SURVEY and ALIGNMENT in accelerators

Hélène Mainaud Durand

Who am I?

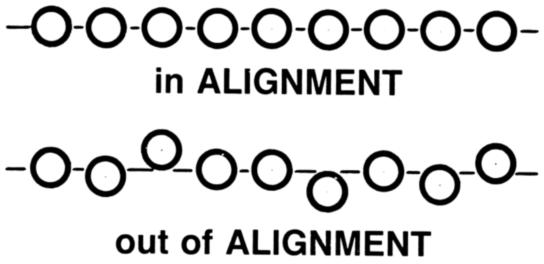
- Education:
  - 1996: PhD in sciences –geodesy, from University Louis Pasteur, Strasbourg
  - 1994: Diploma of topographical engineer from INSA Strasbourg
  - 1994: Research master (D.E.A) on spatial systems and land settlement, University Louis Pasteur, Strasbourg.
- Professional experience:
  - Since 2001: CERN, in charge of projects needing non-traditional alignment solutions. Deputy leader of the SMM group. In charge of survey & alignment for the CLIC project, LHC low beta quadrupoles and HL-LHC project.
  - 1999-2000: project manager at Alcatel Contracting
  - 1996-1999: project engineer on alignment systems at Fogale Nanotech

Introduction

- Lecture based on examples from CERN and other labs
  - Slides in white: lecture
  - Slides in grey: outline
  - Slides in green: short exercise or study case

- References are given in brackets **[Jones]** and full references can be found at the end of the slides.

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, leads to a machine that is uncorrectable – with an unacceptable loss of luminosity

Introduction

Surveying

From Wikipedia, the free encyclopedia

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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 :

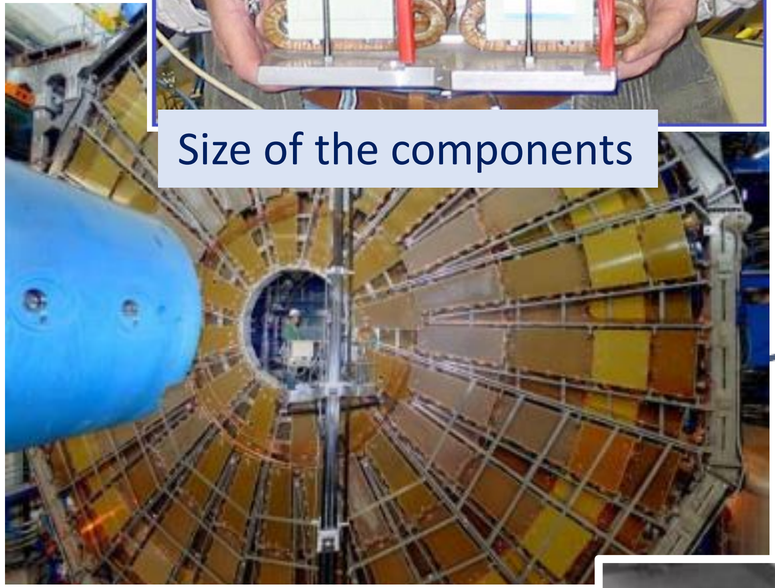
- Geodetic aspects
- Dimensional metrology of accelerator and of detector components
- Positioning and alignment on beam lines
- Quality controls (infrastructure, installations, components)
- The R&D related to these tasks

Our challenges

Accuracy and precision

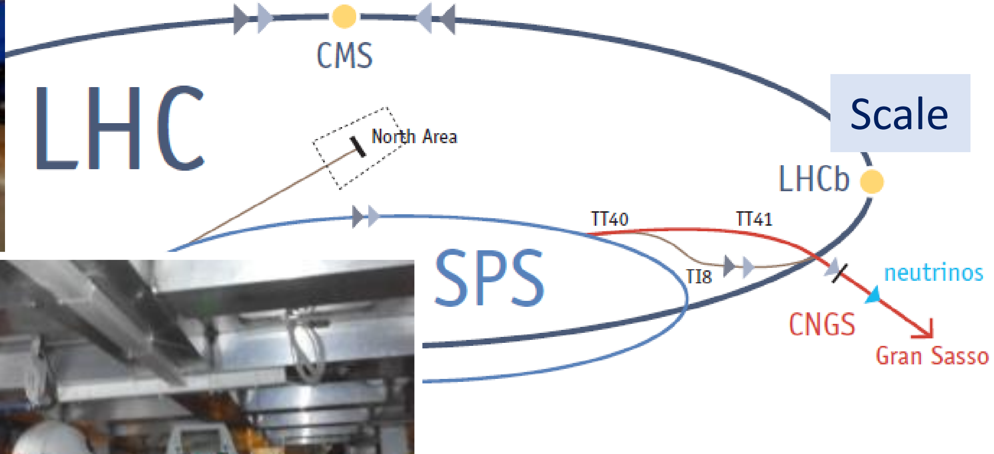
From a few µm to mm

Size of the components

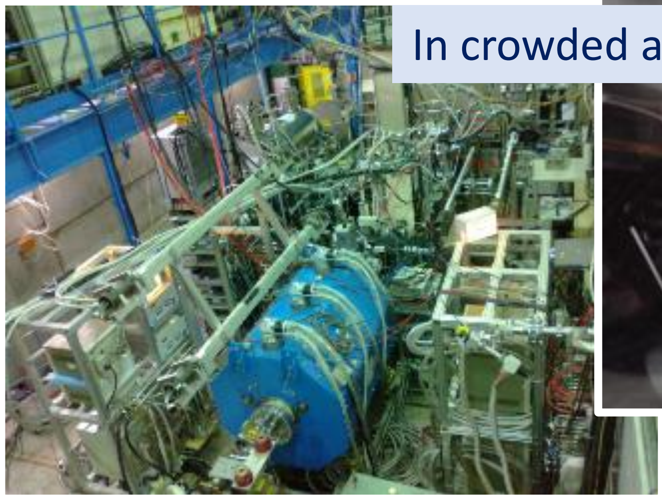


Difficult configuration: straight and narrow

Underground



Scale



In crowded area

Severe environment…

Outline

- Introduction to geodesy
- Steps of alignment
- Instrumentation toolkit
- Application to colliders: LHC, HL-LHC, CLIC and FCC
- Alignment R&D

Study cases

Study cases

Study cases

Introduction to geodesy

- Definition of datums
- Geoid and deflection of vertical
- Geodetic infrastructure
- Impact

Geodesy: definition (1)

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.

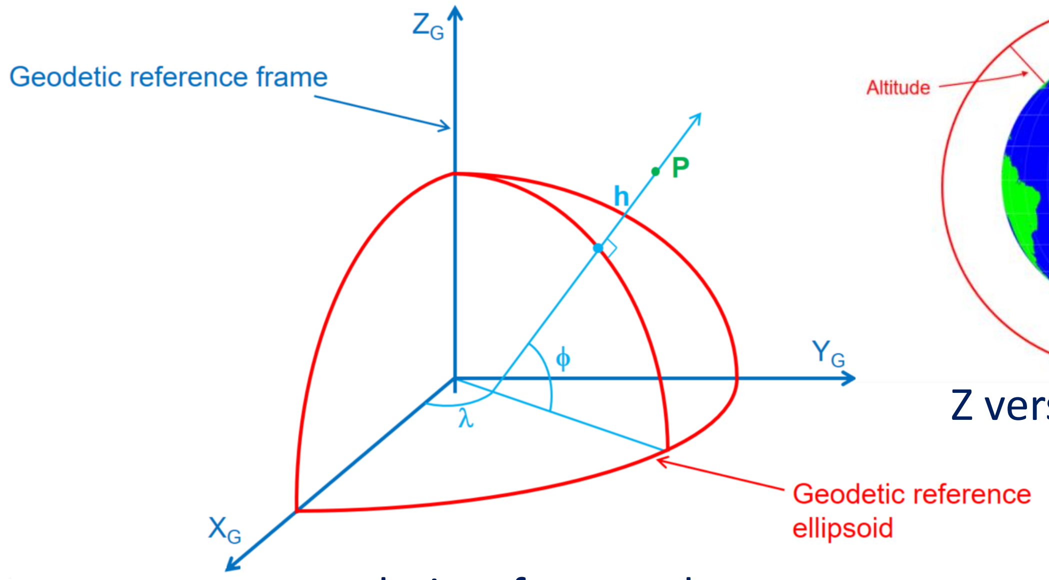
Why is it so important to take it into account?

- 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

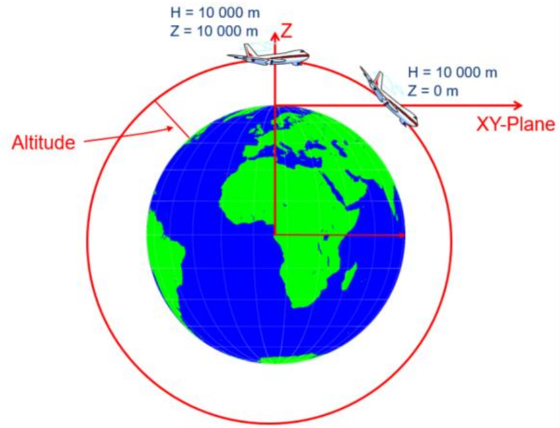
Geodesy: definition (2)

A geodetic datum (or geodetic reference datum or geodetic reference system) is a coordinate system and a set of points, used for locating points on the Earth. Datum may be global, meaning that they represent the whole Earth or local (they represent an ellipsoid best fit to only a portion of Earth). There are hundreds of reference datums.

In such a geodetic system, a point is localized by its Cartesian coordinates (X, Y, Z). But such a geodetic system relies on an ellipsoid, where its geodetic coordinates are its latitude, longitude and height.



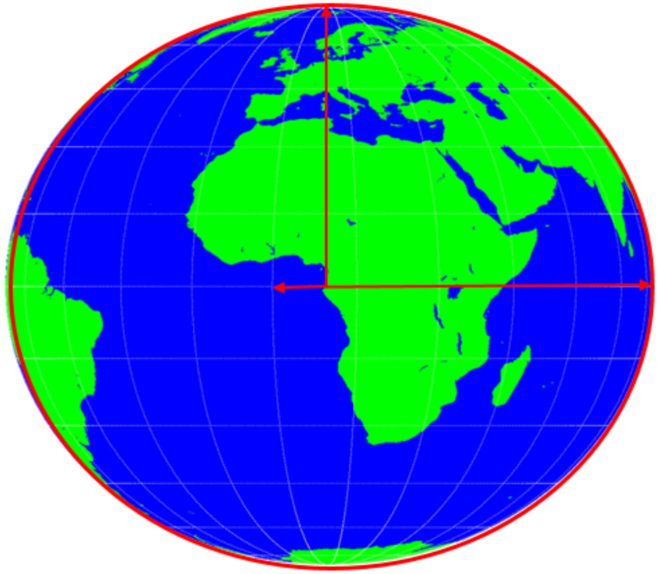
geodetic reference datum



Z versus H coordinate

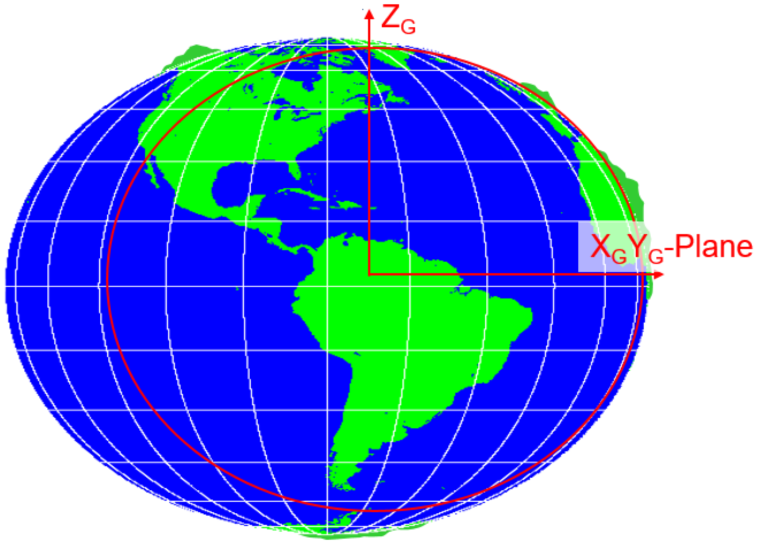
Geodesy: definition (3)

Global Geodetic system



GPS uses the World Geodetic System WGS84 to determine the location of a point on the Earth surface

Local Datum in Europe

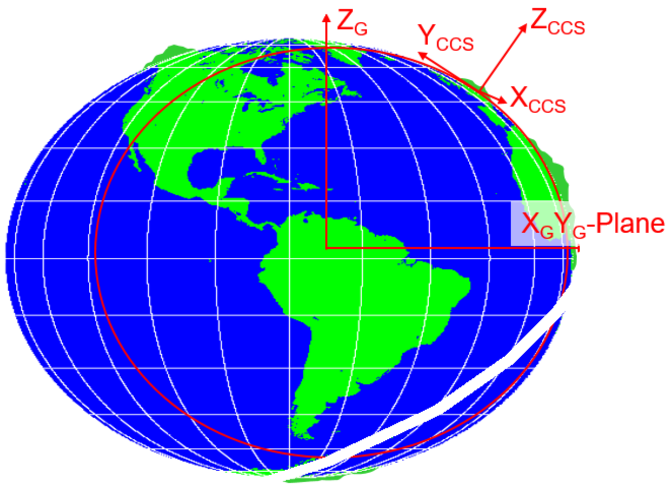


Positioned for a particular application: continents, countries: ED50, MN95, etc.

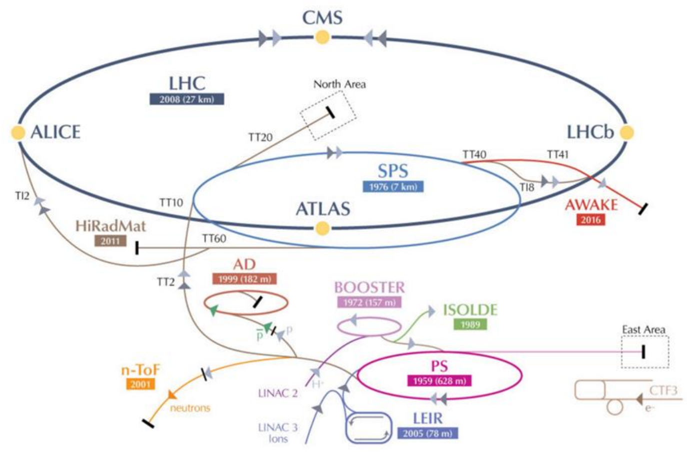
Since reference datums can have different radii and different center points, a specific point on the Earth can have substantially different coordinates depending on the datum used to make the measurement: «datum shift», from zero to hundreds of meters.

Geodesy: definition (4)

CERN Datum

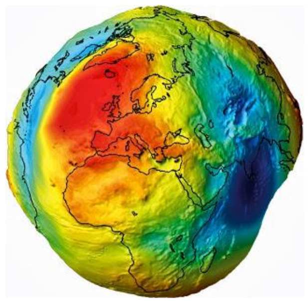


- CERN Geodetic Reference System (CGRF),
- CERN Coordinate System (CCS)
- CGRF is a reference surface depending on the accuracy requested and the size of the project



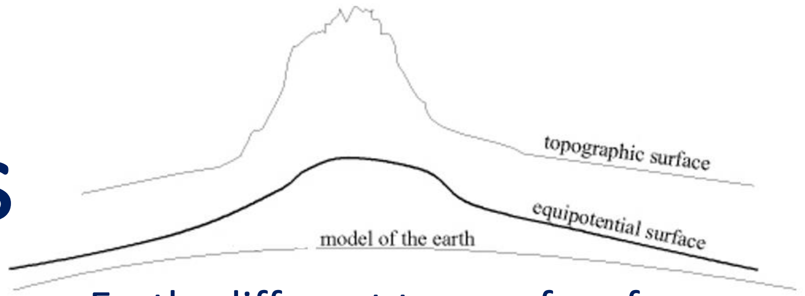
CERN accelerator complex chain

CGRF datum:
= plane for PS (Ø=200 m)
= sphere for SPS (Ø=2.2 km)
= ellipsoid for LHC (Ø=8.6 km) (horizontal)
= geoid for LHC (vertical)



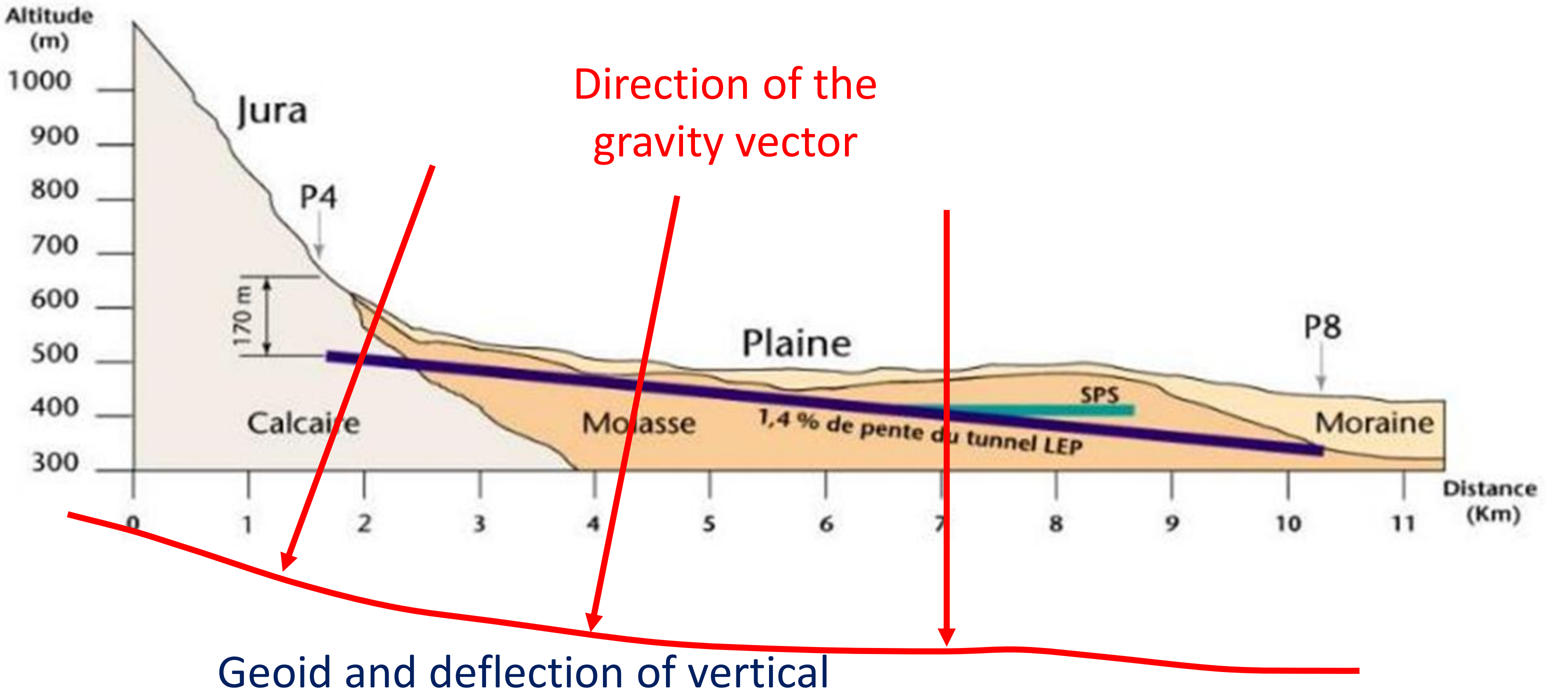
3D view of the geoid
(radial variations exagerated)

Geodesy: CERN reference systems



Earth: different types of surfaces

The geoid is 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)



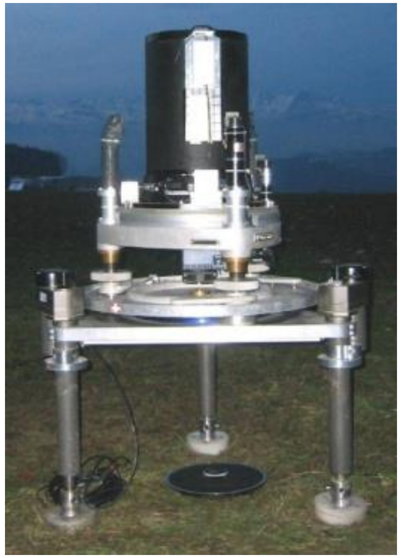
[Jones]

Geodesy: deflection of vertical

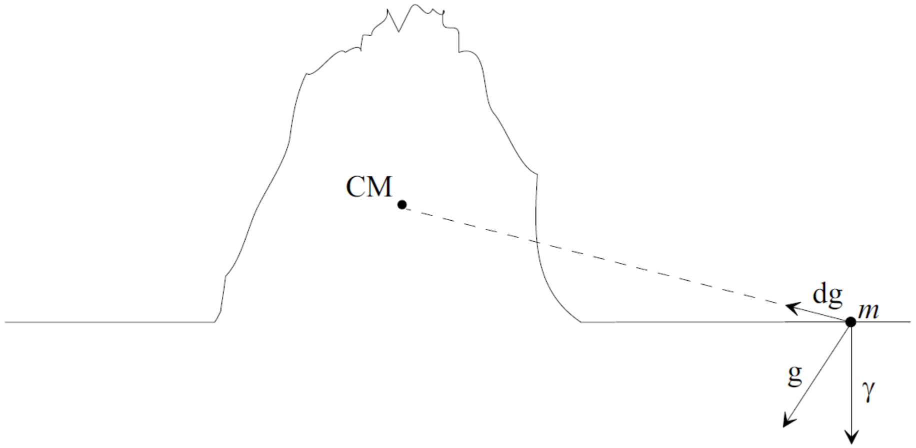
The deflection of vertical is the angle of divergence between the gravity vector (normal to the geoid and the normal to the ellipsoid

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

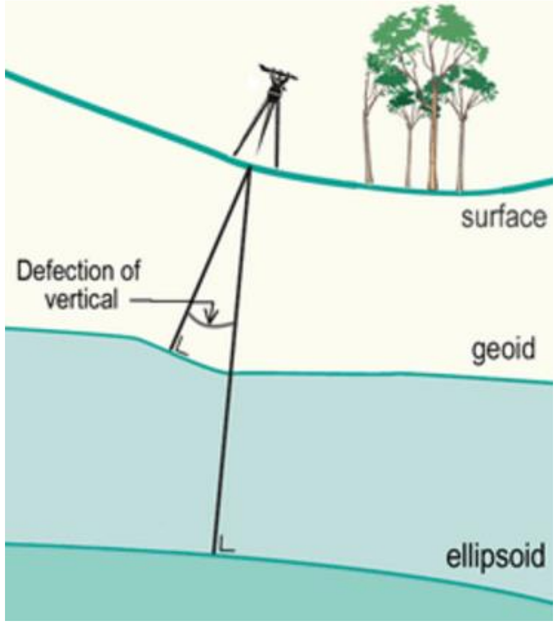


Zenithal camera



Effect of a nearby mass anomaly

[Jones]



Deflection of vertical

Geodesy: deflection of vertical

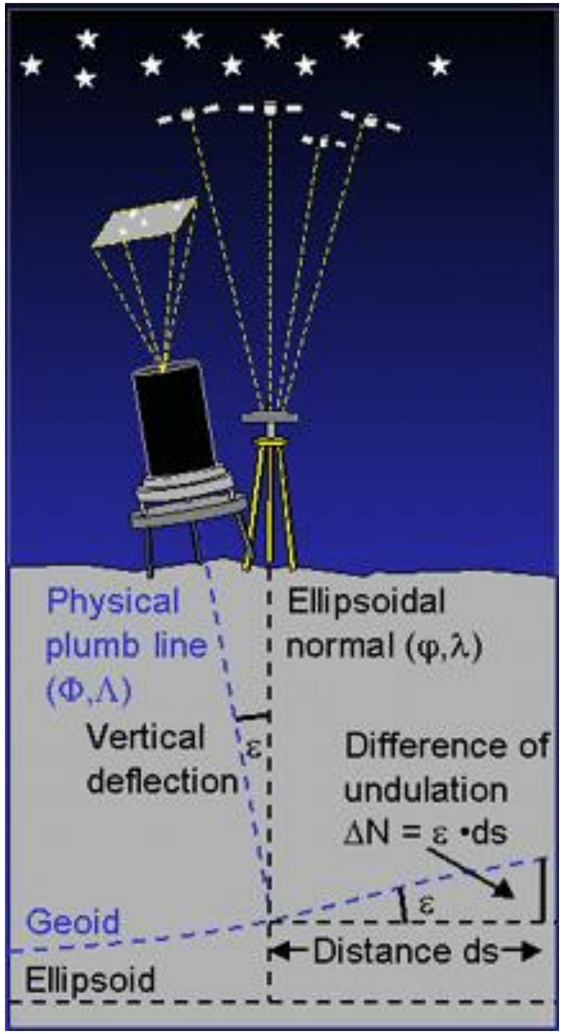
Astro-gravimetric Equipotential Determination

Zenithal camera

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	-	-

Astro-gravimetric equipotential determination: error sources

[Guillaume]



Determination of the vertical deflection

Units

Maximum deviation of vertical = 15’’

- Express it degrees, radian, gon, cc.

Units

Maximum deviation of vertical = 15’’

- Express it degrees, radian, gon, cc.

