	16km/100km	0.2 (0.5*)	0.2 (0.5*)	1.0
FCC-ee	16km/100km	0.1*	0.1*	0.1
HE-LHC	5km/27km	0.2 (0.5*)	0.2 (0.5*)	0.1 ?

Conclusion

Do not forget Survey & alignment in your project, you will gain:

- Time
- Accuracy
- Efficiency

Lines of sight in tunnel, geodetic networks on surface, pits, coordinate systems and geodetic reference frames, must be defined asap

Tolerances of alignment of all the components have to be defined asap to establish a clear strategy of alignment and chose the most appropriate solutions and instrumentation.

The Micron World, in which steel acts like butter and in which temperature excursions are like Gulliver's Travels, has been tamed and industrialized on the laboratory scale. I do not believe the problems that we are going to encounter in the design of future linear colliders on a kilometer scale will turn out to be *fundamental*. Rather, the challenge will be to be innovative enough to find sound engineering solutions that we can *afford*. Further, we should involve the alignment community in all aspects of the design decision making process at the earliest moment.

ALIGNMENT AND VIBRATION ISSUES IN TeV LINEAR COLLIDER DESIGN

G. E. FISCHER

Stanford Linear Accelerator Center
Stanford University, Stanford, CA

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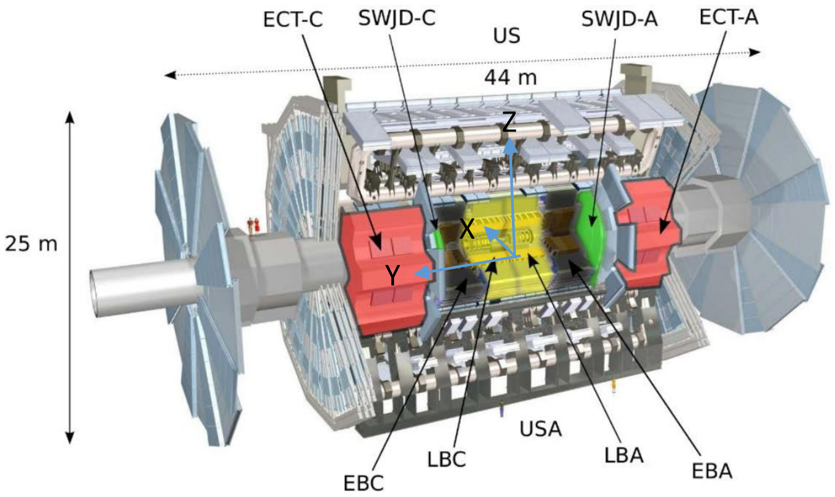
A lot of materials from D. Mergelkuhl, D. Missiaen, JC Gayde, A. Herty, M. Jones, V. Rude, M. Sosin

Additional slides

Monitoring of ATLAS detector closure

Context:

- Regular maintenance and *shut-down periods*
- Implies open/close movements of large sub-detectors of up to 900 t, more particularly:
  - 2 ECT (240 t), 2 SW (103 t), 2 EB (900 t)
- Manual adjustment and survey is iterative and time consuming



ADEPO= ATLAS DETECTOR POSITIONING SYSTEM, a ATLAS-SURVEY collaboration

Technical requirements:

- Relative measurement system to measure «run» position at the beginning and end of the maintenance period
- Measurement range ~ 50 mm in X, Y, and Z directions
- Accuracy: 0.1 mm in dX and dZ
- Measurement time: less than 30’

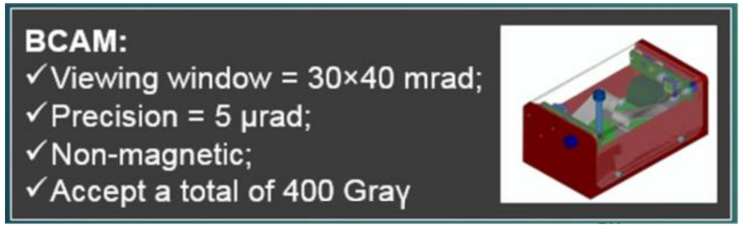
Environmental constraints:

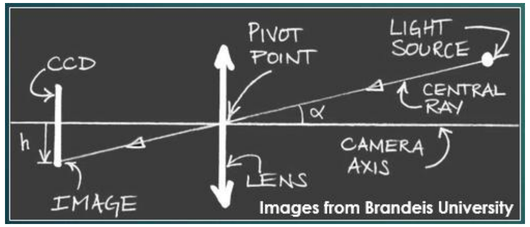
- 1 T magnetic fields
- 2 Gy of radiation dose over life time
- Limited space in existing detectors

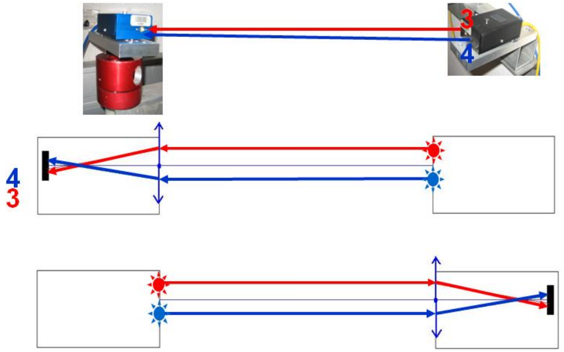
[Gayde]

Monitoring of ATLAS detector closure

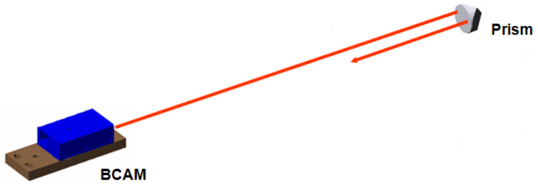
Solution = BCAM camera (Brandeis CCD Angle Monitor)







Bilateral observation



Unilateral observation

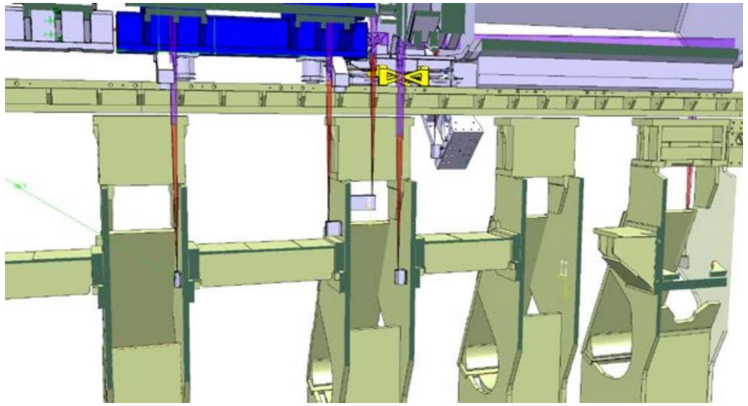
- Optical measurement system
- Measurements on passive glass corner cubes
- Already used in ATLAS

[Gayde2]

Monitoring of ATLAS detector closure

System based on:

- 28 BCAMs on feet/rail system
- 44 passive targets (corner cube Reflectors)
- 1 driver & 4 multiplexers
- 24 protections
- Application of IRLS (Iteratively Reweighted Least Square) for the data adjustment.



- BCAM on feet//rail systems (fixed parts)
- Passive targets on sub-detectors (moving parts)

Integration and installation were a challenge as well.

Monitoring of ATLAS detector closure

Results during ATLAS closure

- Intensive use of ADEPO during closure (TS 2015-2016)
- Six detectors closed with an average of 3 iterations using BCAM measurements
  - Maximum of 7 iterations
  - Average time for mechanical corrections~ 20’
- Average difference of ADEPO results to reference position : 0.3 mm along monitored X and Z directions
- Results for each detector confirmed by Laser Tracker measurements (single iteration)

Medium term results over 1 month:

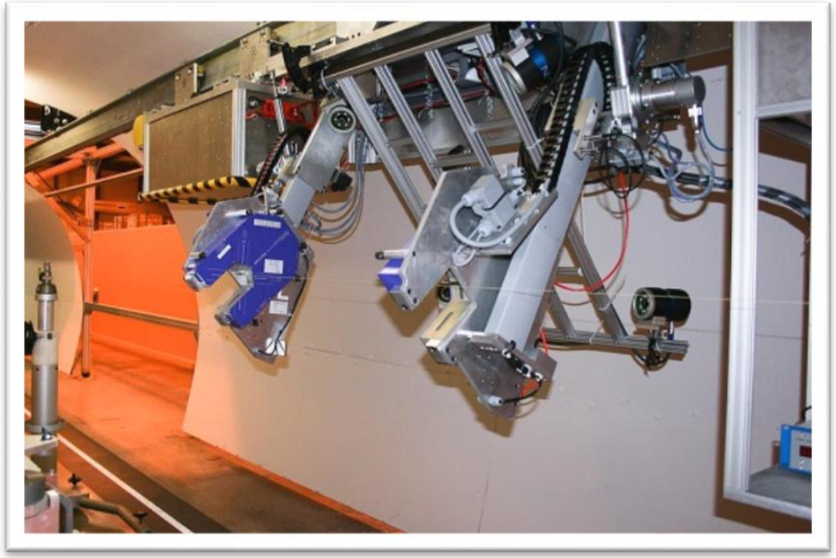
- Average repeatability over 1 month: 2-3 µm
- BCAM lines of 1.5 – 3.0 m measure the stability of a detector within ± 0. 15 mm

Substantial gain of time (25%) and relative precision, for all YETS!

A BCAM system installed in LHCb to monitor the positions of the Inner Tracker stations during the LHCb dipole magnet cycles

Remote determination of collimators position

Standard alignment measurements no longer possible in collimators area (IP3 and IP7 due to the high level of radiations)
→ Development of a remote measurement system: design of a survey wagon on the TIM train.



[Bestmann]

Remote determination of collimators position

Measurements campaign in 2012:

- 26 reference magnets
- 35 collimators

} over 500 m

Repeatability < 60 µm in altimetry and planimetry

Comparison with classical methods (levelling and wire offset measurements): 0.22 mm rms

Duration in the tunnel: a few hours (train) / 4 days at 3 persons (classical method)

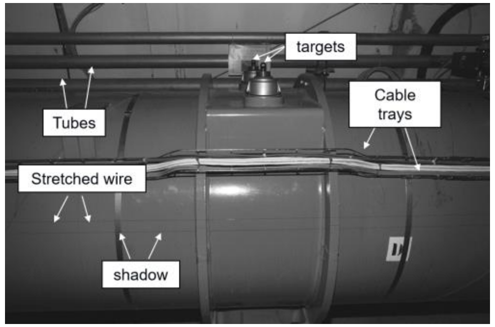
Current objective: mechanical optimization and control robustness improvement for a smooth operation during LS2

Next steps: upgrade of the train for remote measurements in the LSS during LS3 for the HL-LHC project and remote measurements in the arcs for LS4.

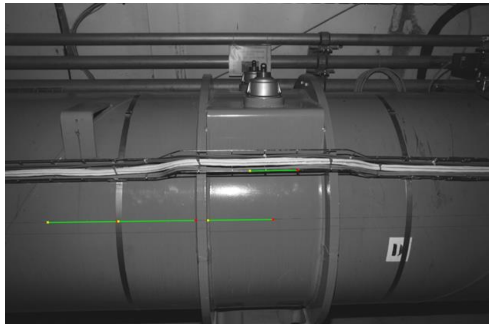
[Charrondière]

Remote determination of collimators position

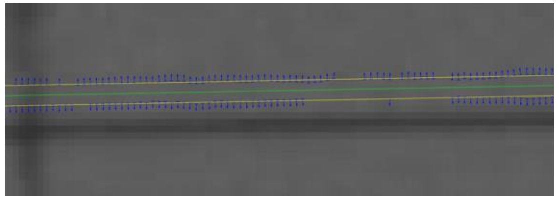
From the survey point of view: use of photogrammetry to measure the position of the wire:

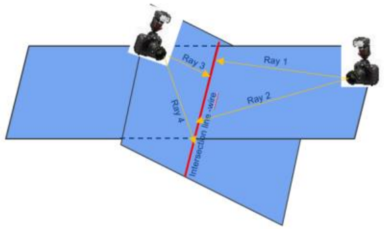


Automatic wire detection

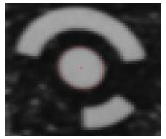


Wire position measurements

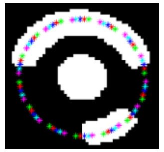




Automatic target detection



Target position determination



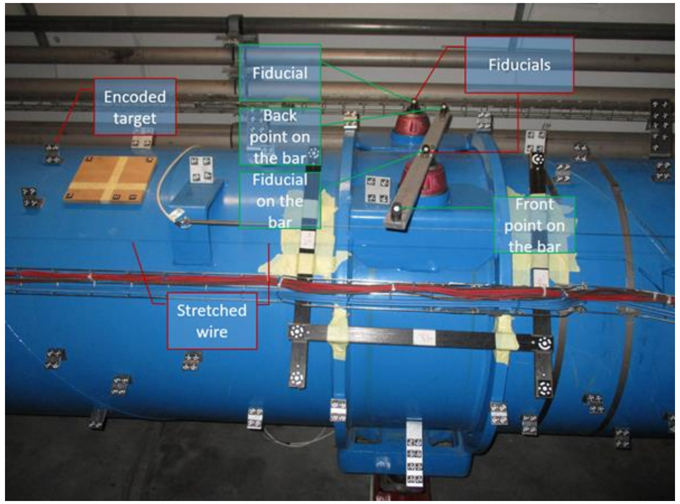
Target decoding

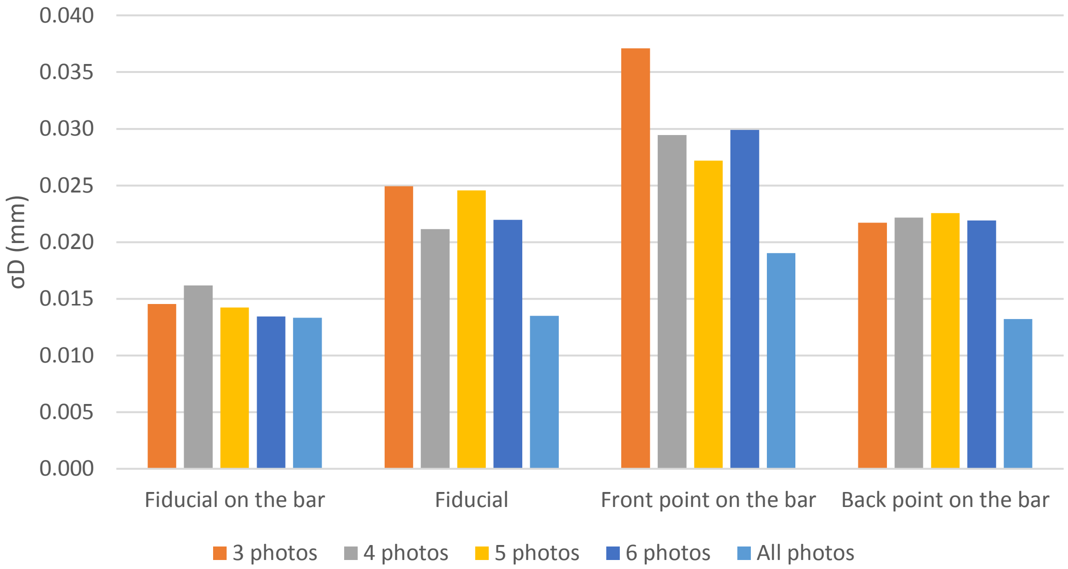
Bundle adjustment
Final calculation:

- Target precision: ± 7µm/m
- Wire precision: ± 6.5 µm/m

[Mergelkuhl]

Remote determination of collimators position





Configuration with 4 cameras is a good compromise.

Precision of the 3D offset distance with respect to a stretched wire at a level of ±15 µm to ±20 µm for the fiducials

From the survey point of view ➔ next steps:

- 4 cameras to be implemented in a carbon frame
- 2 bi-directional inclinometers added to provide link to gravity
- Chain of calculation to be automatized.