Second of arc (“)	Minute of arc (‘)	Degree (°)	Radian (rad)	Gon (gr)	Centi centigrad (cc)
15’’	0.25	0.0042	0.000073	0.00463	46.3

Units in survey & alignment:

- 1’’ (second of arc) = 1°/3600
- 1°= π/180 rad
- 1 gon = π/200 rad = 1 gradian
- Subdivision of gradian : c (centigrad) and cc (centi-centigrad)
- 1 cc = 1 dmgon = 10^{-4} gon

Study case

What is the impact of curvature of the Earth on:

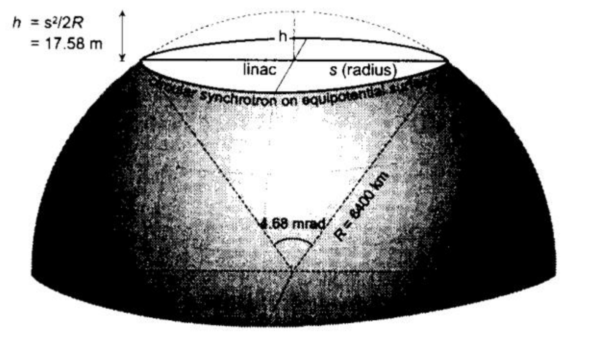
- A linac of 20 m
- A linac of 100 m
- A synchrotron (Ø = 200 m)

Geodesy: impact

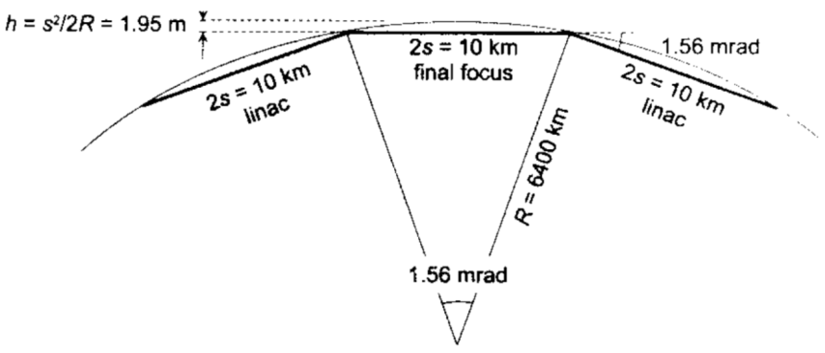
- Accelerators built in a tangential plane (slightly tilted to accommodate geological deformations)
- All points around an untilted circular machine lie at the same height.
- Linear machines cut right through the equipotential iso-lines:
- Center of a 30 km linear accelerator is 17 m below the end points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

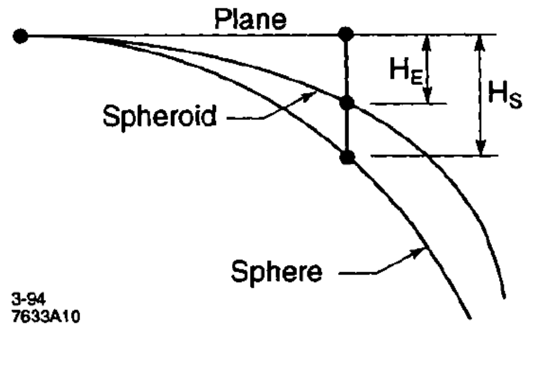


Effect of earth curvature on linear and circular accelerators



Three plane lay-out

[Ruland]



Curvature correction.

[Ruland2]

Steps of alignment

Time scale

Definition of alignment tolerances

Definition of alignment strategy

Installation and determination of surface geodetic network

Transfer of reference in the tunnel

Installation and determination of an underground geodetic network

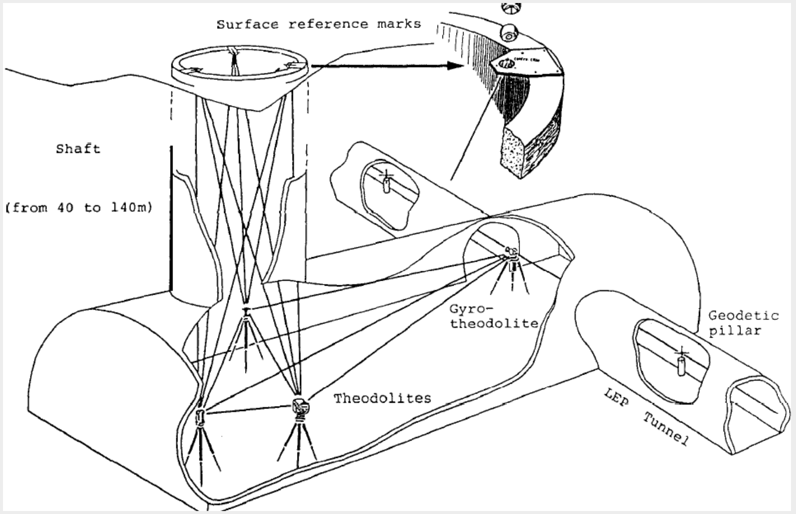
Fiducialisation of the components

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.

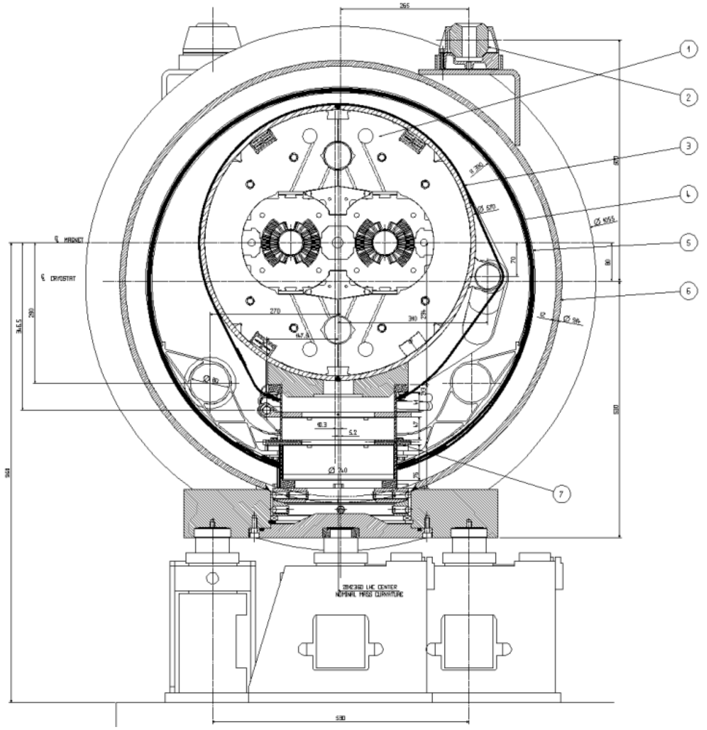
(i) (2) Mechanical aperture limitation in the dipole 0.65 mm r.m.s.

(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.

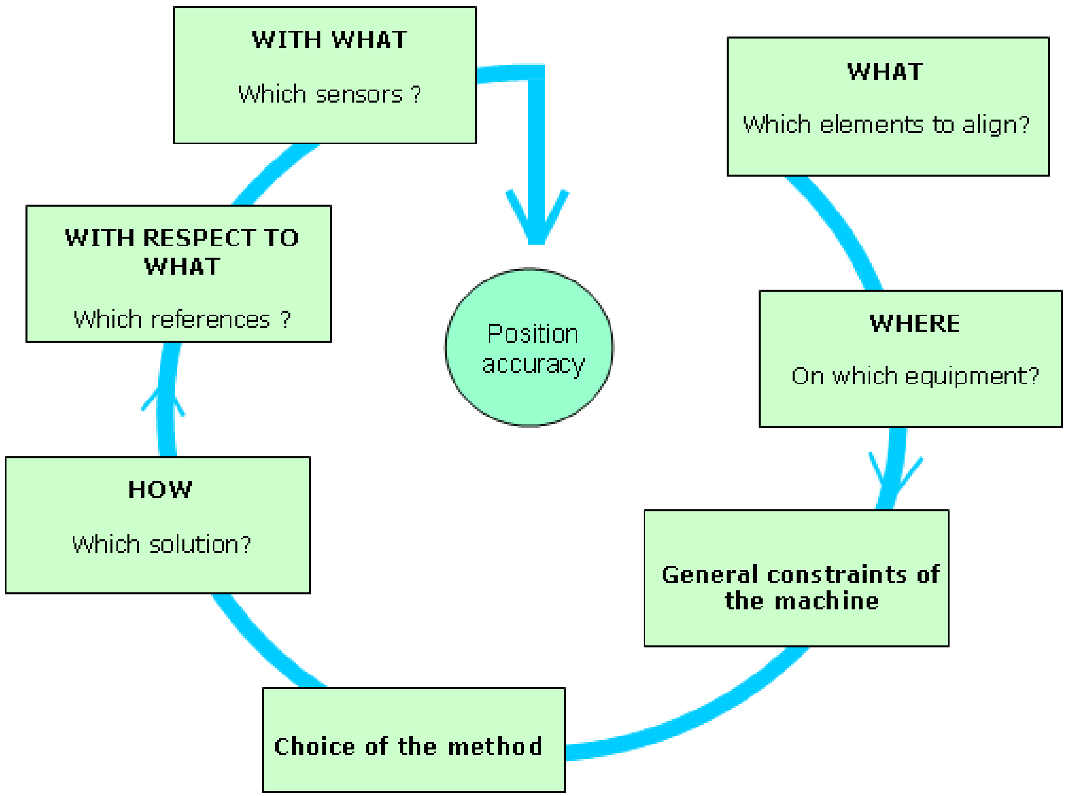
(iii) Magnetic axis of the correctors / theor. orbit 0.80 mm r.m.s.

[Quesnel]



LHC Dipole Cross Section

Definition of alignment strategy



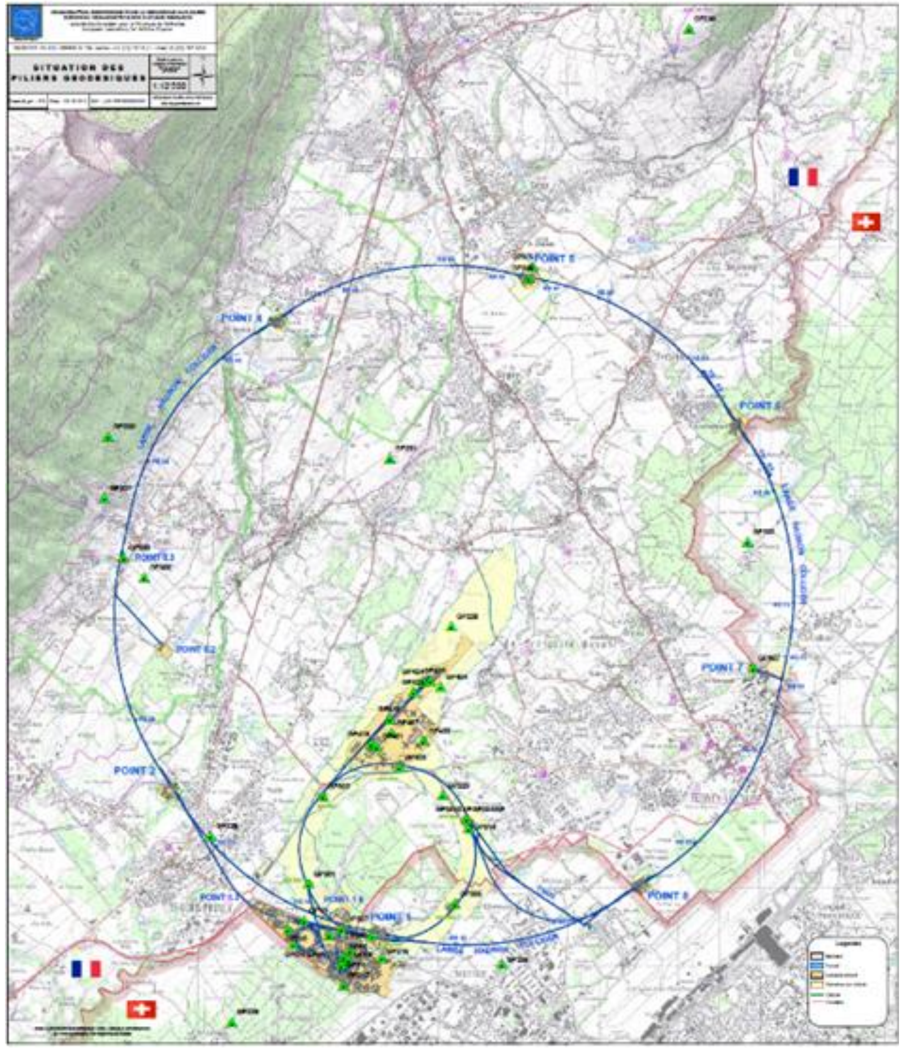
Geodetic surface reference network

- Physical realization of points in an underlying reference system (CGRF/CCS)
- Absolute reference for all subsequent geodetic and survey work
  - Civil engineering
  - Infrastructure
  - Alignment

GNSS station

Geodetic pillar

- Networks with different orders of precision
- Mixture of permanent GNSS stations and geodetic pillars



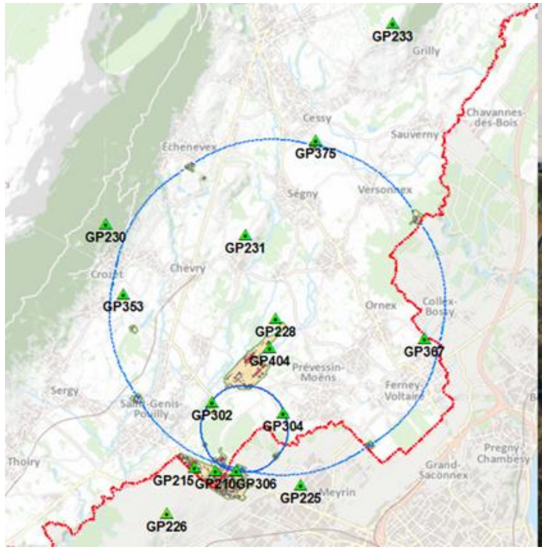
Configuration of CERN geodetic surface reference network

Distance measurements between geodetic pillars using terrameter

GNSS measurements on a Geodetic pillar

What was achieved for HL-LHC

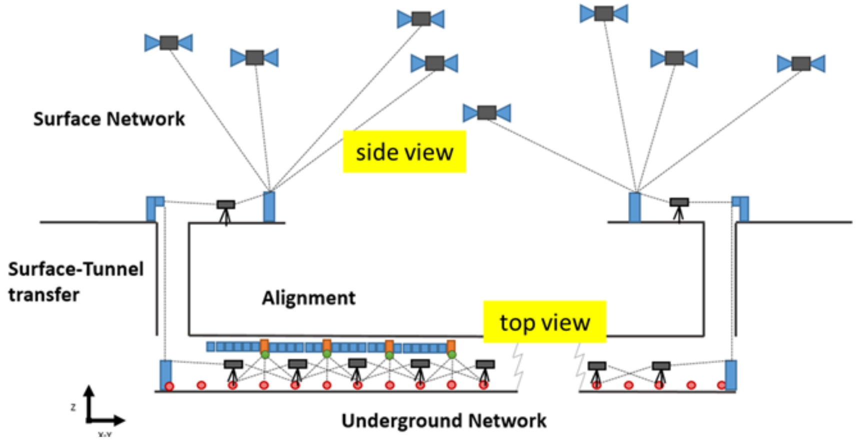
- Objectives: provide to Civil Engineering companies datum and associated accurate and precise reference points from the surface reference network.
- 15 pillars selected from the primary network, spread over the whole surface of LHC.
- Points determined from Global Navigation Satellite System (GNSS) observations, in order to get a precision and accuracy below 2 mm in planimetry and below 5 mm in altimetry. All points measured simultaneously twice, stationed during 48 h each time with individually calibrated geodetic antennas.



Geodetic network

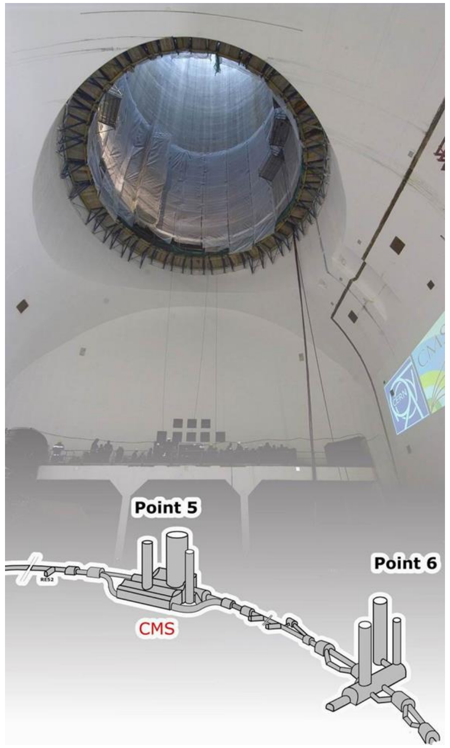
Geodetic pillar

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.

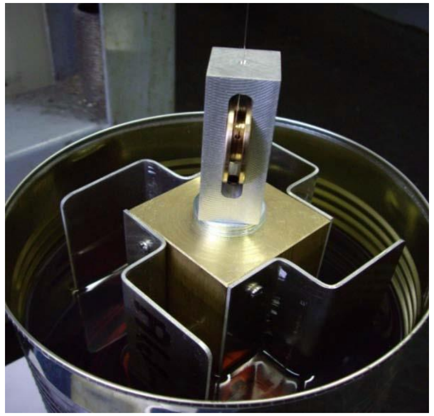
These reference points will be transferred from the surface to the tunnel through pits, using a combination of 3D triangulation and trilateration measurements coupled with angular measurements w.r.t. plumb line. These methods were validated in a LHC pit (depth of 65 m), with an accuracy of 0.5 mm.



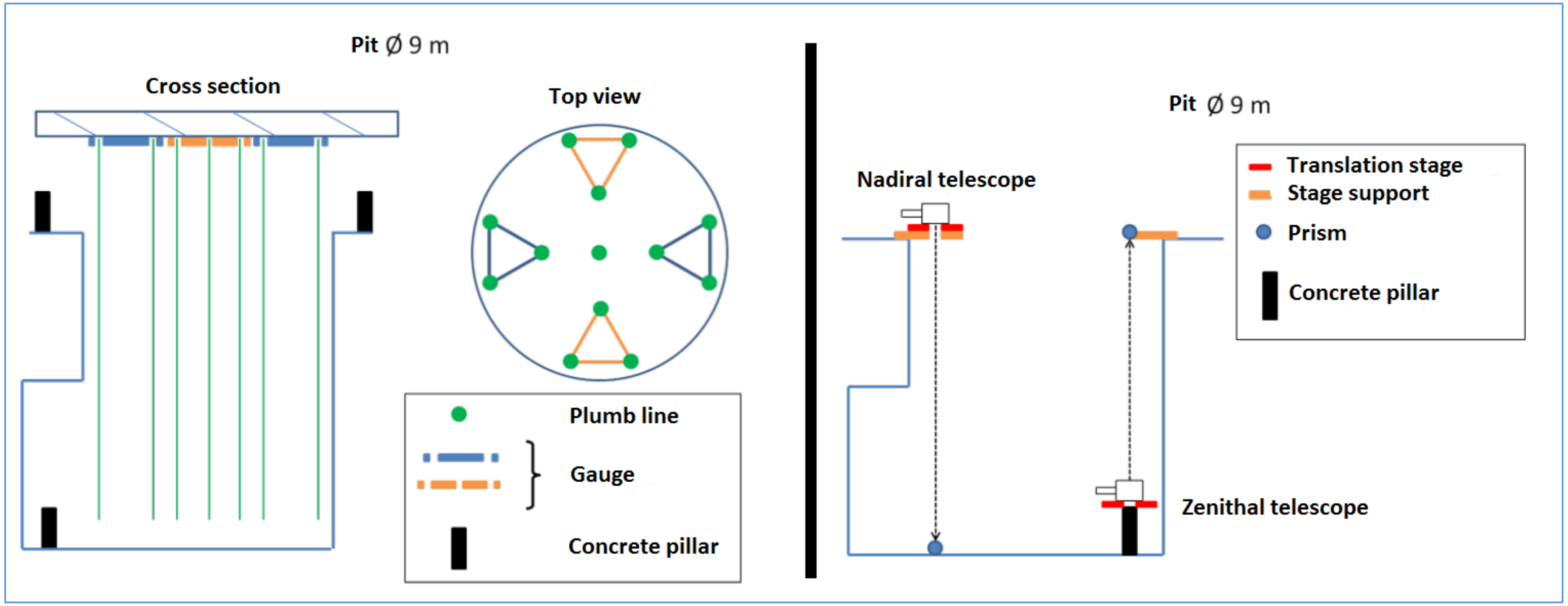
Transfer of vertical through pits

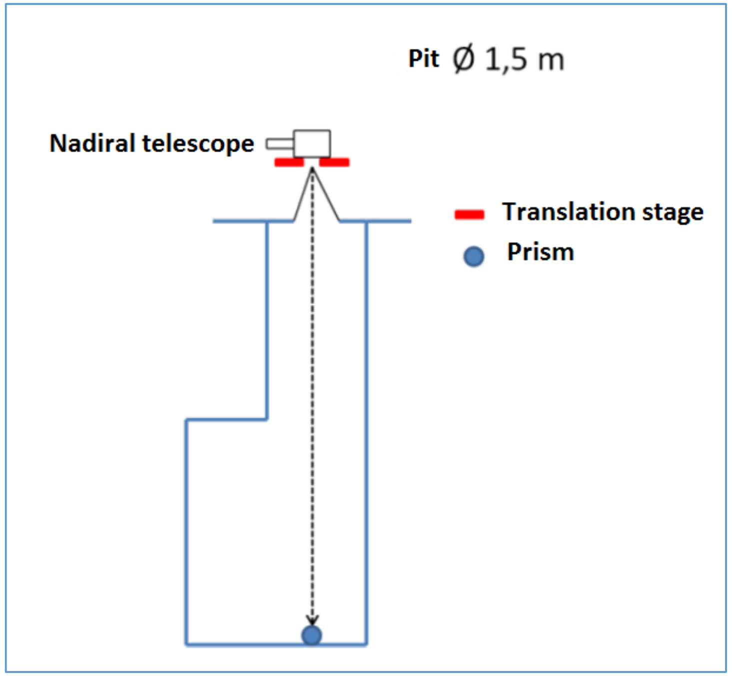
Transfer of geodetic network

Nadir & zenith plummet



Blades weight in an oil bath





[Hugon]

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:

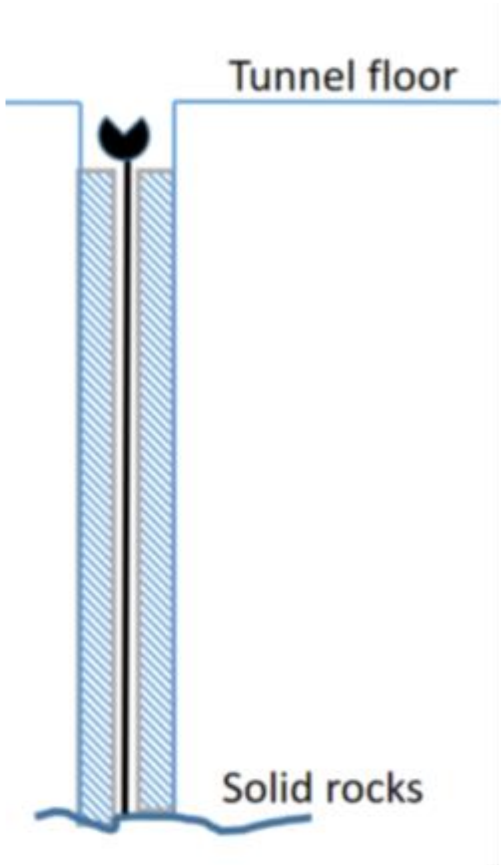
- an absolute accuracy of 3-4 mm along 3 km
- a relative accuracy in planimetry between 3 consecutive monuments of 0.3 mm r.m.s. by adding wire offset measurements and in altitude between 3 consecutive monuments of 0.1 mm.

LHC underground geodetic network

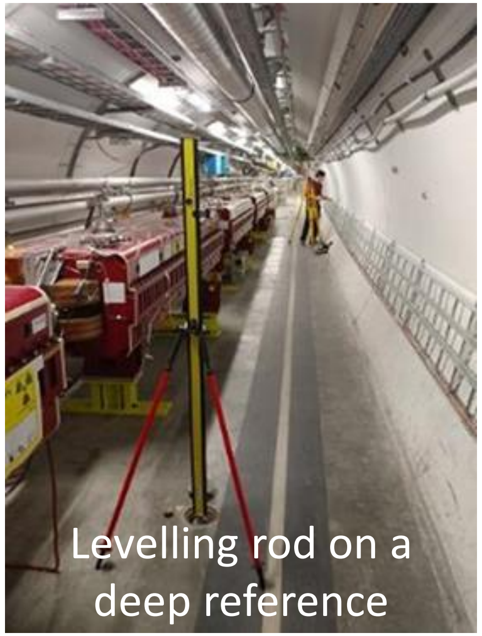
LHC underground geodetic network

Underground geodetic network

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.



Deep reference concept

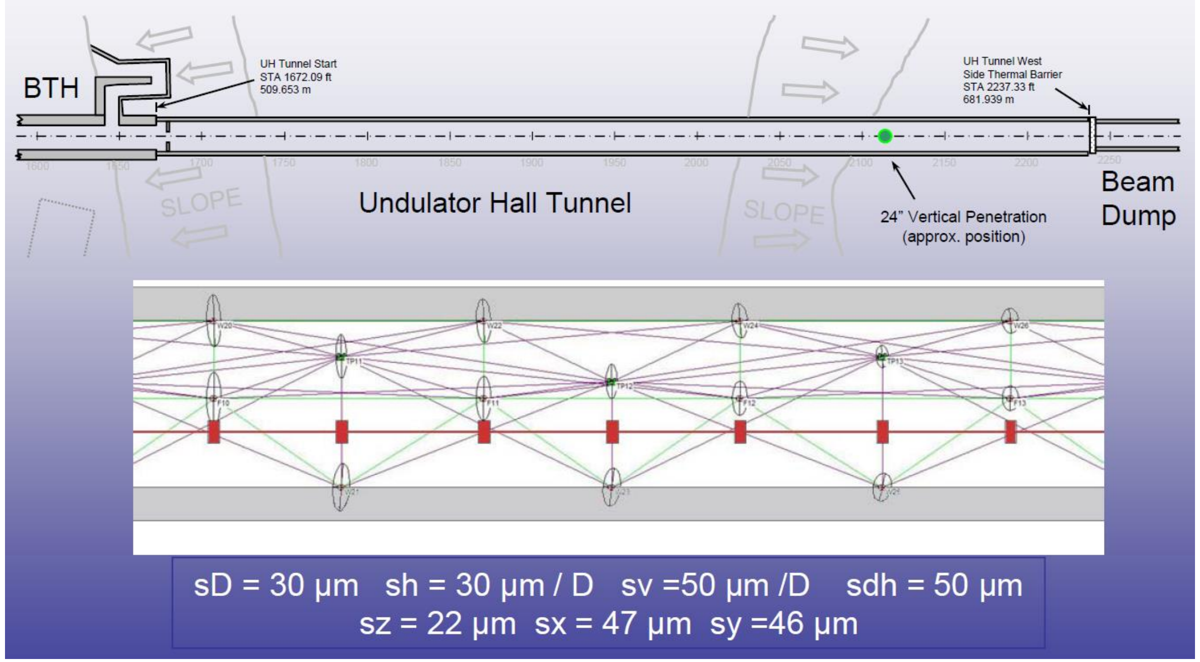


Levelling rod on a deep reference

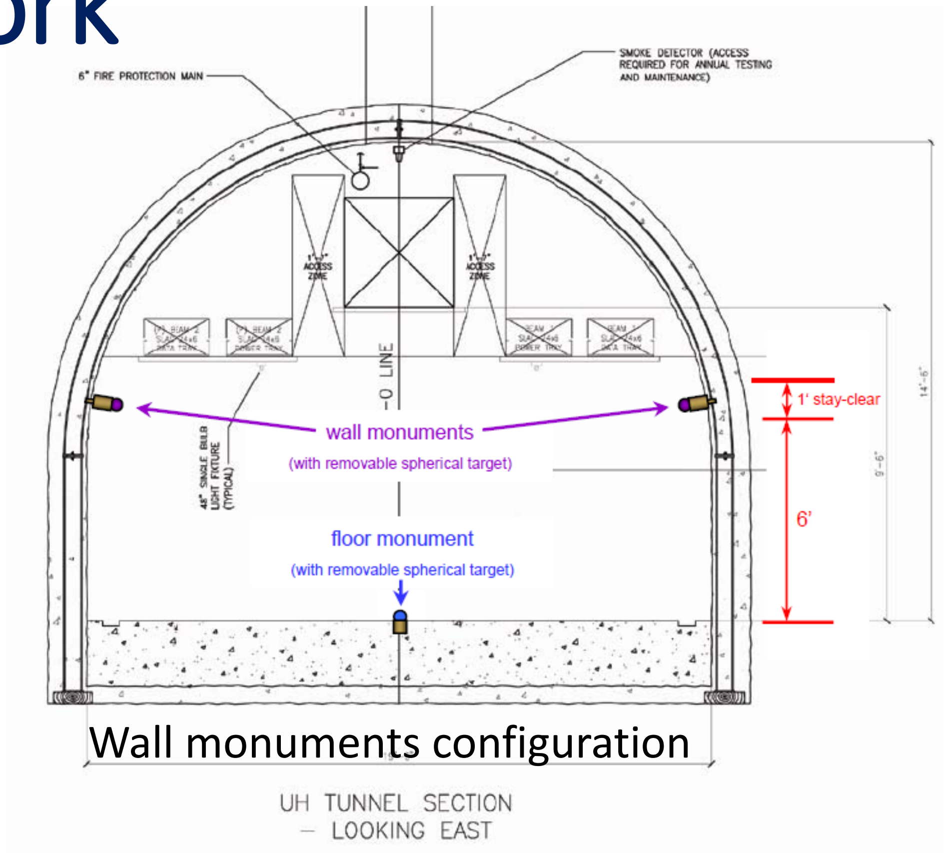
Conical interface of a deep reference

Underground geodetic network

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



Geodetic network in a narrow tunnel



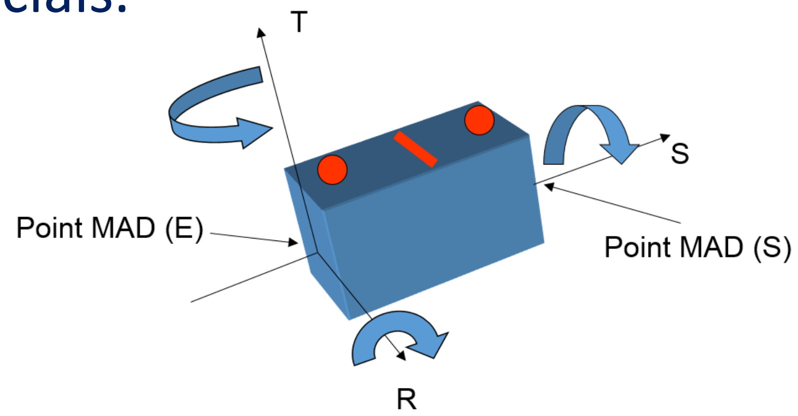
Wall monuments configuration

Wall monument

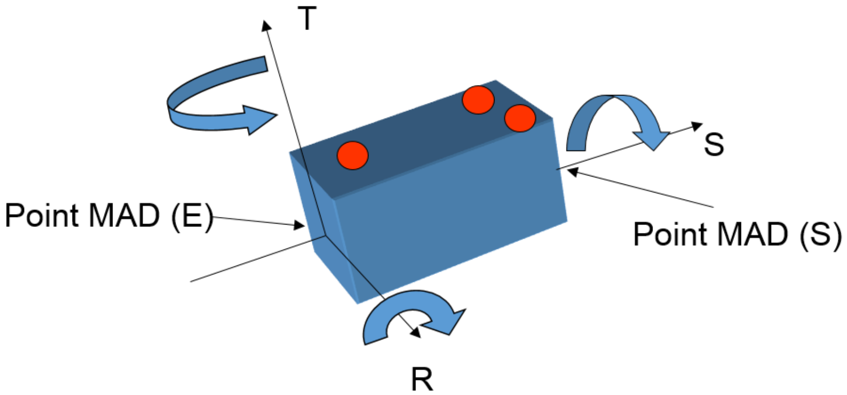
[Lecoq]

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.



Coordinate system associated with a component: 2 fiducials + 1 roll surface



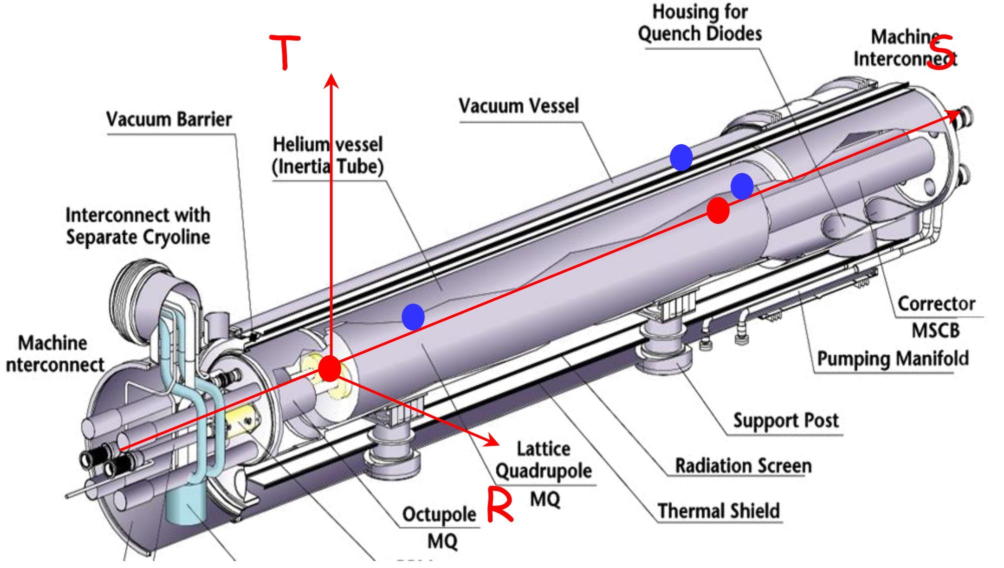
Coordinate system associated with a component: 3 fiducials

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

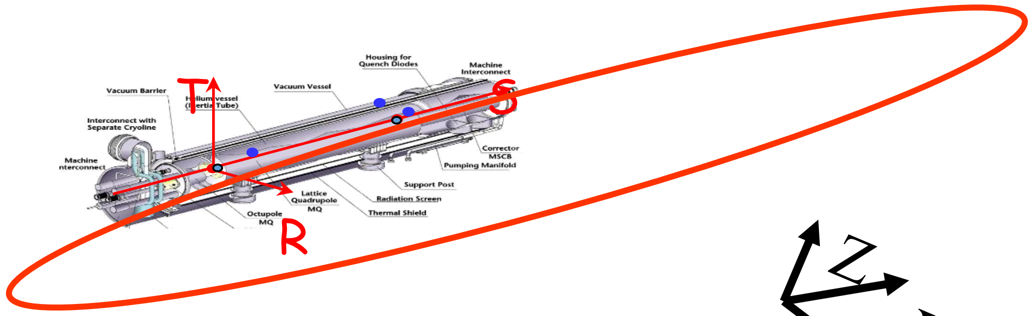
Definition of the theoretical trajectory

To align the objects, we need their theoretical trajectory, defined by physicists, using the MAD-X software [*general-purpose tool for charged particle optics design and studies in accelerators and beam lines*]:

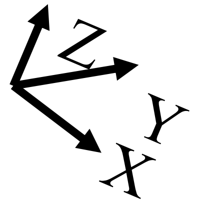
- First in a horizontal local coordinates system x, y, z
- Then in the CCS system



Local coordinate system associated with a component



Component in the CCS



Fiducialisation

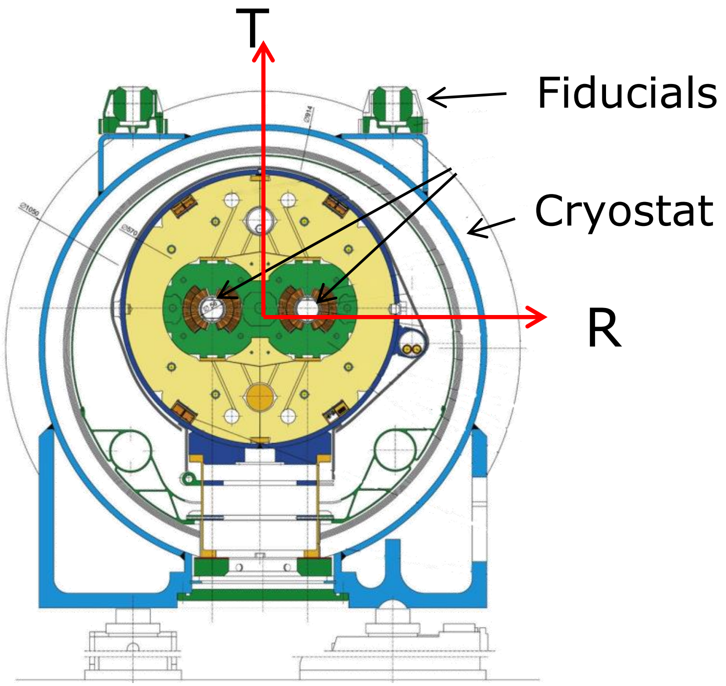
Fiducialisation is the determination of the reference axis of the component w.r.t. its external alignment targets (fiducials) accessible to survey measurements.

3 types of measurements according to the accuracy needed:

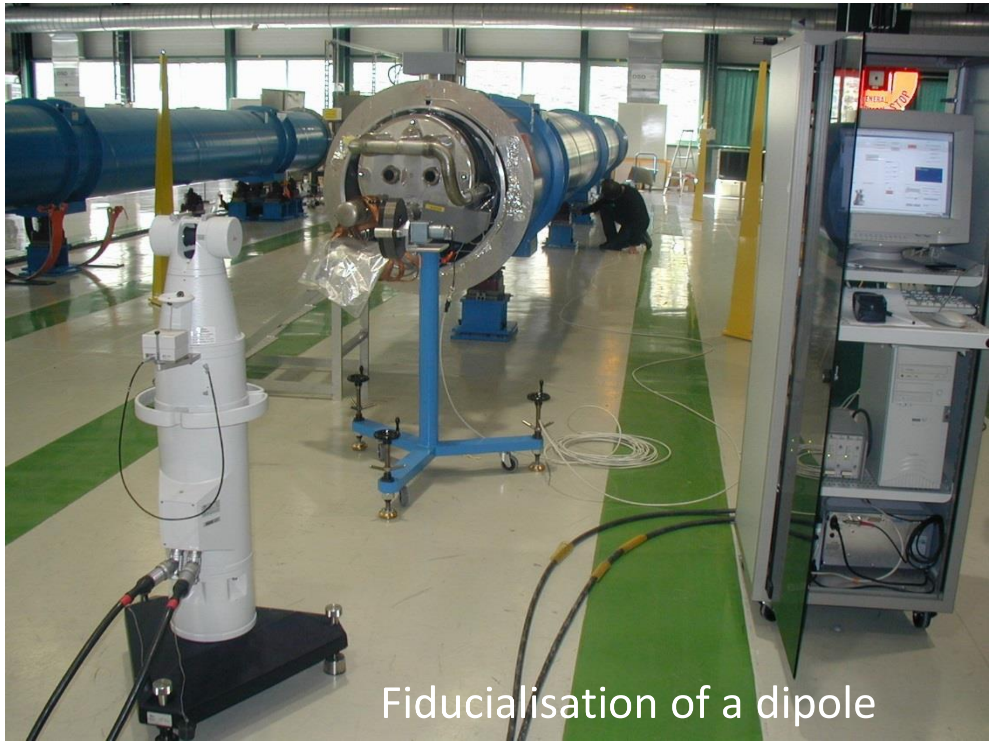
- Mechanical measurements using a gauge (typically for warm magnets)
- Laser tracker measurements when the requirements are of the order of 0.1 mm rms
- CMM measurements, for smaller components and requirements of the order of micrometers.

3D Coordinate Measuring Machine (CMM)

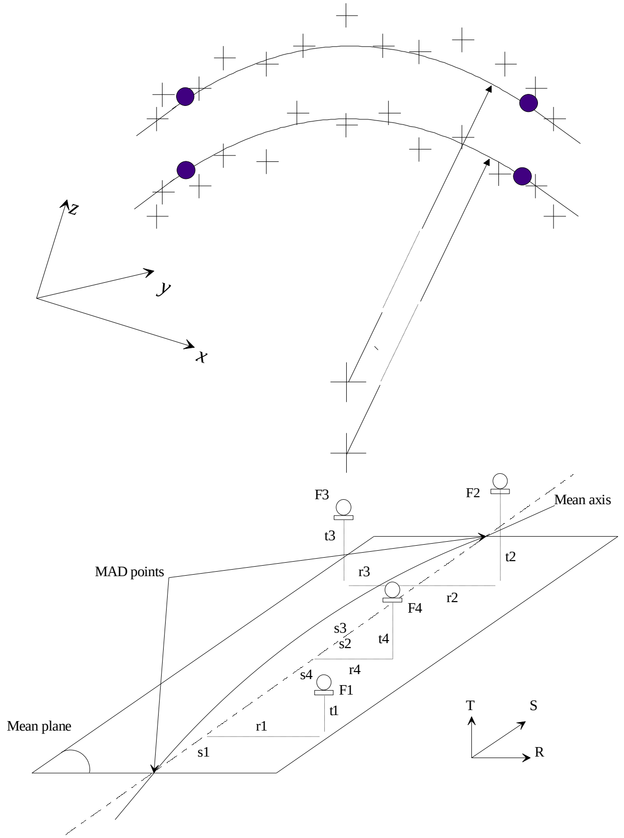
Fiducialisation



LHC dipole cross section



Fiducialisation of a dipole



LHC dipole measurements

Measuring mole

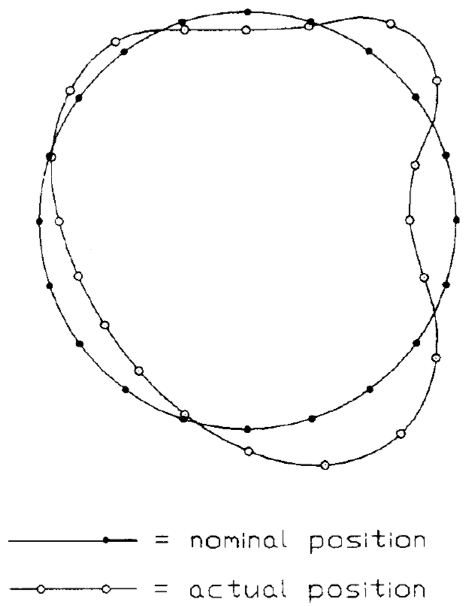
The geometric axis is defined as the best fit of a series of points located in the center of each cold bore tube (with an auto-centering device going through it) and measured from both extremities

Alignment tolerances

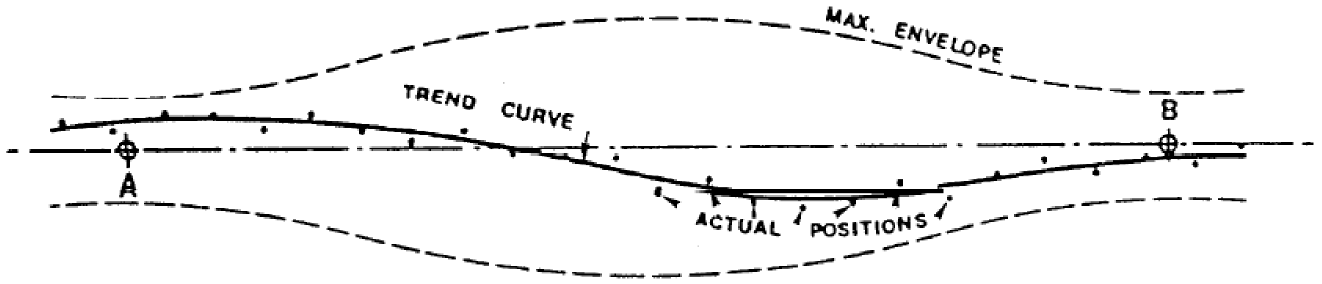
Beam simulations provide the parameters of components and position tolerances (maximum permissible displacements in the direction of the 3 coordinates and roll)

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]



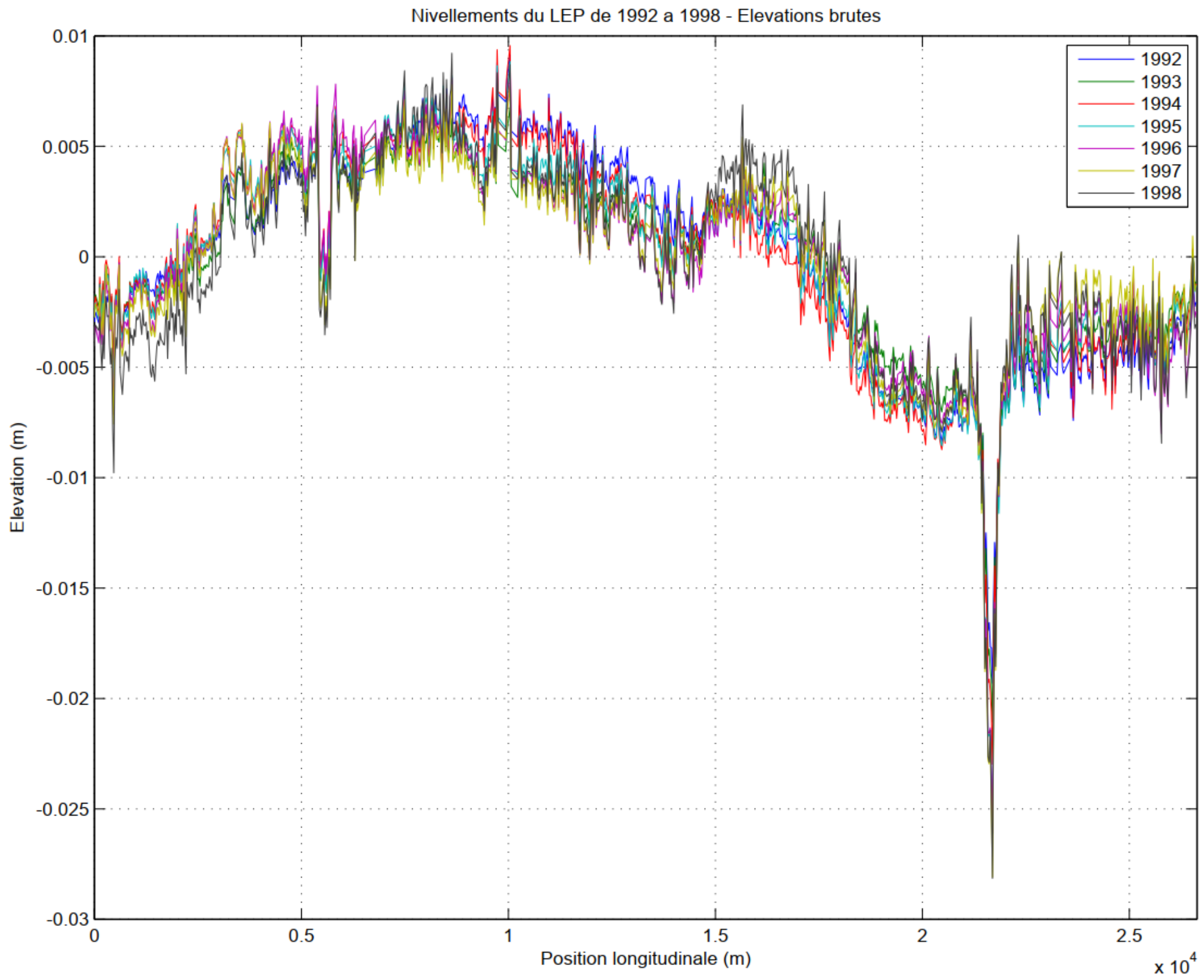
Position of magnets with respect to theoretical orbit

[Mayoud]

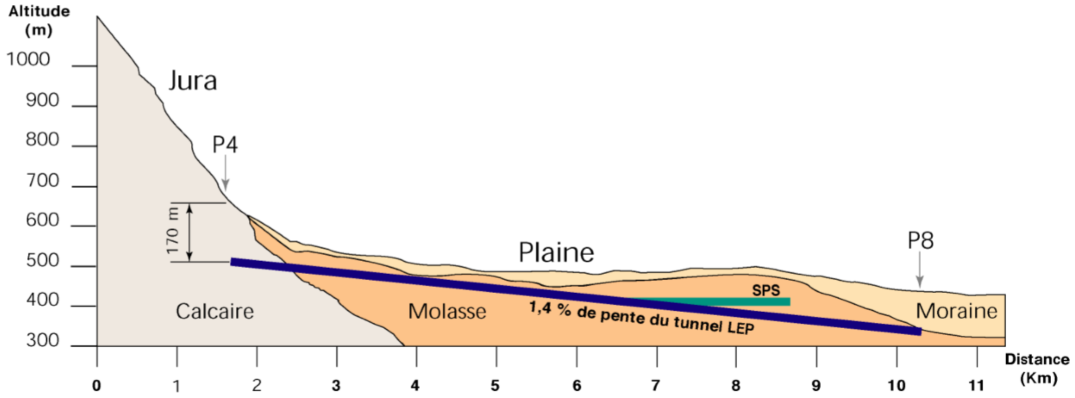
Alignment tolerances

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	

Ground motion



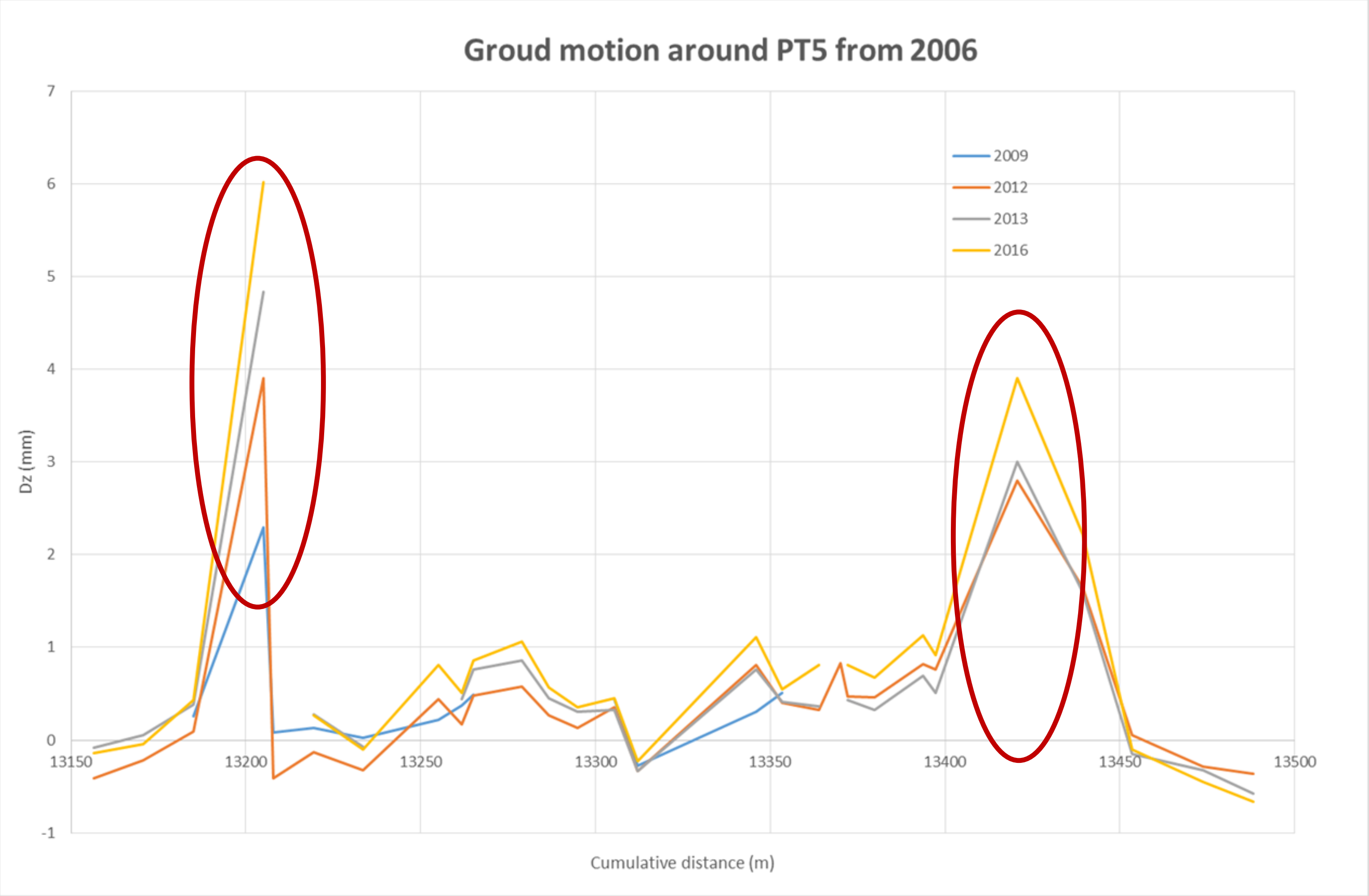
LEP levelling between 1992 and 1998



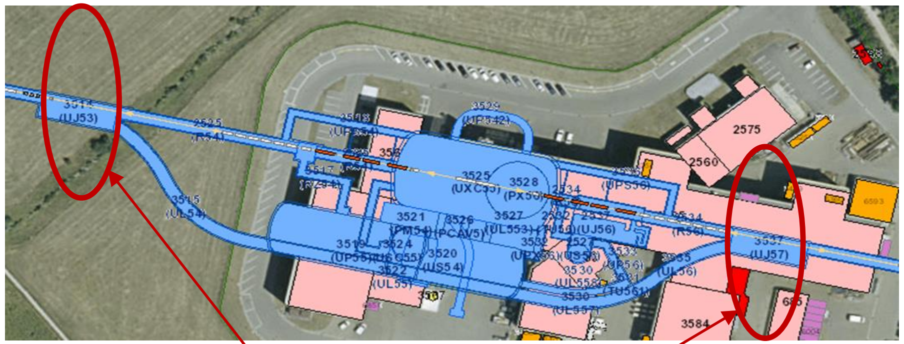
Example 1: vertical displacements along the LEP tunnel

- LEP tunnel is not in an horizontal plane: levelling measurements are corrected to be considered as a vertical offset w.r.t. LEP plane
- Some components were realigned from one year to another. What has been taken into account is not only the vertical offset, but also the vertical displacements performed on the jacks.

Ground motion



Example 2: zoom of the vertical displacement of the tunnel floor around point 1 and point 5 of the LHC (~ 300m from both sides of IP) between 2006 and 2018

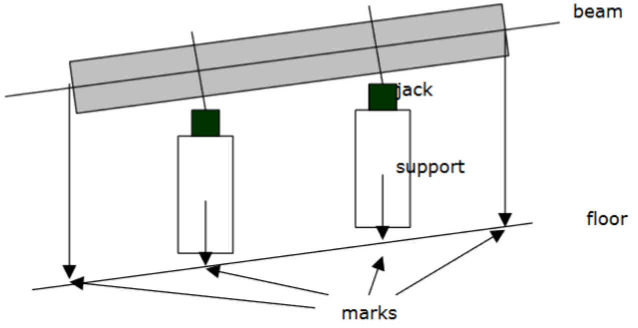


New technical galleries dug during LS1

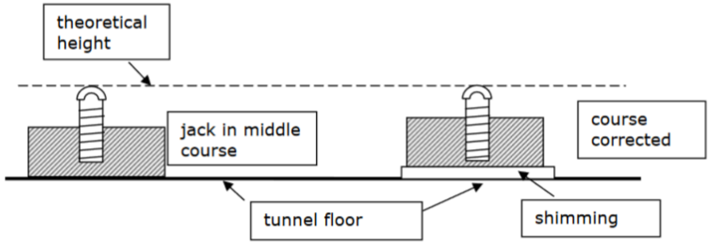
Absolute alignment

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:

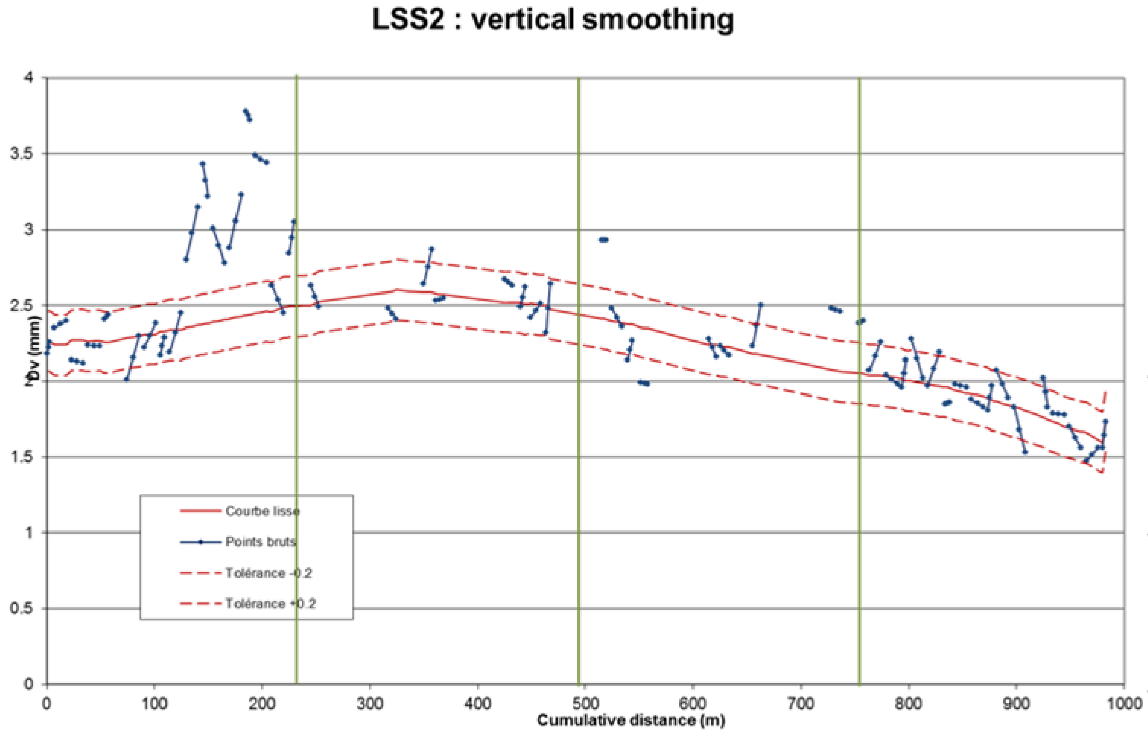
- **First positioning:** it takes place once the components are installed on their jacks. Each component is aligned independently with respect to the underground geodetic network. A component is considered aligned once its fiducials have reached their theoretical position.

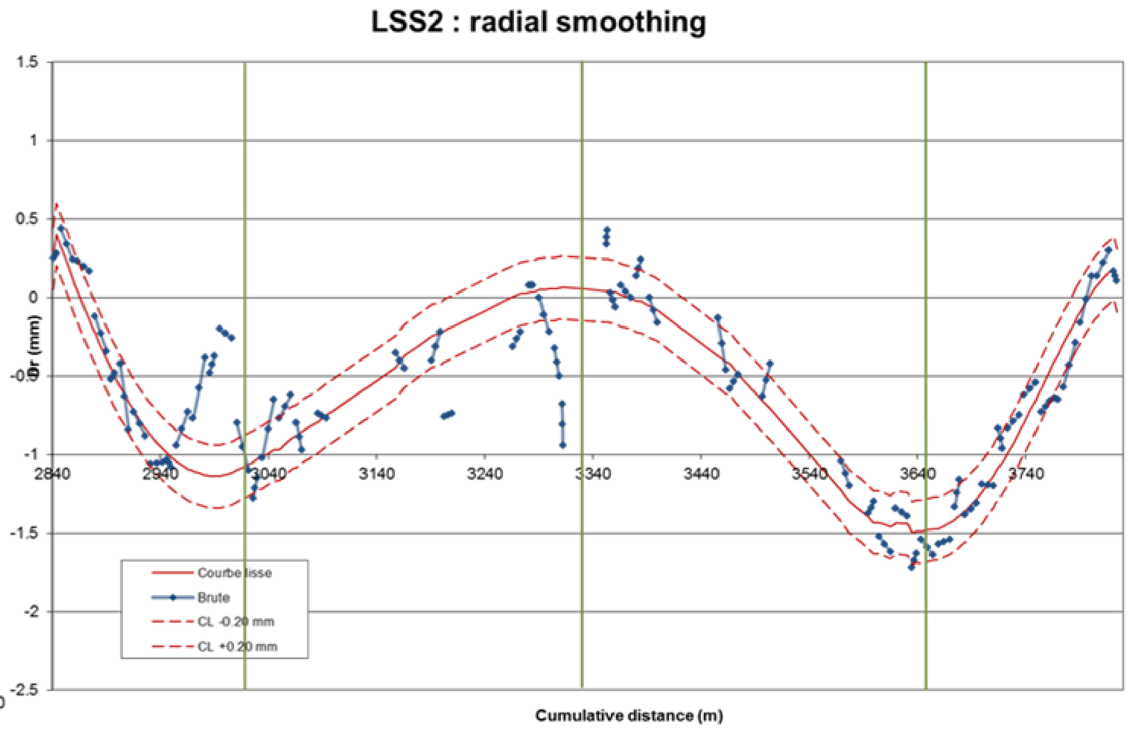
- At the same time, a small local smoothing from magnet to magnet is carried out to decrease the influence of the small relative errors between the points of the geodetic network.

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.

Relative alignment: smoothing





Measurements of the Long Straight Section (LSS2) components of the LHC in 2013, 4 years after their final realignment, in vertical and in radial.

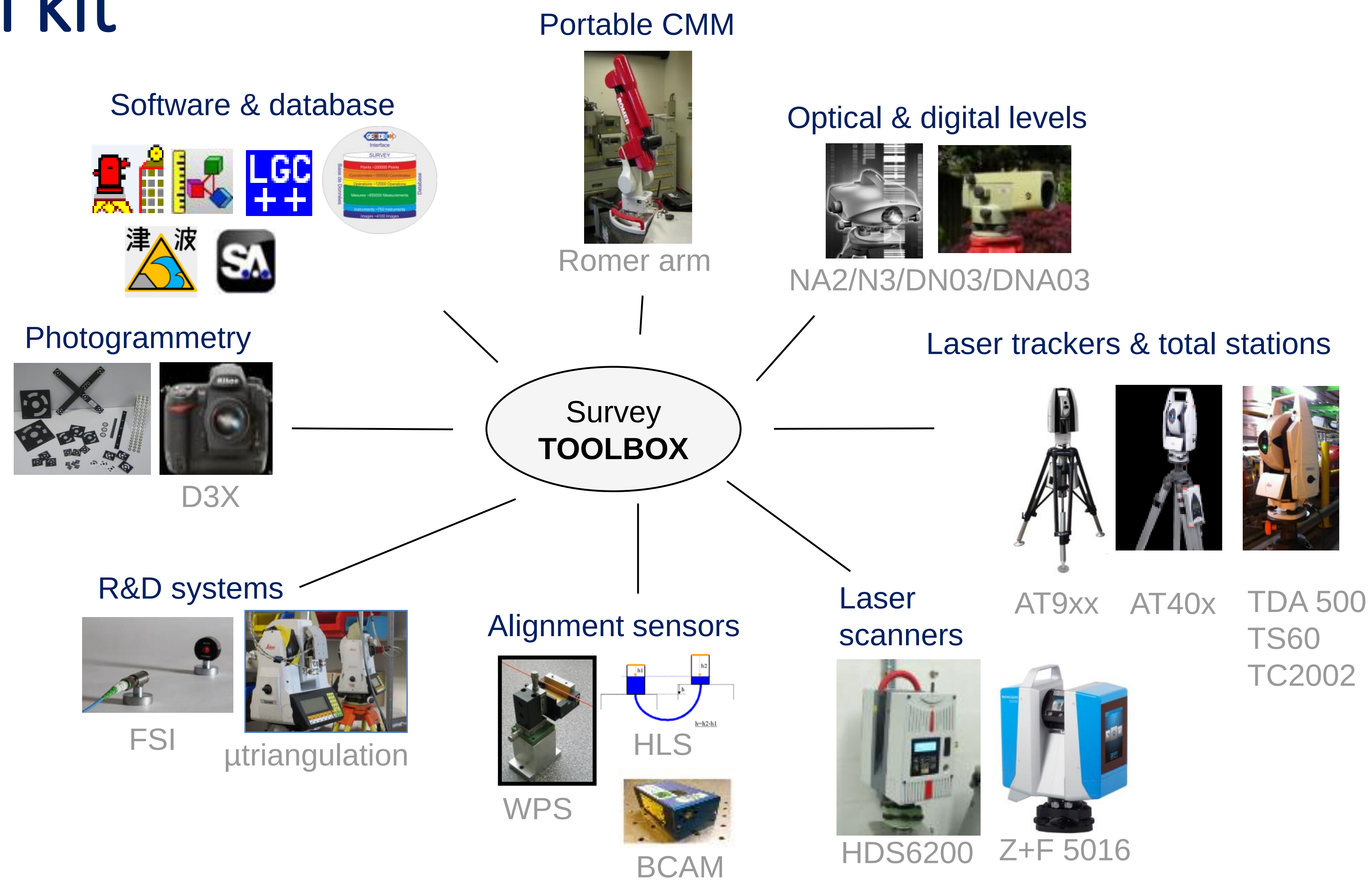
The instabilities are located in the area at the junction between the transfer tunnel TI2 and the LHC

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…

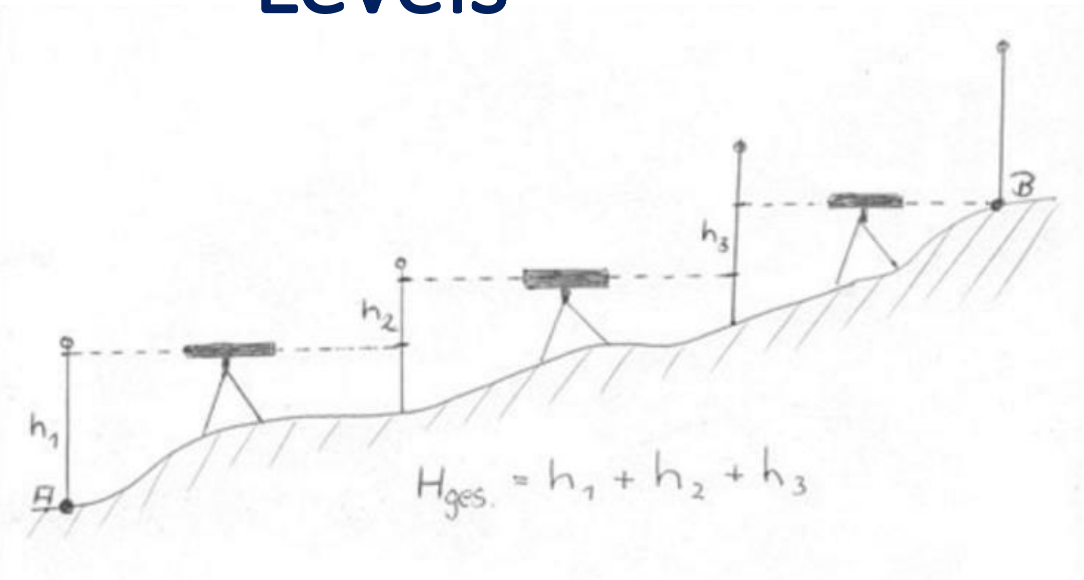
Our tool kit


Software & database
Portable CMM
Romer arm
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
Z+F 5016

Instrumentation toolkit

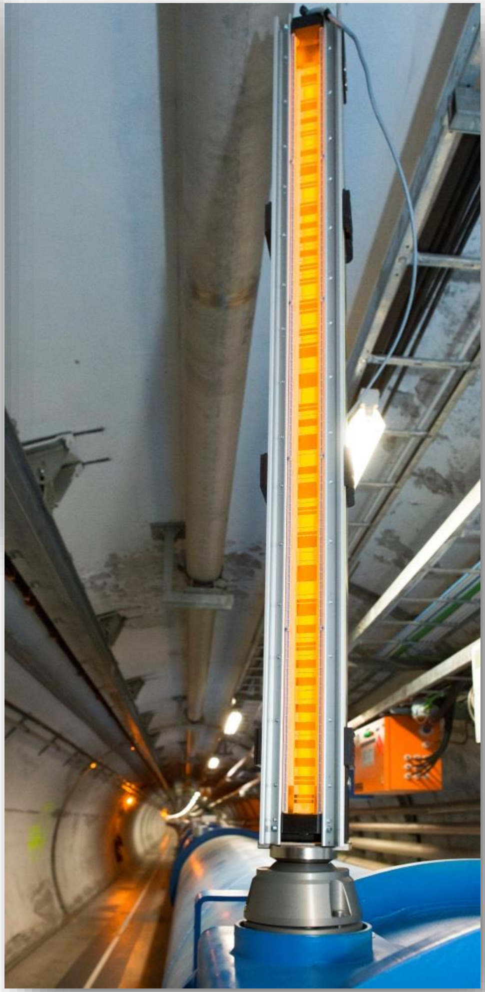
- Determination of the position
  - Standard instruments
    - Levels
    - Laser tracker
    - Total station
    - AT40x
    - Photogrammetry
  - Alignment systems
- Adjustment

Levels



Height measurements between B and A using levels

Digital level and barcode rod



Barcode rod

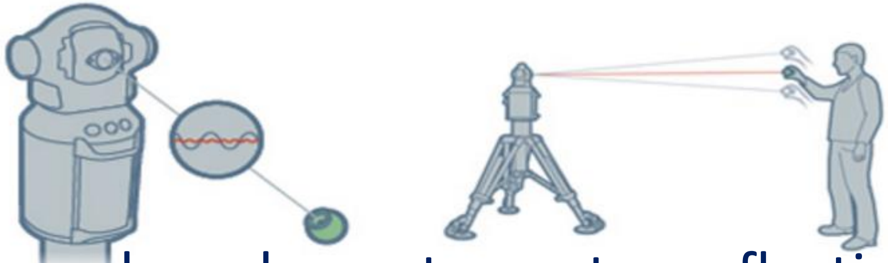
Digital level

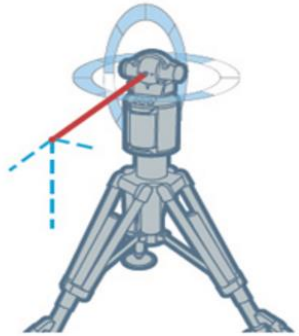
Leica NA2 & NA2K levels

- 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

Laser tracker





Laser tracker

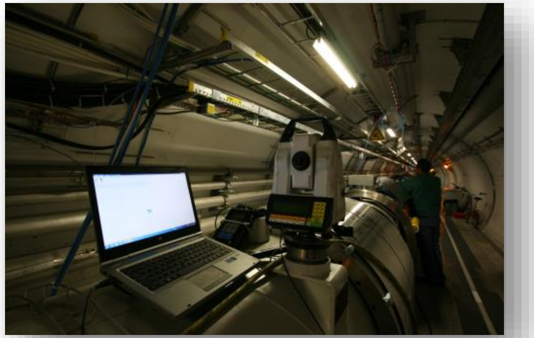
- Measure 3D coordinates by tracking a laser beam to a retro-reflective target
- Combination of two techniques:
  - A distance meter to measure absolute distance (laser interferometer or Absolute Distance Meter)
  - Angular encoders to measure the laser tracker's two mechanical axes

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

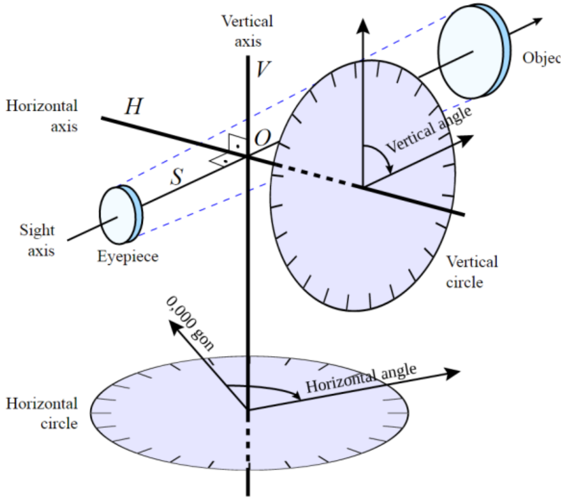
* All accuracies are specified as maximum permissible errors (MPE) and calculated per ASME B89.4.19-2006 & draft ISO10360-10 using precision Leica 1.5" Red Ring Reflectors up to 60 m distance unless otherwise noted.

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

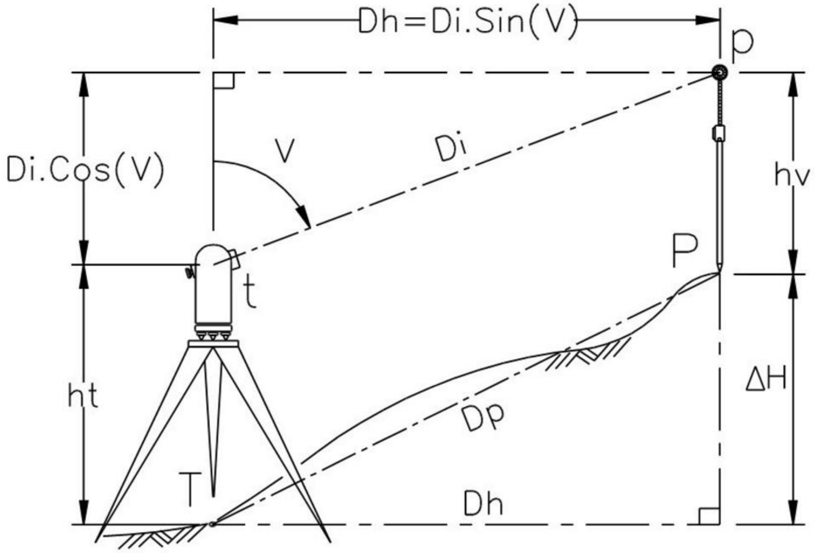
Total station



A total station in the LHC



Total station: angle measurements



Total station: point measurement

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

Different types of total stations

Corner Cube Reflector (CCR)

LEICA AT40x

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

AT40x in the LHC

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.

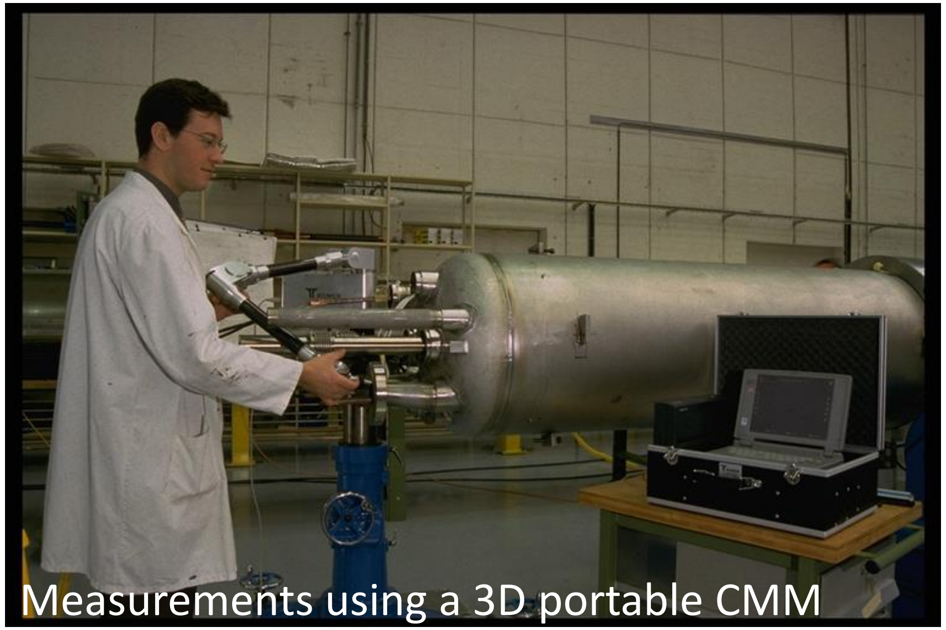
Reflector:

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

*Maximum Permissible Error (MPE)

A 3D portable CMM


3D portable CMM


Measurements using a 3D portable CMM

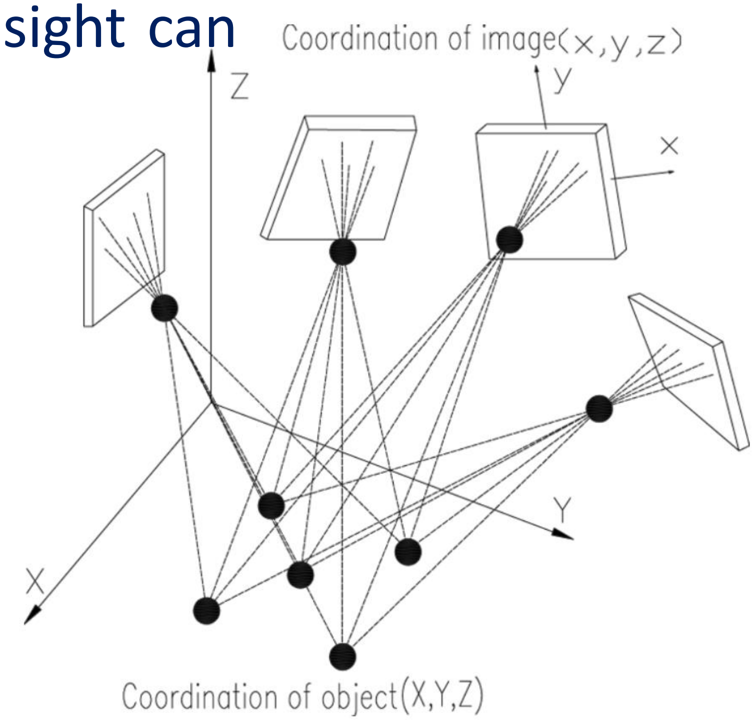
		B89.4.22		ISO 10360-2		
Model	Measuring range	Point repeatability	Volumetric accuracy	MPEp	MPEe	Arm weight
7312	1.2 m / 3.9 ft.	0.014 mm / 0.0006 in.	± 0.025 mm / 0.0010 in.	8 µm	5+L/40 ≤ 18 µm	10.2 kg / 22.5 lbs
7512	1.2 m / 3.9 ft.	0.010 mm / 0.0004 in.	± 0.020 mm / 0.0008 in.	6 µm	5+L/65 ≤ 15 µm	10.8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

Photogrammetry

Photogrammetry = science of making measurements from photographs. Fundamental principle = triangulation. By taking photographs from at least 2 different locations, lines of sight can be developed from each camera to points on the object.

Advantages of photogrammetry

- Image acquisition needs no stable station
- Flexible use following object size
  - Components < 1 m (1 sigma < 50 µm)
  - 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



Concept of photogrammetry

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

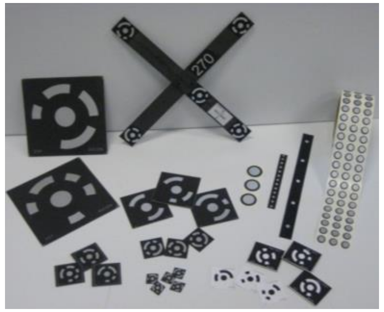
Used in combination with other systems

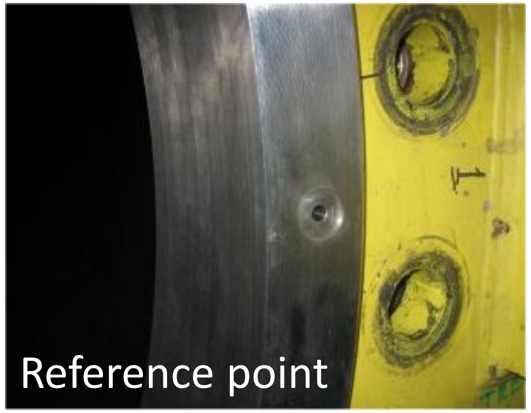
- scale, link to accelerator geometry

Used in all LHC experiments and others

Nikon D2X

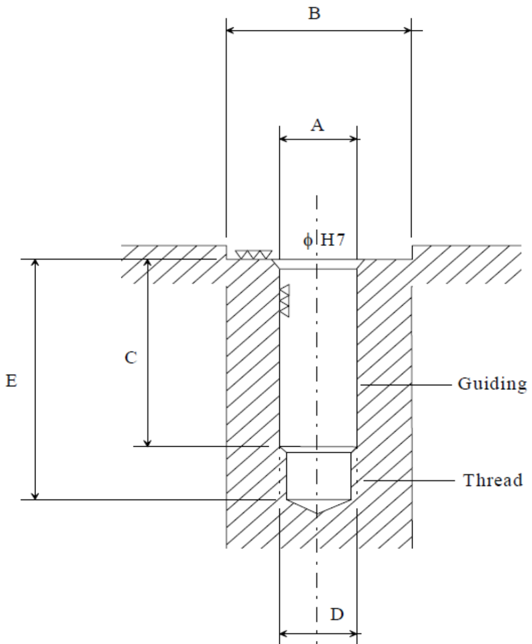
Targets





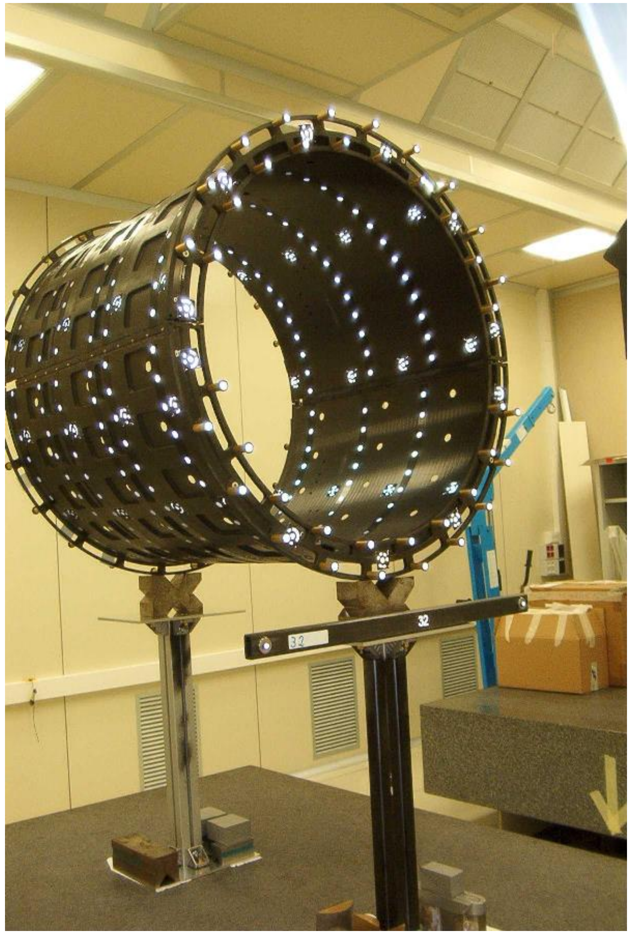
Reference point

Reference point

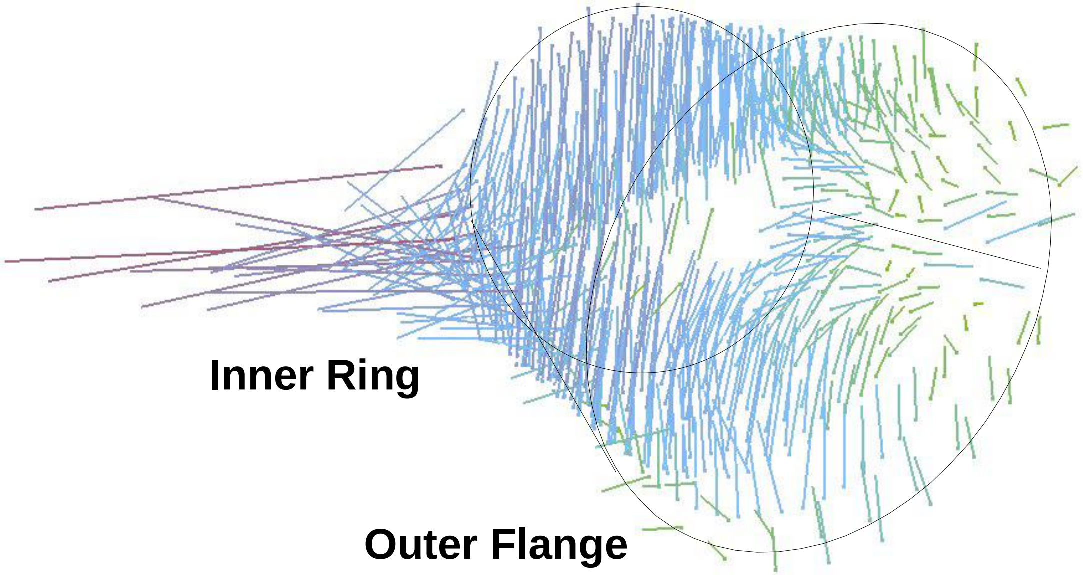


Reference point

Photogrammetry: applications



CMS Tracker Barrel



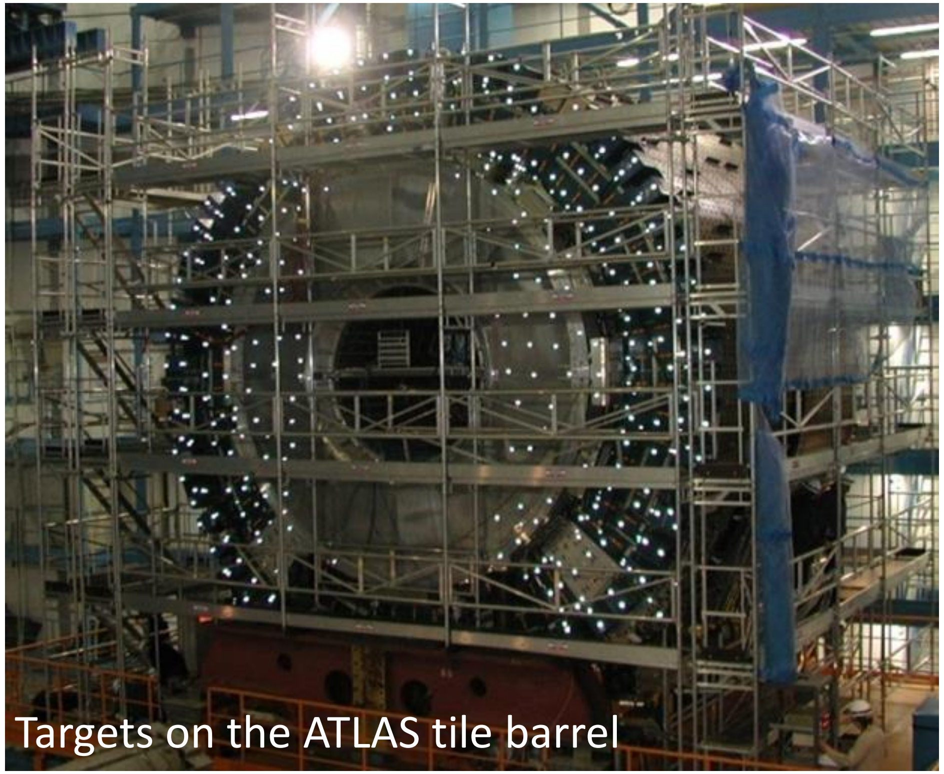
Photogrammetric measurements on the CMS tracker barrel

Max. difference to best-fit cylinder

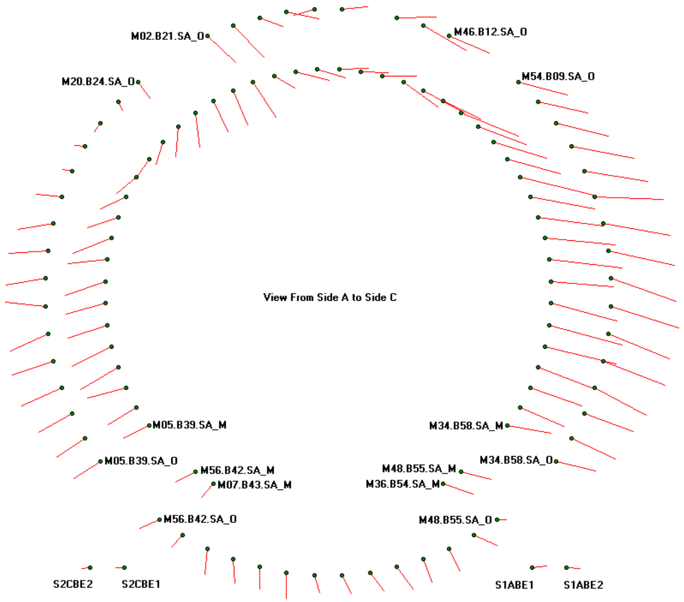
- +1.49 mm
- - 0.95 mm
- Deformation max. 0.38 mm
- Comparison on identical points

Photogrammetry: applications

Atlas Tile Barrel



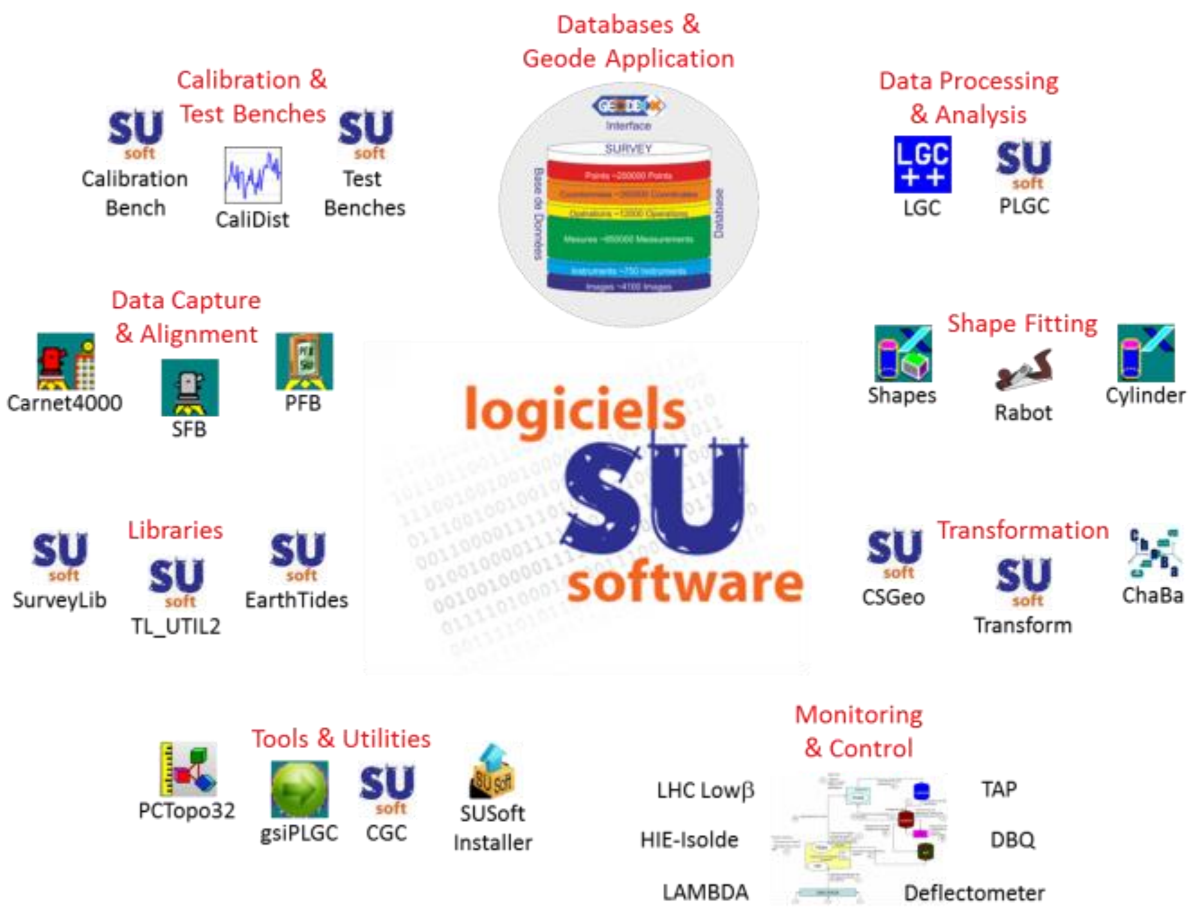
Targets on the ATLAS tile barrel



Deformations to theoretical data on the ATLAS tile barrel

- Control of assembly of 64 modules, 9 m diameter (~ 1800 tons)
- Differences/deformations to theoretical data (+- 8 mm)
- Image acquisition from scaffolding (distance < 2.0 m)
- 350 photos each side, precision 0.2 mm (1 sigma)

Software and Database Applications



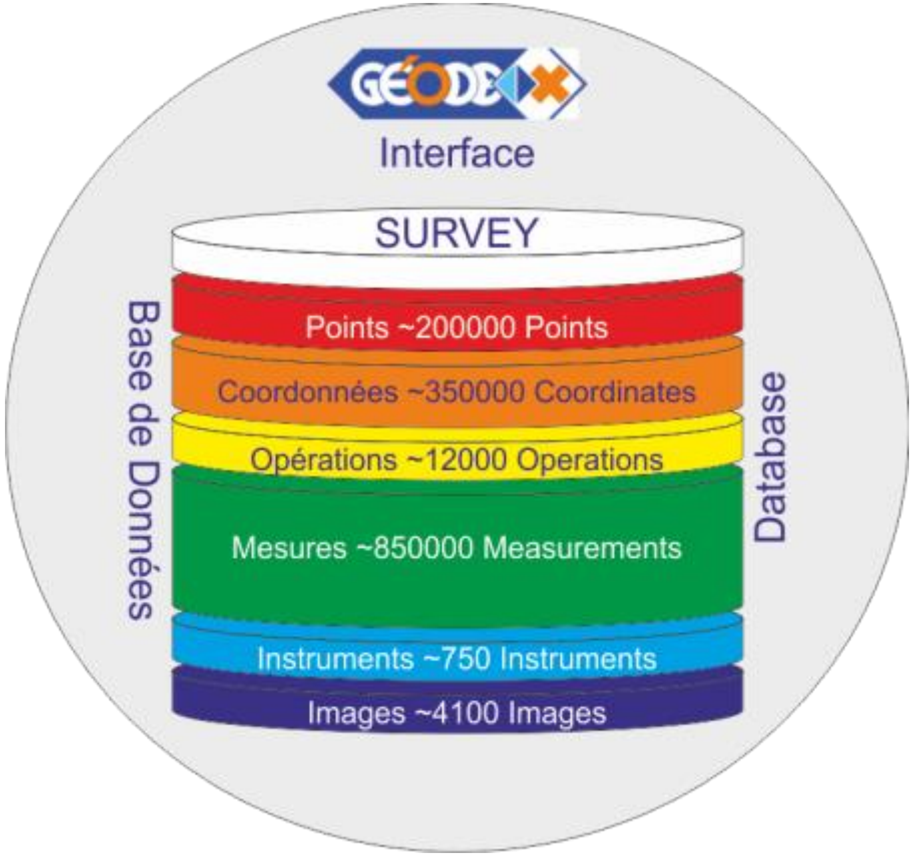
Data processing& analysis

- Local 3-D adjustment on the ellipsoid GRS80;
- Altitudes are referred to the known local geoid and are converted into ellipsoidal height;
- 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

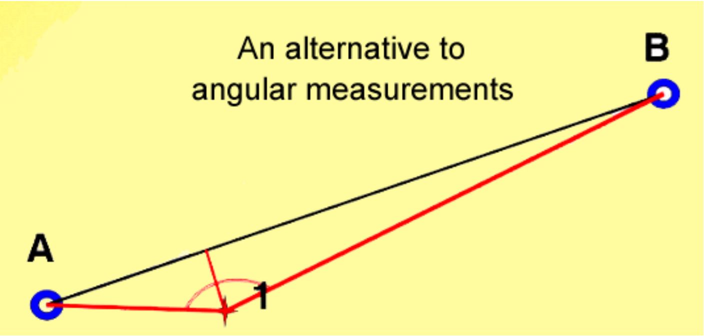
- Other Clients
  - Operators, Layout, Integration, GIS

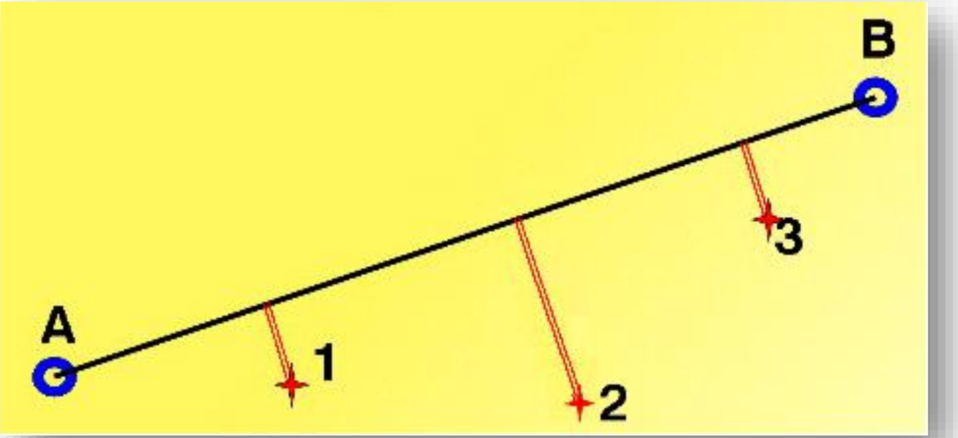


Instrumentation toolkit

- 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]

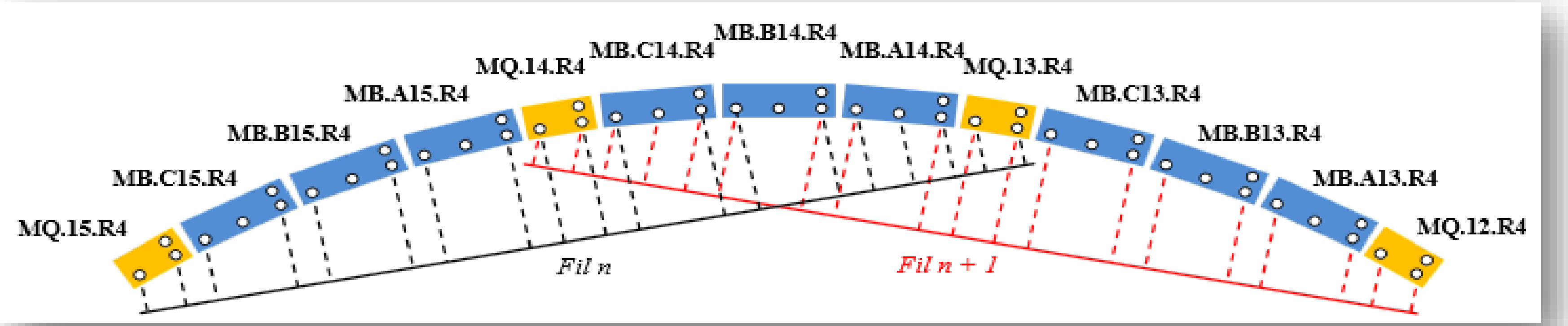
Manual device
Accuracy 0.07mm

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.

Wire offset measurement

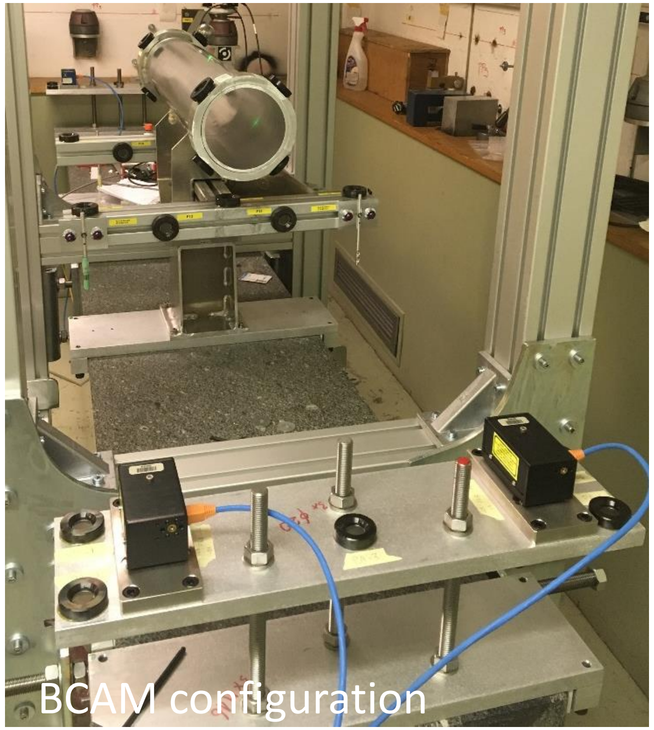


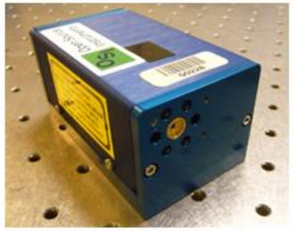
Wire measurements configuration in the LHC

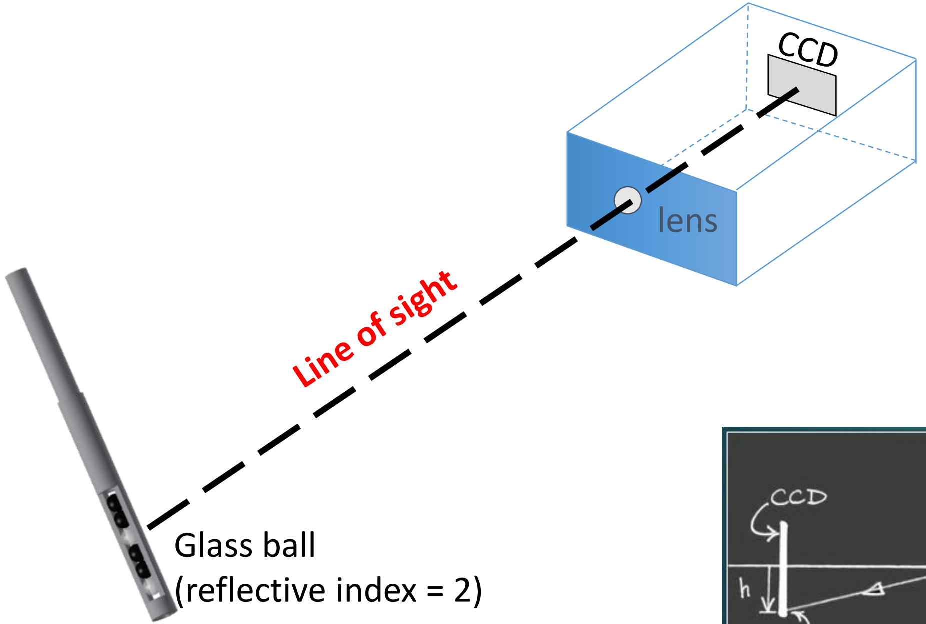
Wire offset measurement

BCAM : Brandeis Camera Angle Monitor

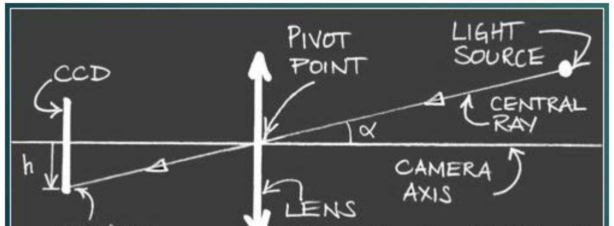
Based on image acquisition of reflective targets


BCAM configuration


BCAM



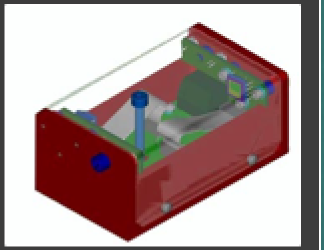
BCAM measurement concept



Images from Brandeis University

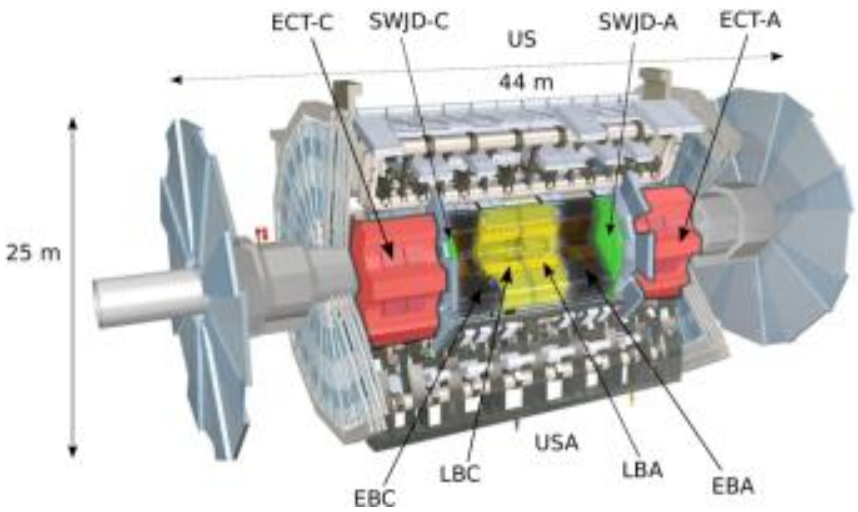
[Gayde]

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

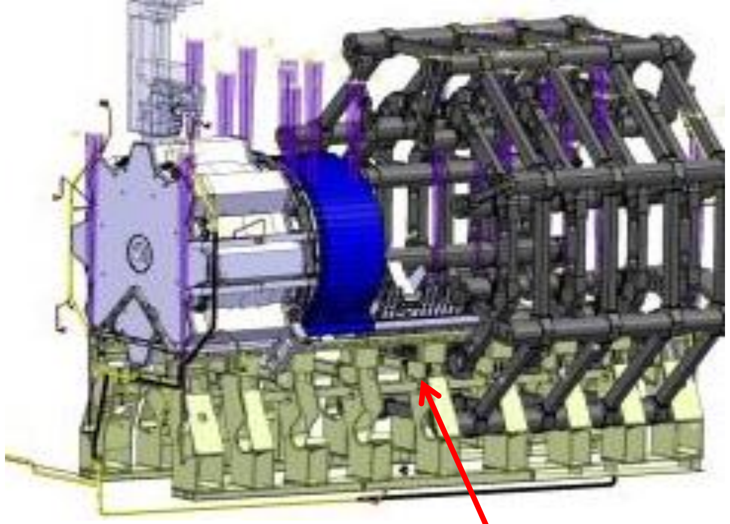


Monitoring

- To gain time
- Improve accuracy
- No access needed



ATLAS detector



BCAM implantation in ATLAS detector

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

[Gayde2]

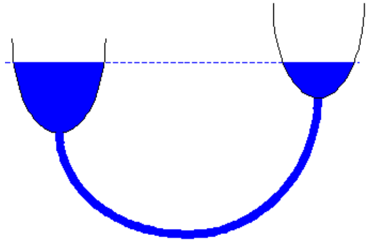
System is based on:

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

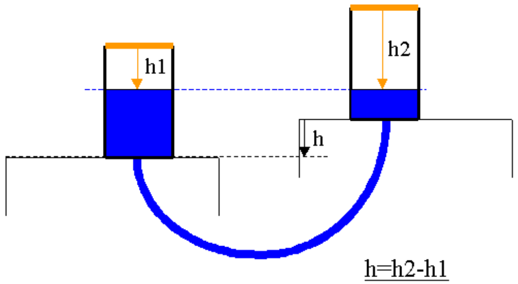
Instrumentation toolkit

- 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)



Communicating vessels



Difference of height measurement

Hydrostatic Levelling Sensor (capacitive-based)

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

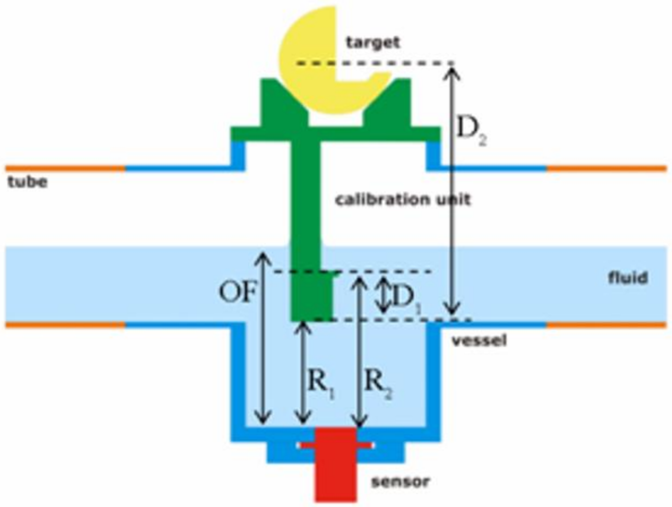
$$C = \frac{\varepsilon_o \varepsilon_r S}{d}$$

Resolution: 0.2 mm

Measurement range: 5mm

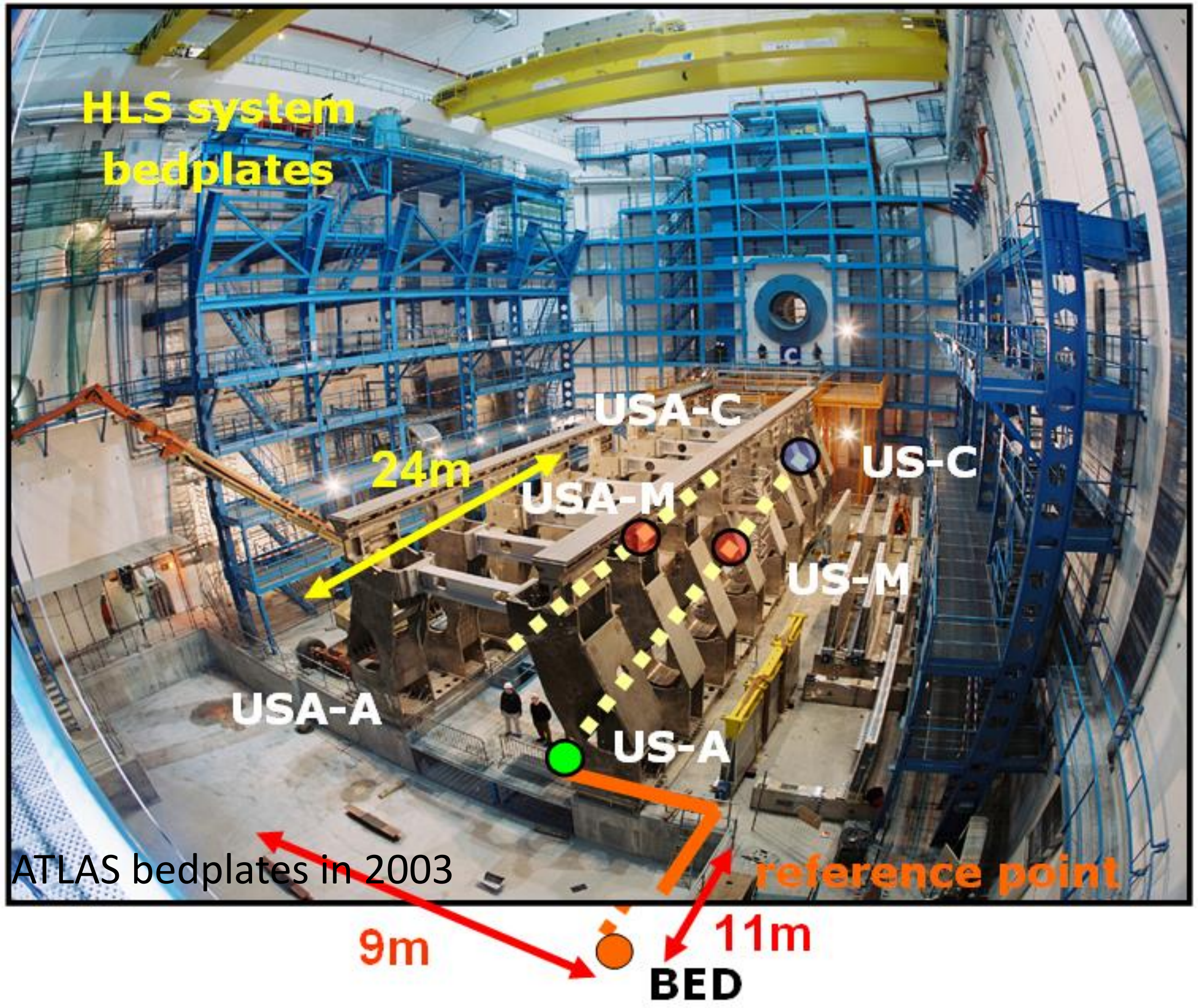
Repeatability: 1 mm

Bandwidth: 10 Hz

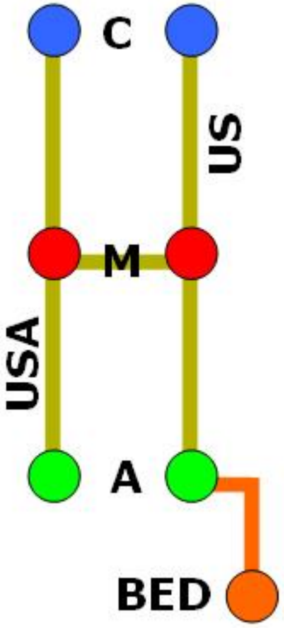


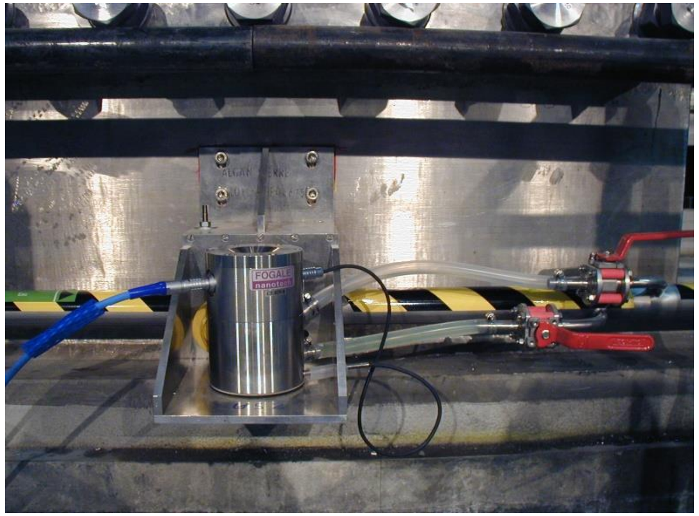
Hydrostatic Levelling Sensor (ultra sound)

HLS applications: ATLAS bedplates



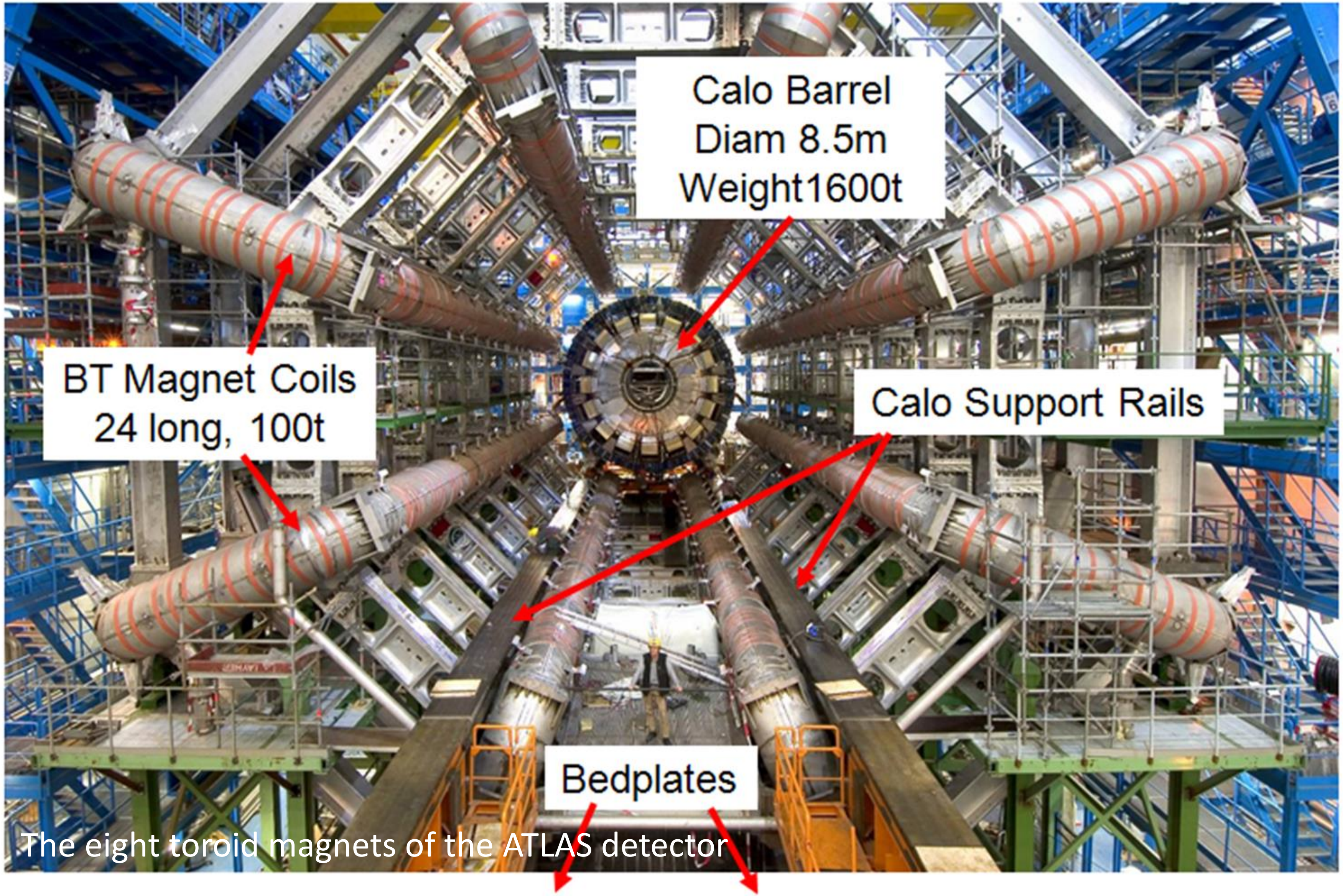
ATLAS bedplates in 2003




HLS in ATLAS bedplates

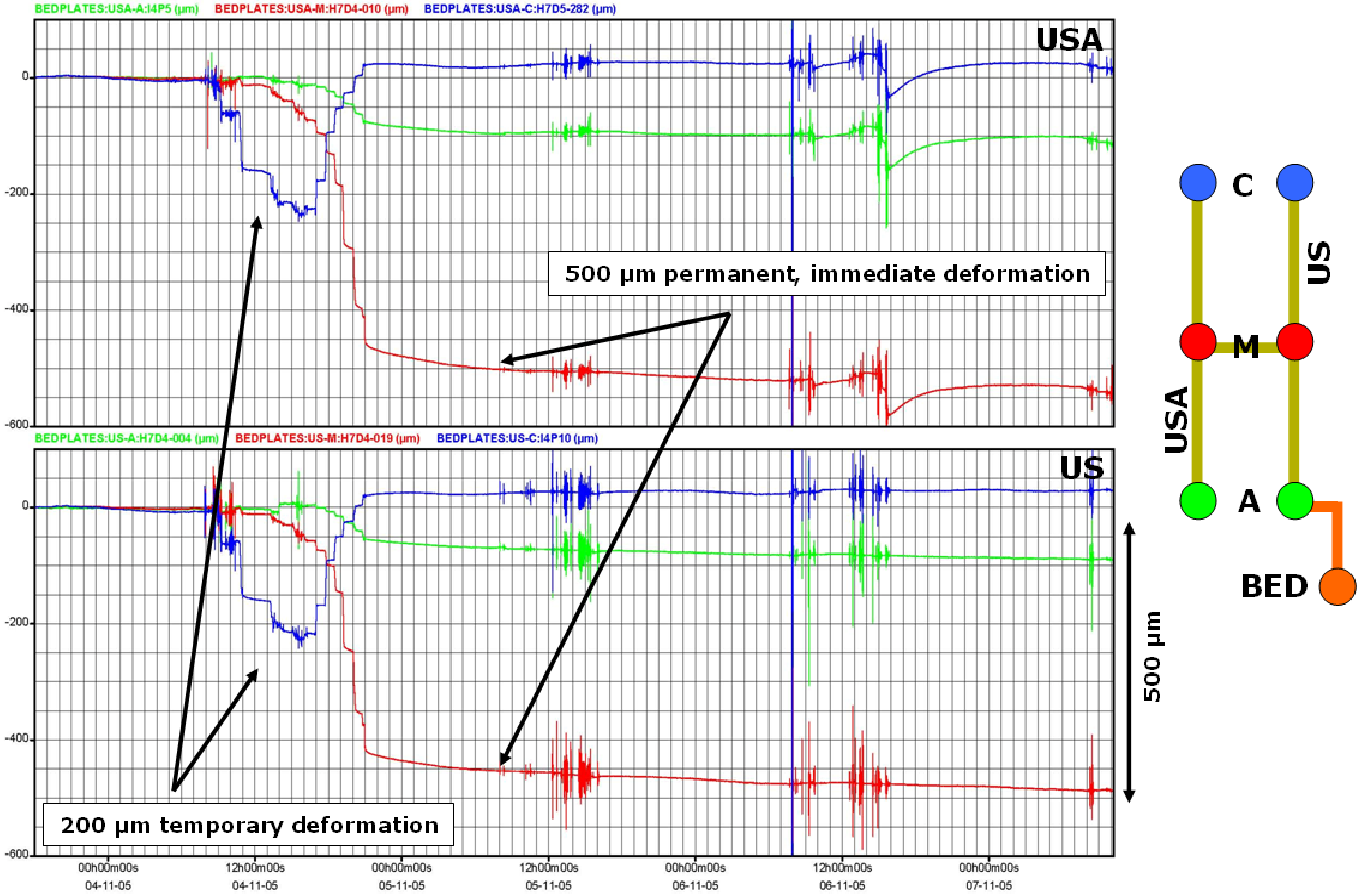

«among» ATLAS bedplates

HLS applications: ATLAS bedplates



The eight toroid magnets of the ATLAS detector

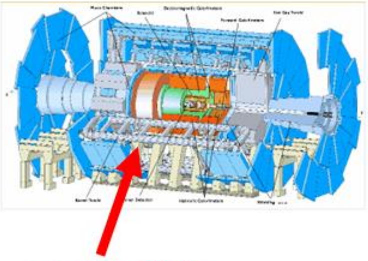
HLS applications: ATLAS bedplates

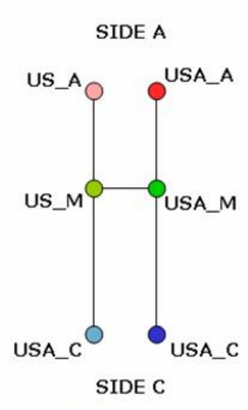


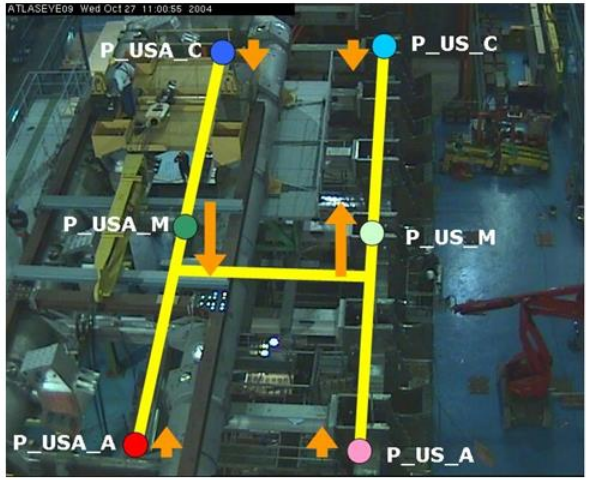
HLS measurements during the installation of the ATLAS calorimeter from C to M position

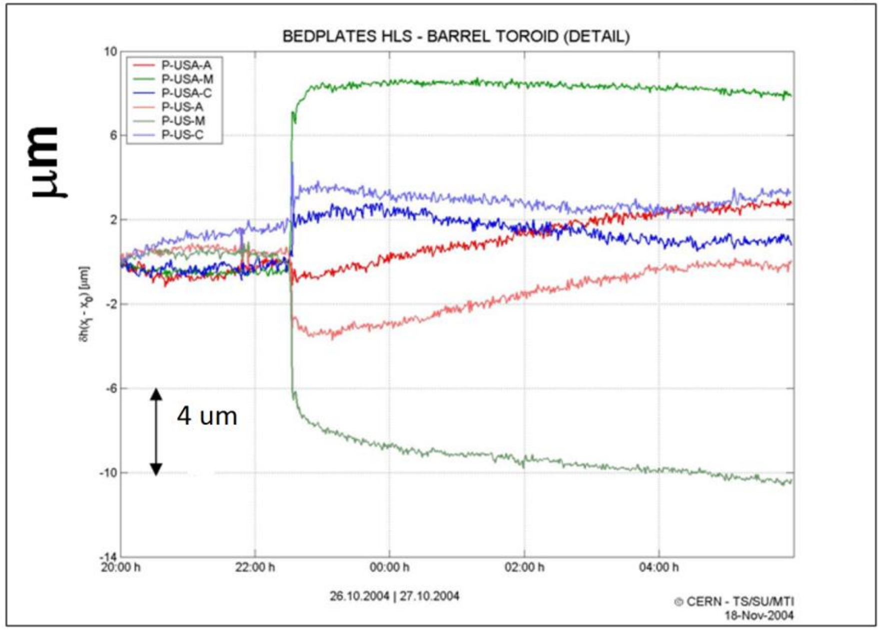
HLS applications: ATLAS bedplates

HLS MEASUREMENT – BARREL TOROID COILS INSTALLATION







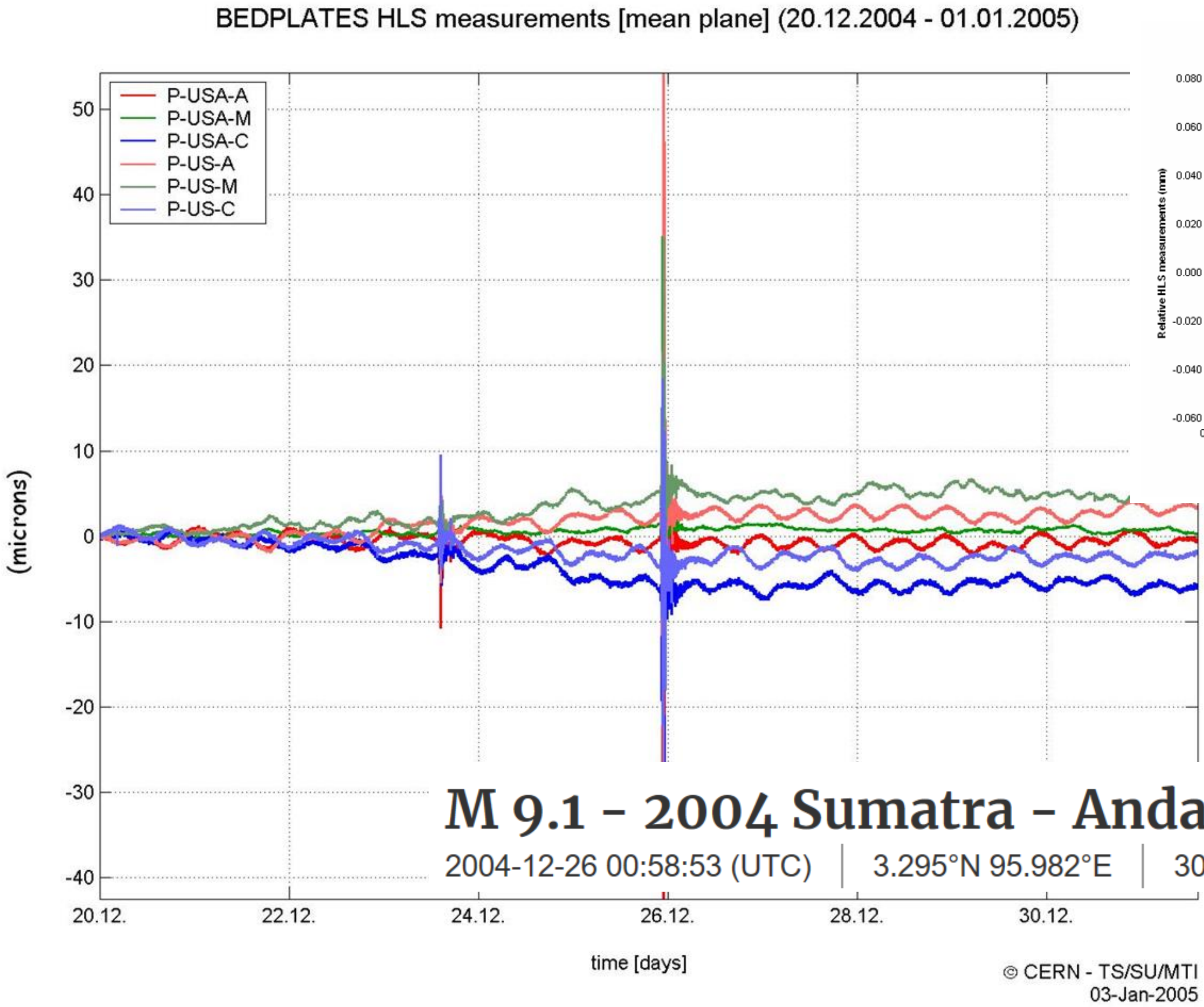


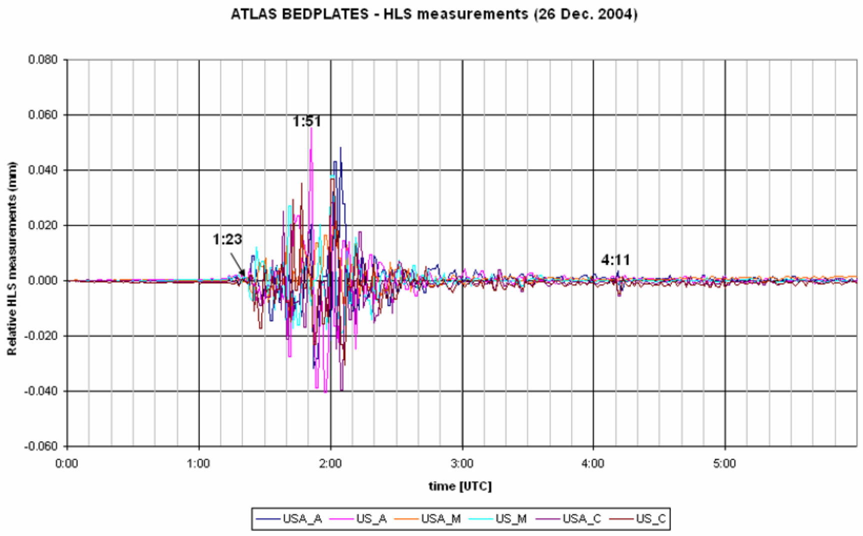
Installation of one BT coil (24m long, 100t)

…

effect on the Bedplates measured with the HLS

HLS applications: ATLAS bedplates

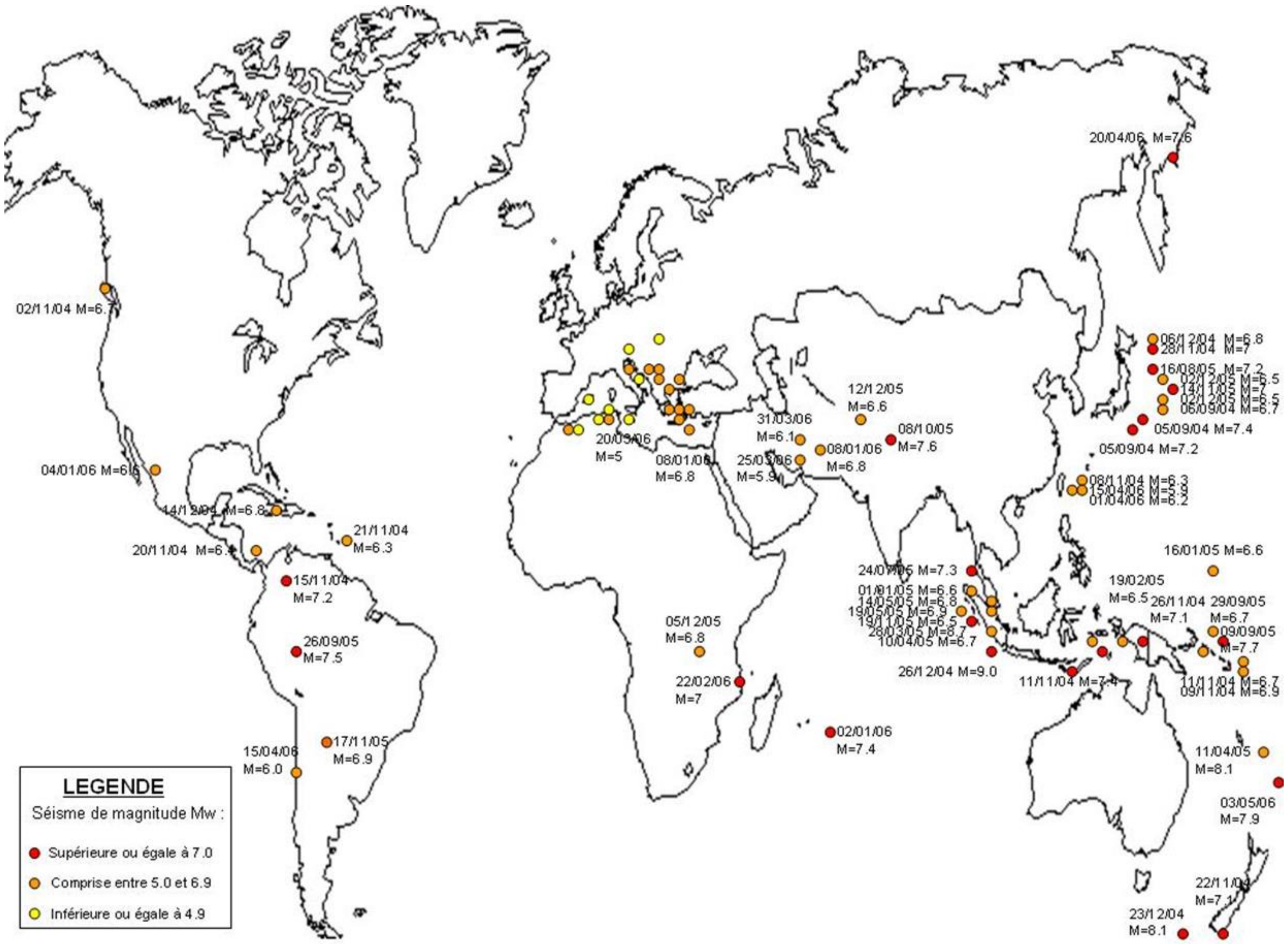




M 9.1 - 2004 Sumatra - Andaman Islands Earthquake

2004-12-26 00:58:53 (UTC) | 3.295°N 95.982°E | 30.0 km depth

Earthquakes «seen» by HLS sensors at CERN in 2005



Instrumentation toolkit

- Determination of the position
  - Standard instruments
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    - Wire offsets
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    - Hydrostatic Levelling System (HLS) & applications
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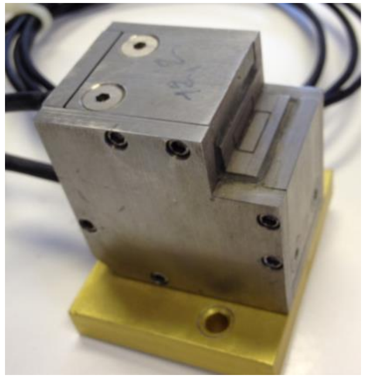
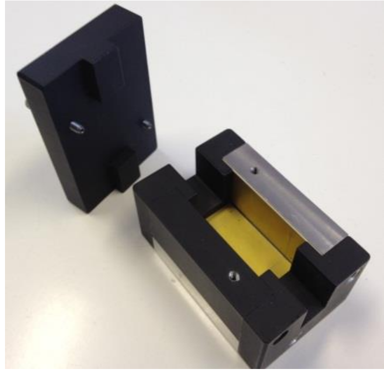
Wire positioning System (WPS)

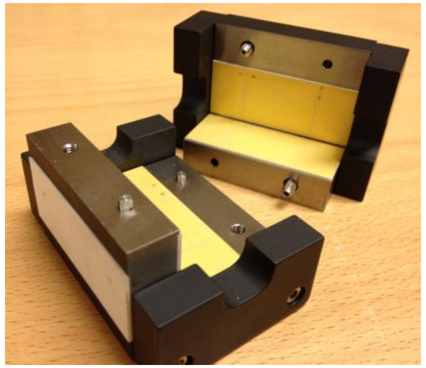
Prototype (1990)



Version 1 in 1994

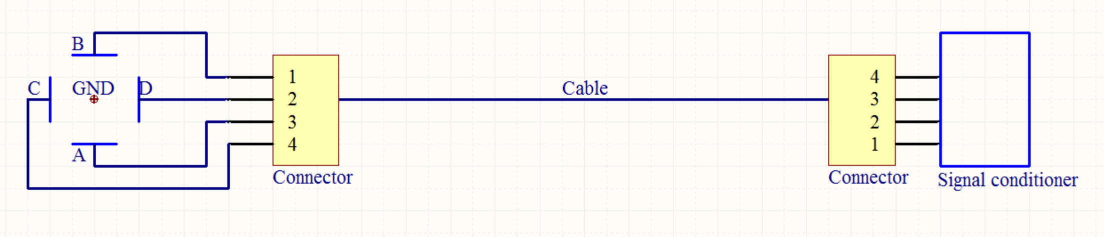


Version 2 in 2000



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 measurement chain

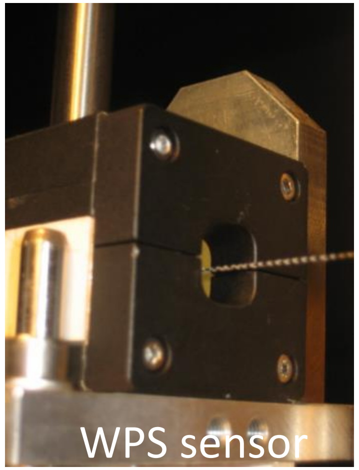
WPS: associated wire

Carbon Kevlar

Carbon PEEK/PES

Zoom on carbon Kevlar wire

Wire reel



WPS sensor

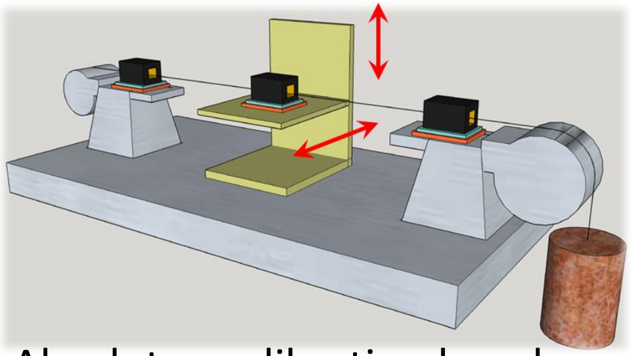
Carbon peek wire:

- 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

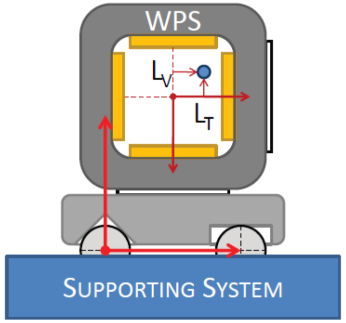
WPS performances



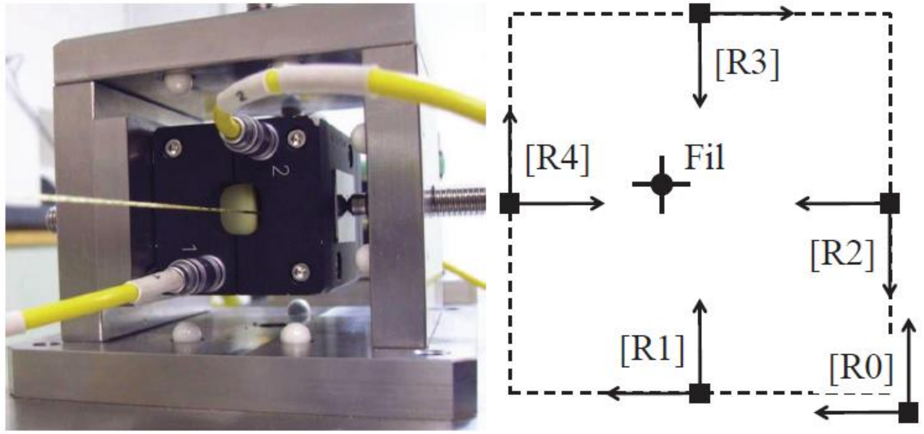
«Absolute» calibration bench

Voltage: 0-10 V

Full Range : +/- 5 mm



WPS kinematic supporting system



Zoom on «Absolute» calibration bench

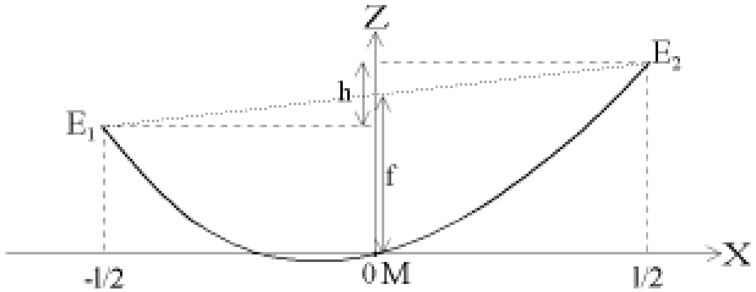
CERN

Repeatability : +/- 1 µm (1σ)

Linearity : 2 µm / mm (1σ)

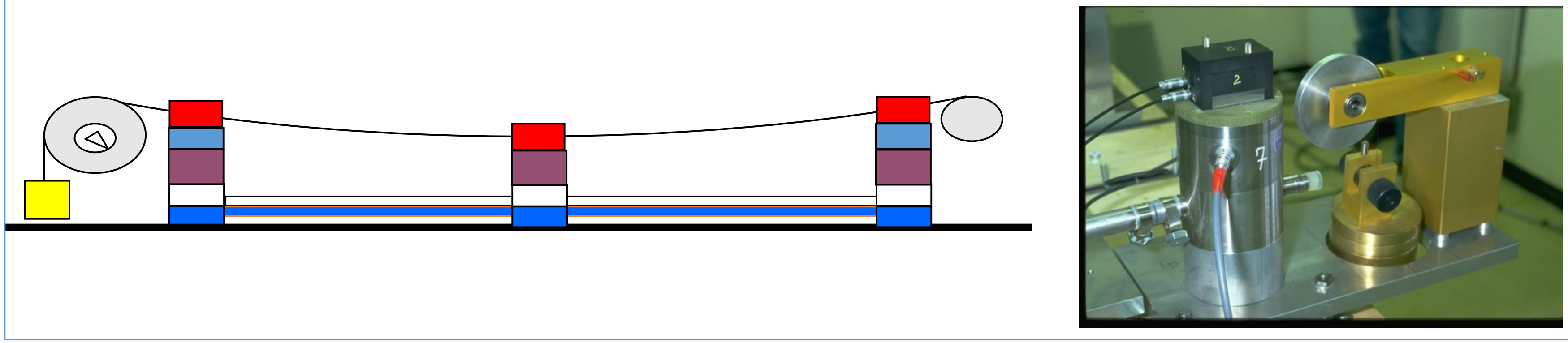
Accuracy : 5 µm (1σ)

WPS: impact of sag



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

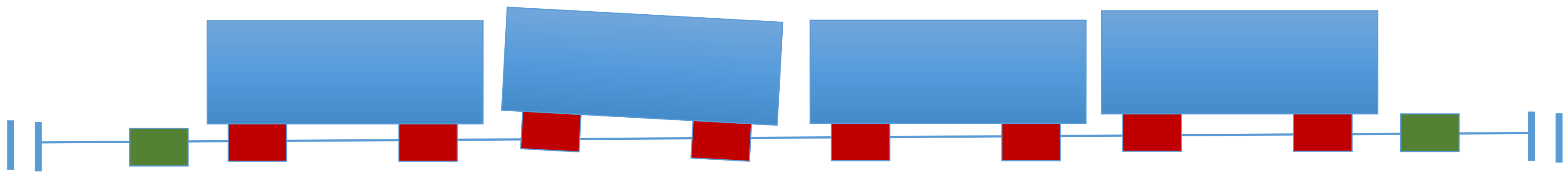
Catenary of a wire



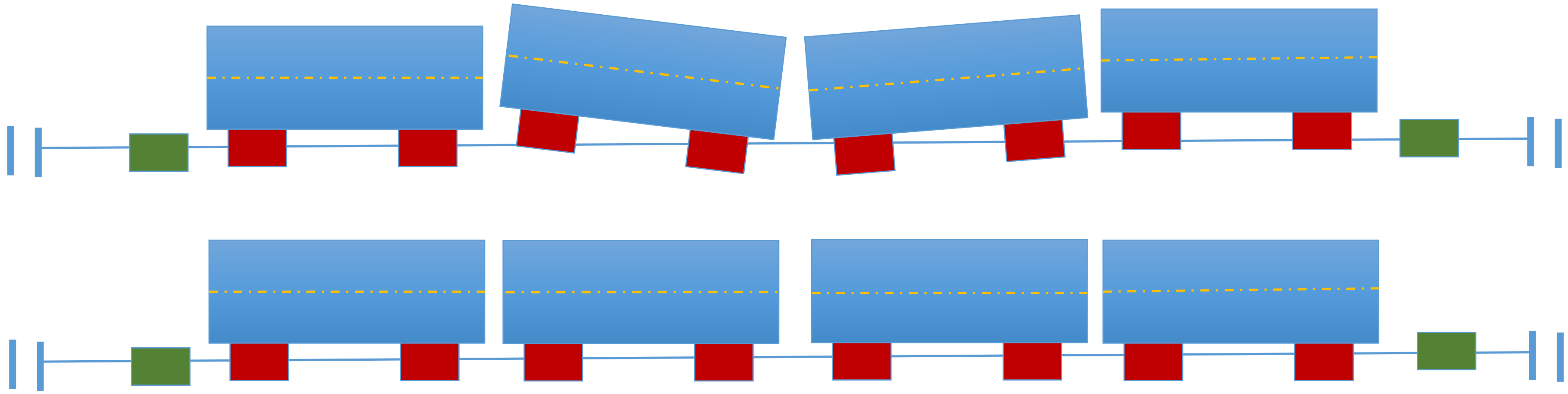
Determination of the wire sag using a superposition of HLS and WPS sensors

WPS: two configurations

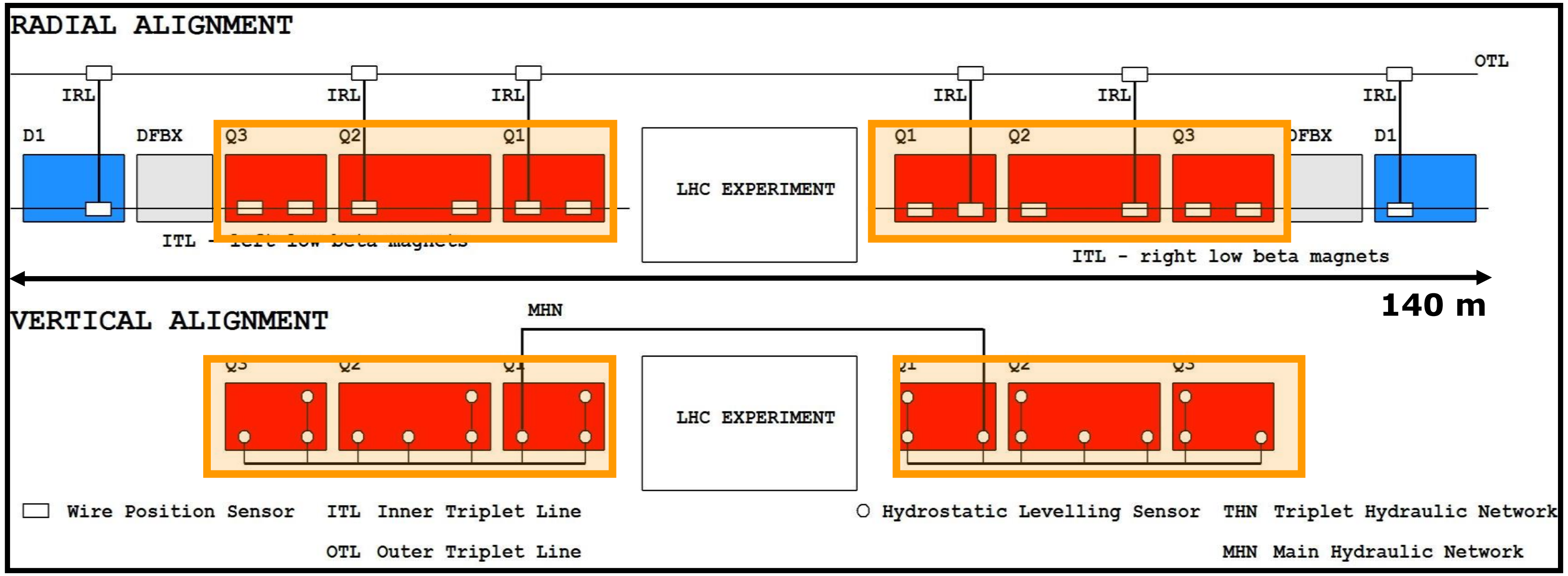
"Relative" alignment (monitoring)



"Absolute" alignment (pre-alignment)

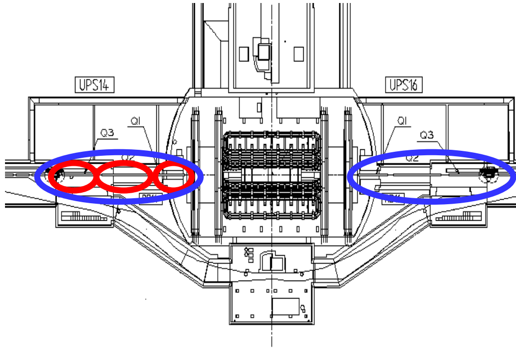


WPS & HLS: alignment of LHC inner triplets

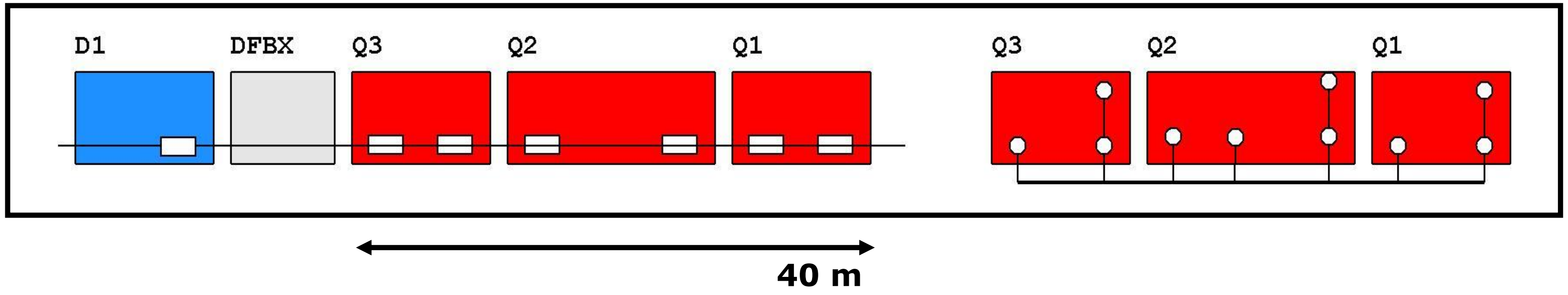


Sensors configuration on inner triplets

low beta triplet



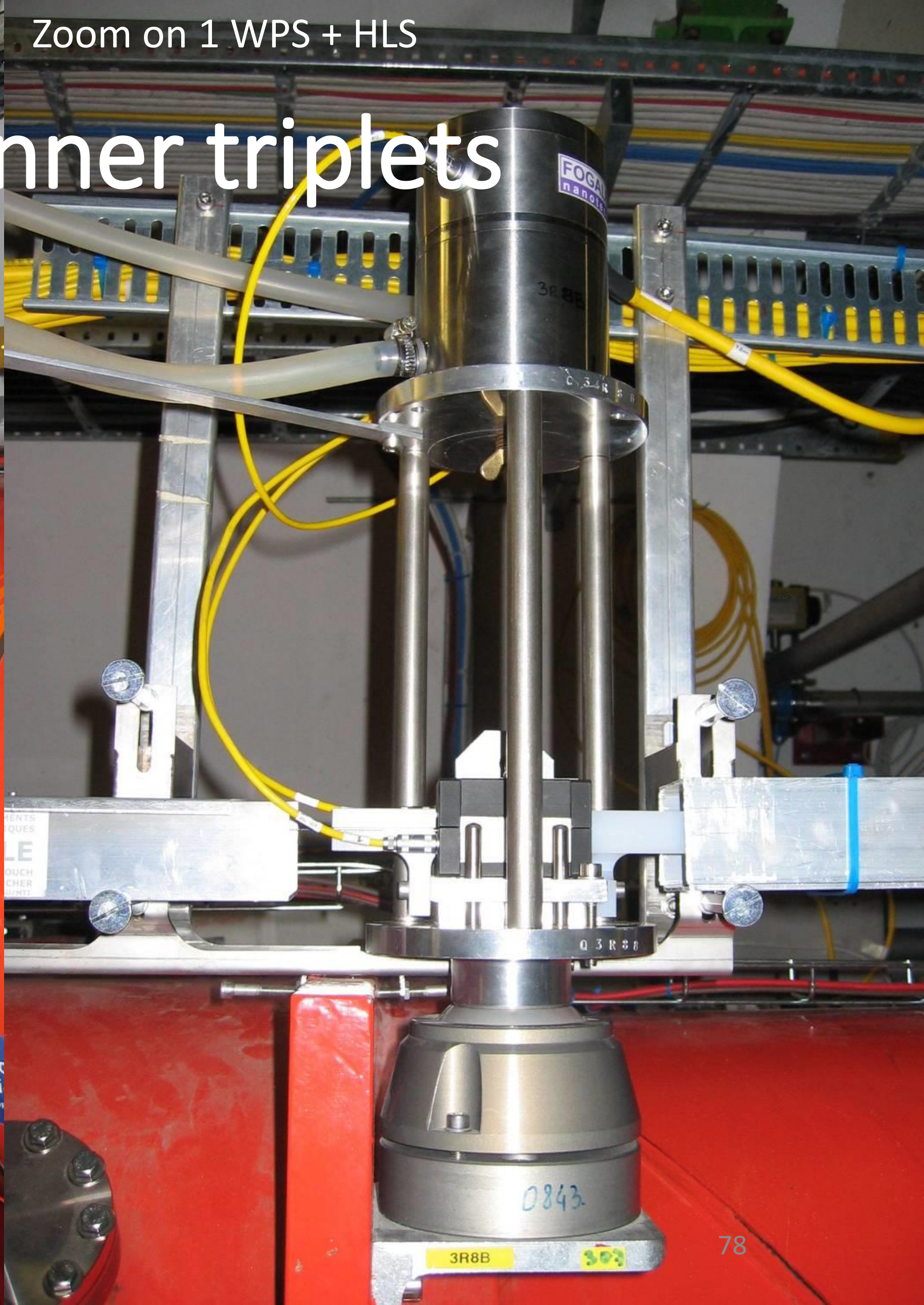
Location of inner triplets



Courtesy of A. Herty

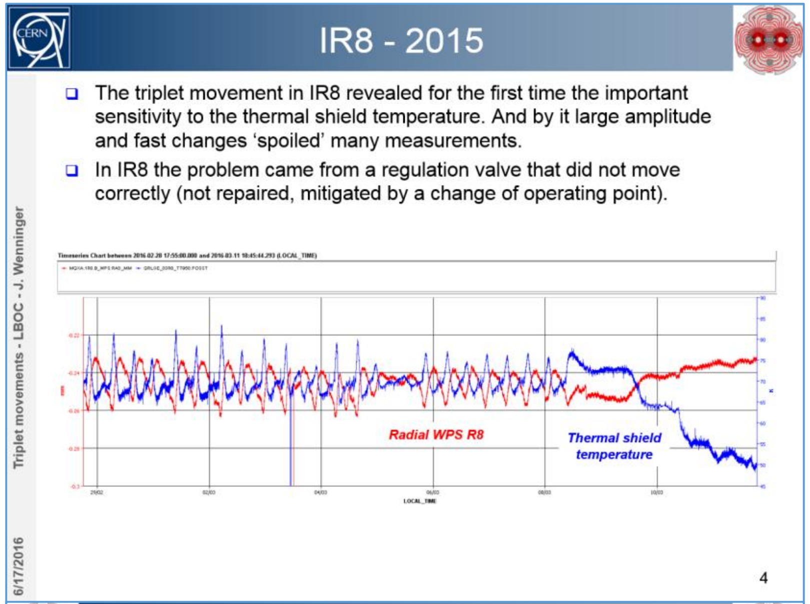
WPS & HLS: alignment of LHC inner triplets

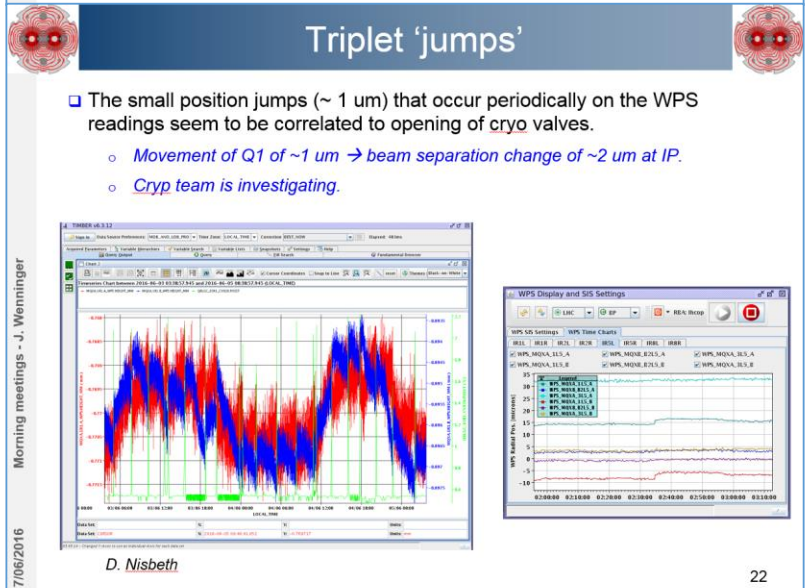
LHC inner triplet with alignment sensors and motorized jacks

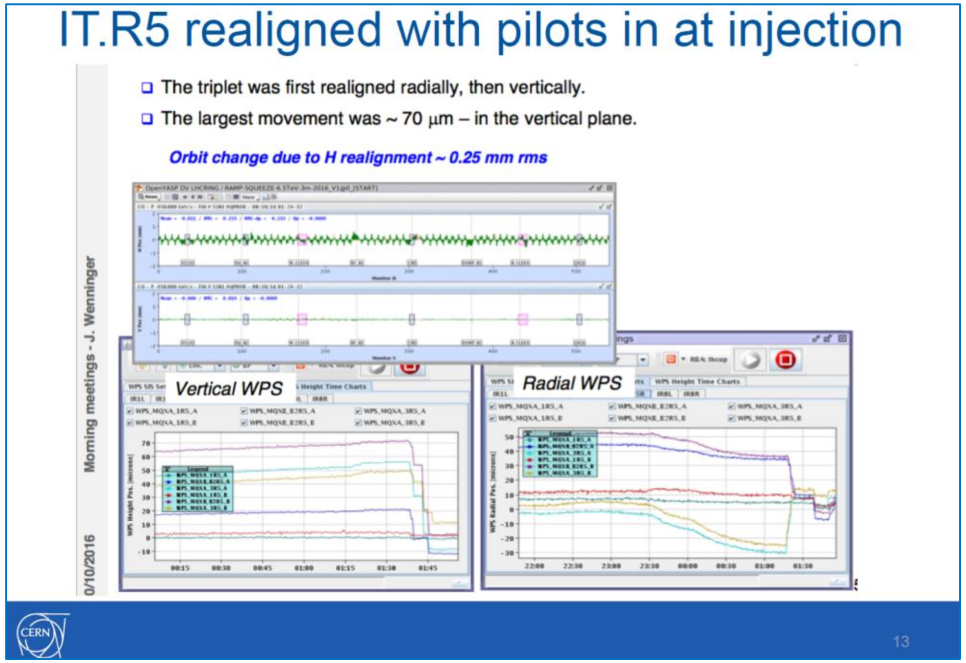


Zoom on 1 WPS + HLS

WPS & HLS: Alignment of LHC inner triplets







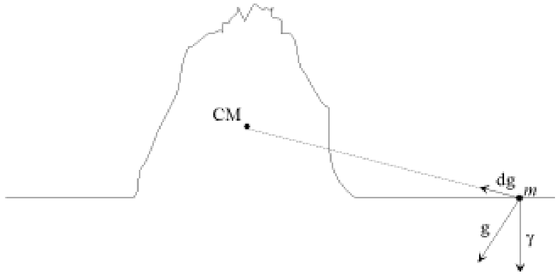
- LHC sensors readings under the spot line: used by OP to have a better understanding of the displacements observed on the beam
- Triplet 5R realigned with pilot beam on. First time in the world !!!

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

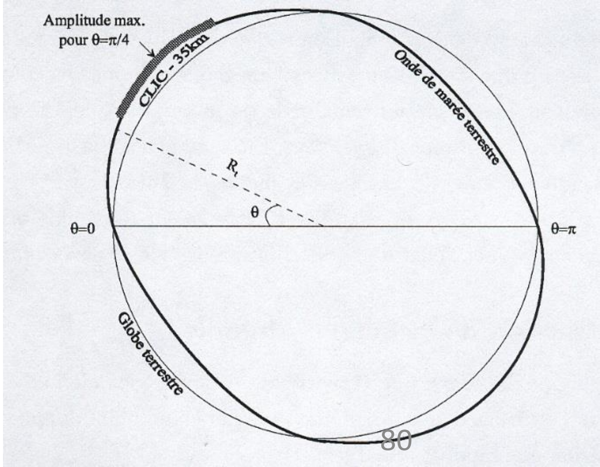


Maxi. deviation of the vertical: 15" at CERN

- ✓ 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

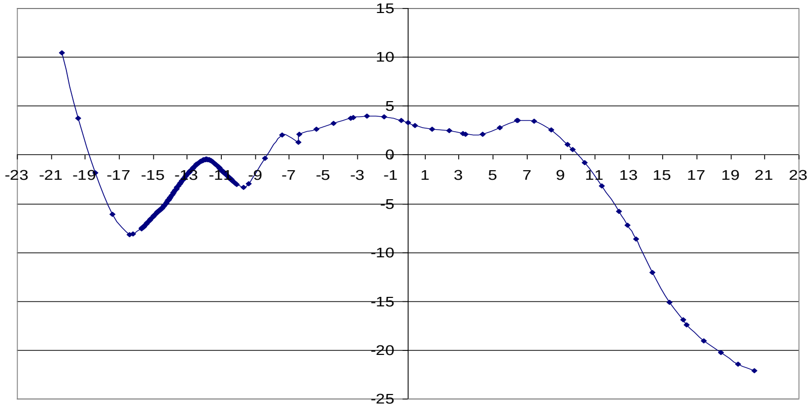
Impact on WPS system:

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].** **[CLIC Note]**

Study case

What would you suggest as an alignment strategy for :

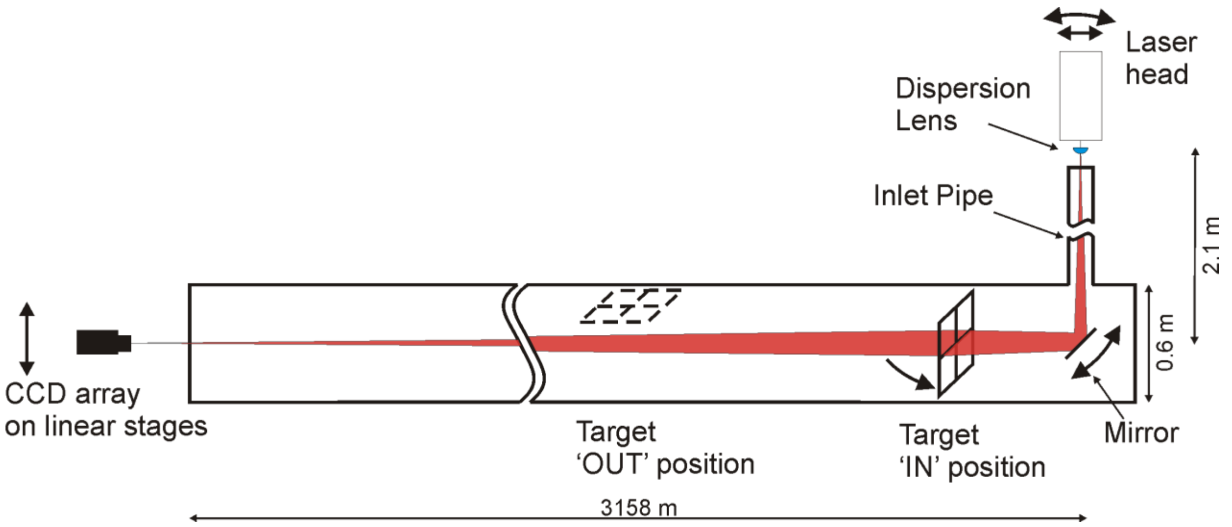
- Case 1:
  - A linac of 10 m,
  - Six 1 m long RF cavities,
  - Tolerance of alignment (1σ) of their mechanical axis: 0.2 mm

- Case 2:
  - A linac of 100 m,
  - 80 different components (quadrupoles, sextupoles, RF cavities),
  - Tolerance of alignment (1σ) of their reference axis: 0.2 mm

Instrumentation toolkit

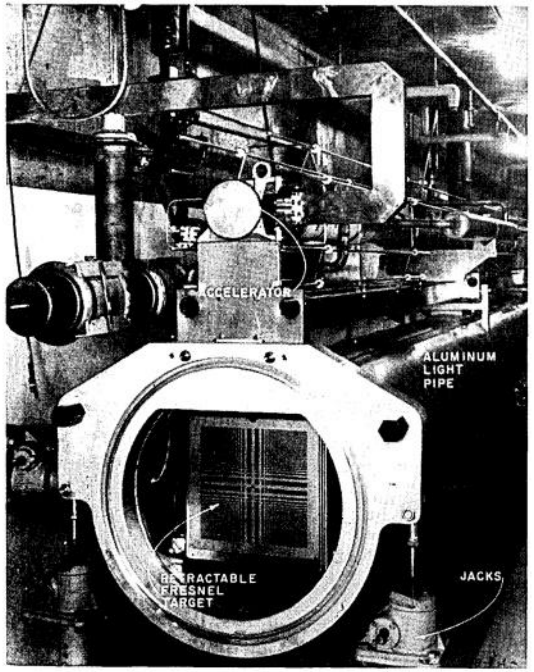
- Determination of the position
  - Standard instruments
  - Specific alignment systems
    - Wire offsets
    - Hydrostatic Levelling System (HLS) & applications
    - Wire Positioning System (WPS) & applications
    - Drawbacks of WPS & HLS
    - Laser based alignment systems
- Adjustment

Observing diffraction pattern of Fresnel zones plates (SLAC)

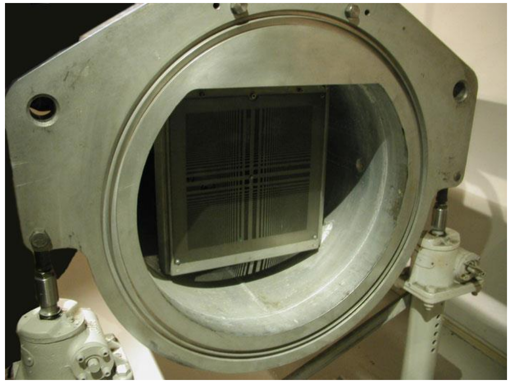


Fresnel Zone plates configuration (SLAC)

[Herrmannsfeldt]

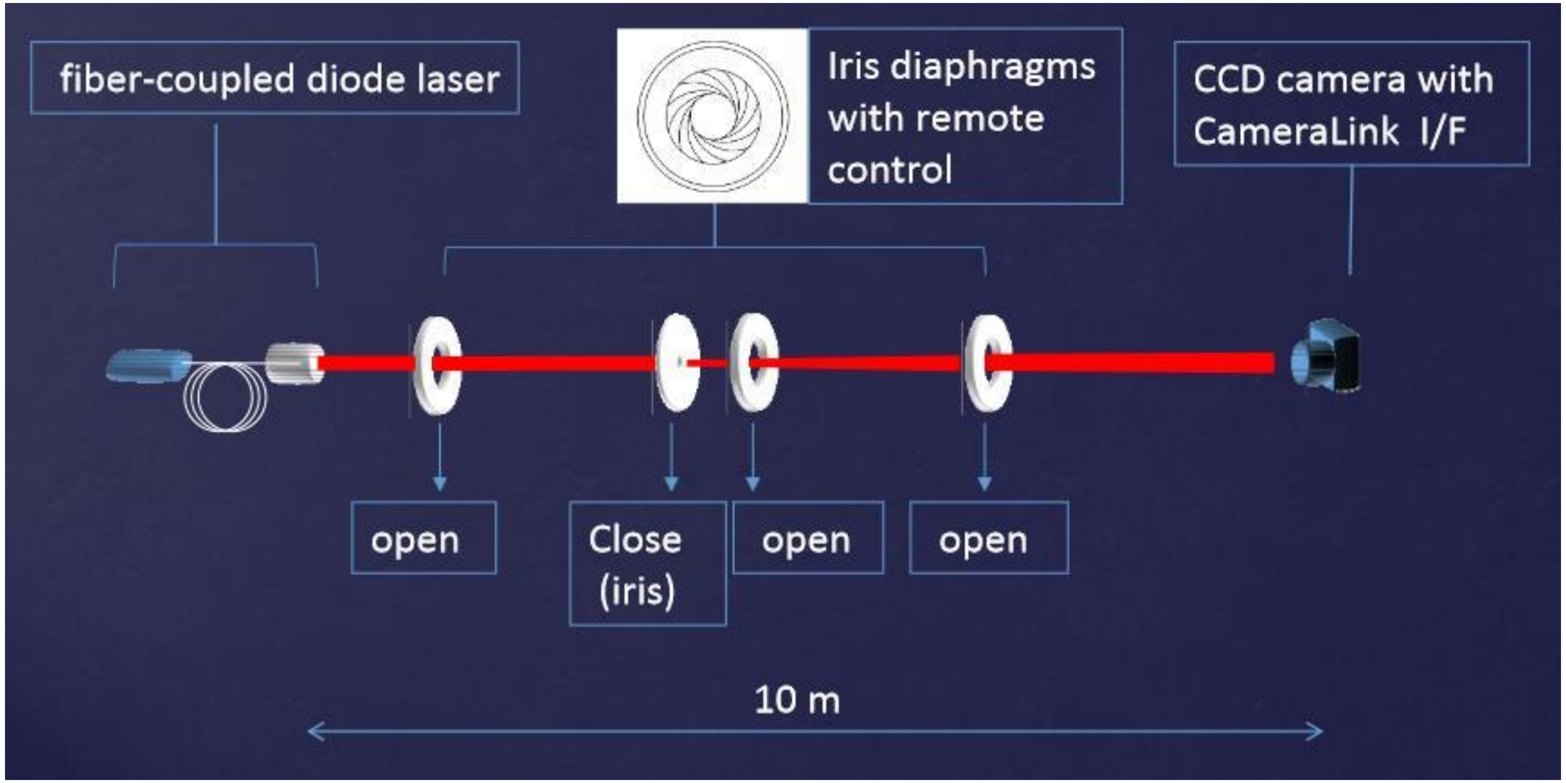


Advantages	Drawbacks
Large number of targets (~300)	Repositioning of targets
Rad-hard	Non compact targets



Fresnel Zone plate (SLAC)

Observing diffraction pattern of an iris (Spring 8)

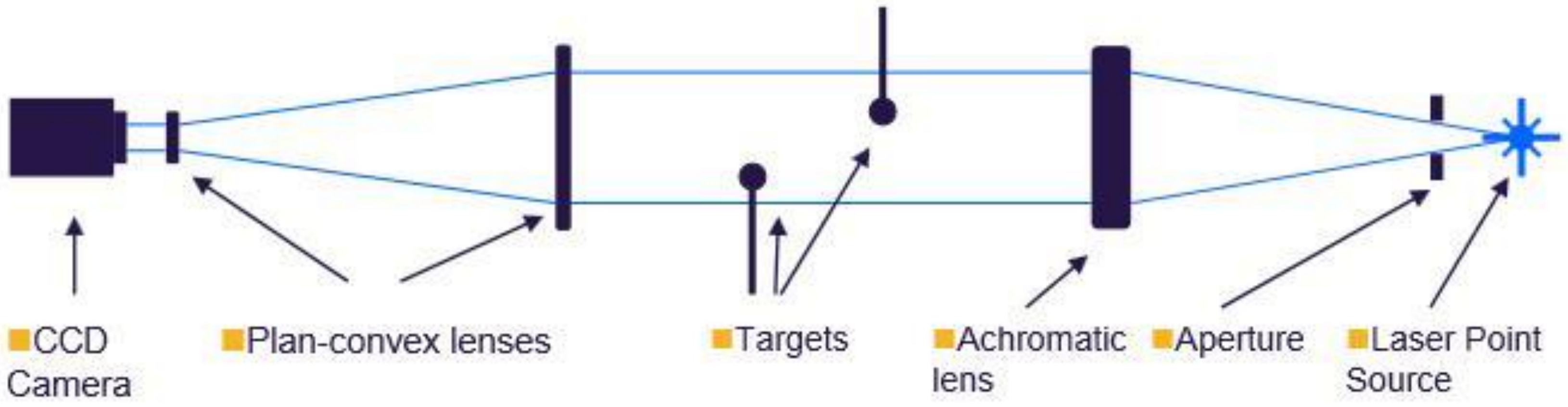


[Zhang]

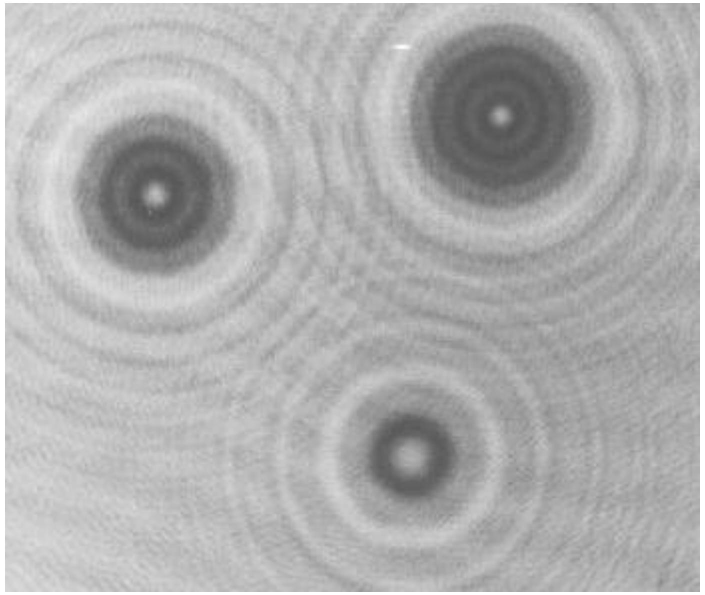
Iris diffraction pattern based alignment

Advantages	Drawbacks
Static targets	Measurement uncertainty depends on longitudinal position

Observing diffraction pattern of spheres (DESY)



«poisson» measurement concept (DESY)

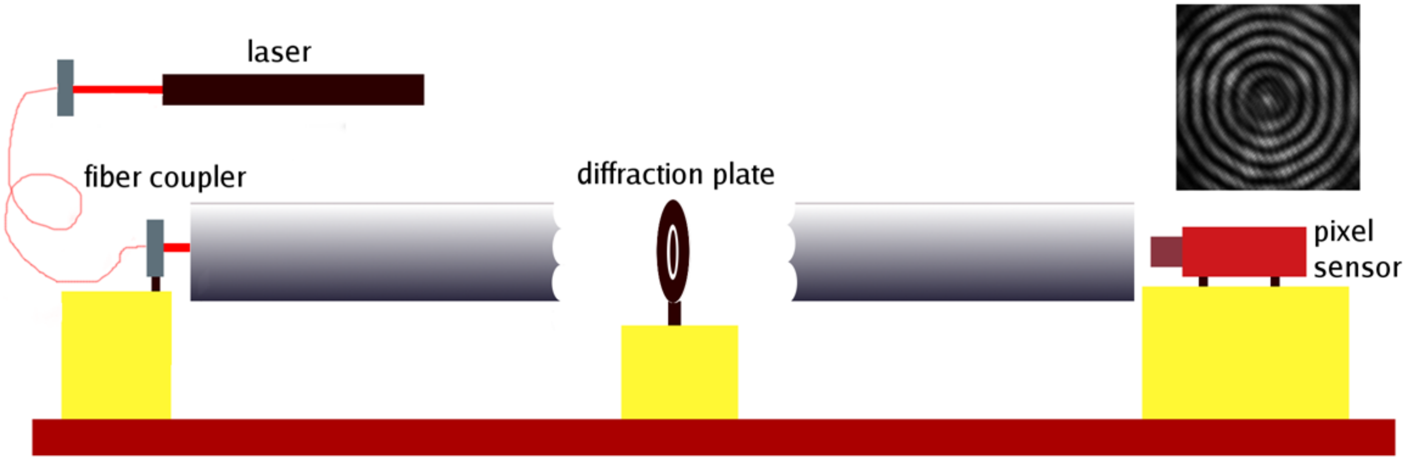


Diffraction pattern of spheres (DESY)

[Prenting]

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

Observing diffraction pattern of a plate (NIKHEF)

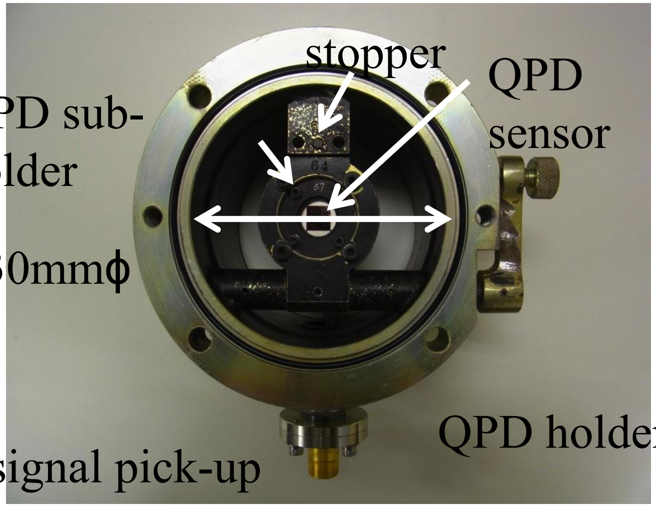


[Van der Graaf]

Optical Alignment System from NIKHEF concept

Advantages	Drawbacks
Static plate	Only 1 target

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



QPD picture (KEK)

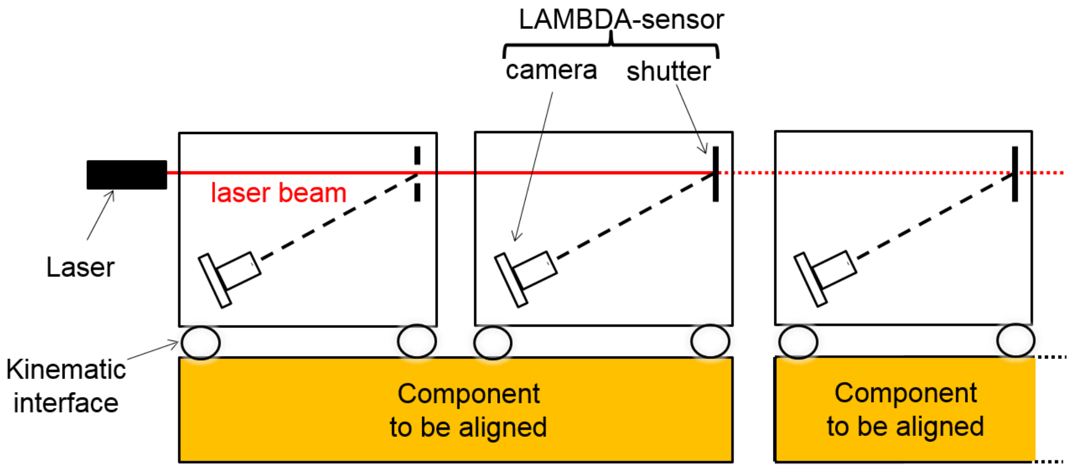
QPD: quadrant photo-detectors

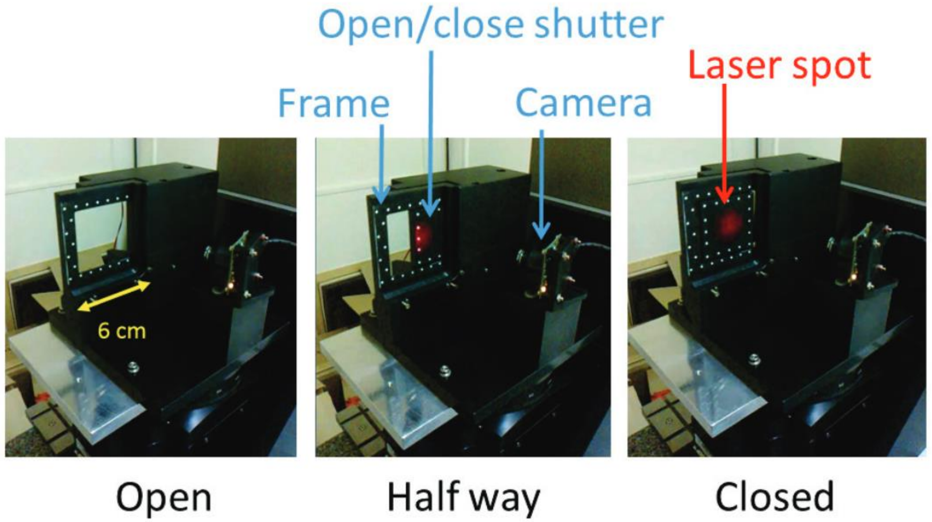
[Suwada]

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

Laser based system

LAMBDA project: principle





Open and close shutter (CERN)

[Stern]

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

Comparison of several laser based alignment systems

		Requested 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

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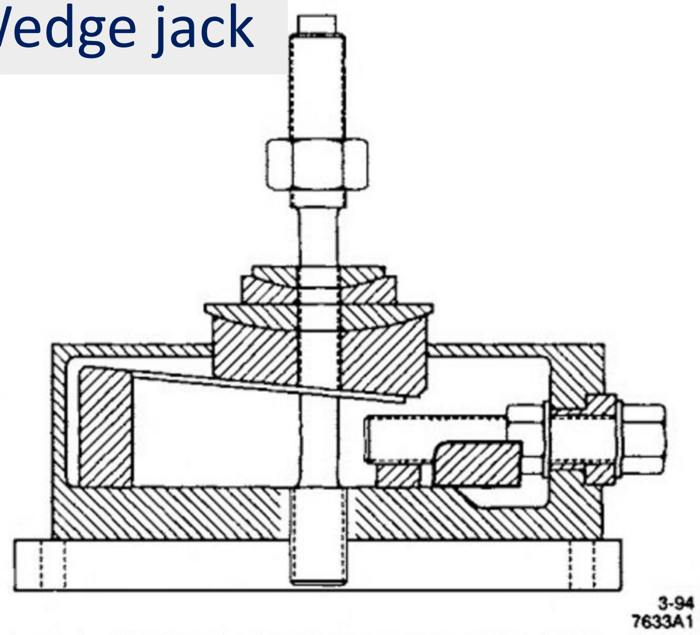
Standard means of adjustment

Wedge jack

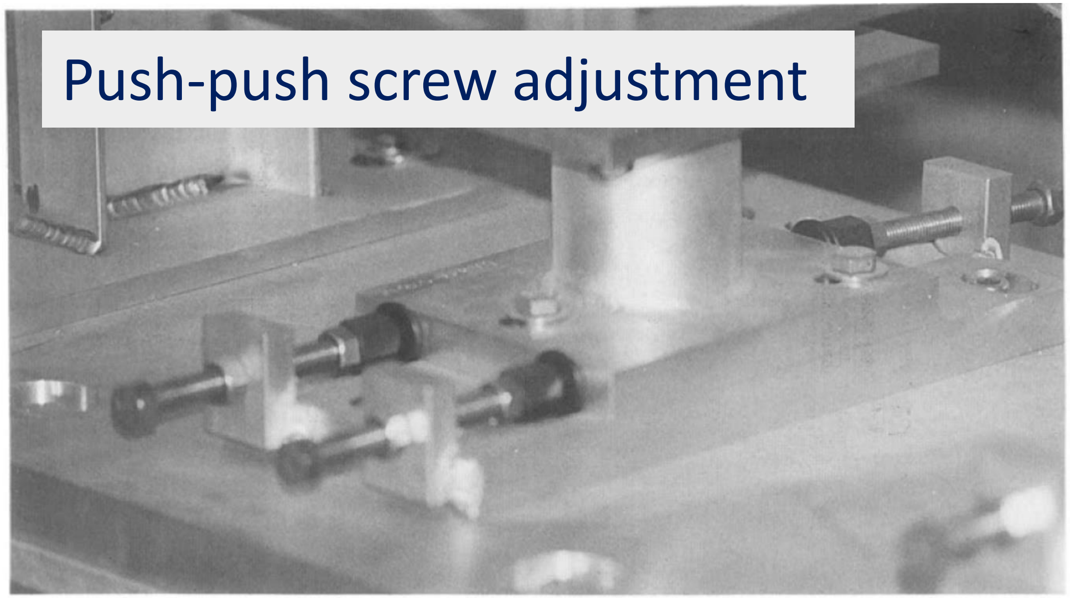


Wedge jack adjuster as used in APS.

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

[Ruland2]

Push-push screw adjustment

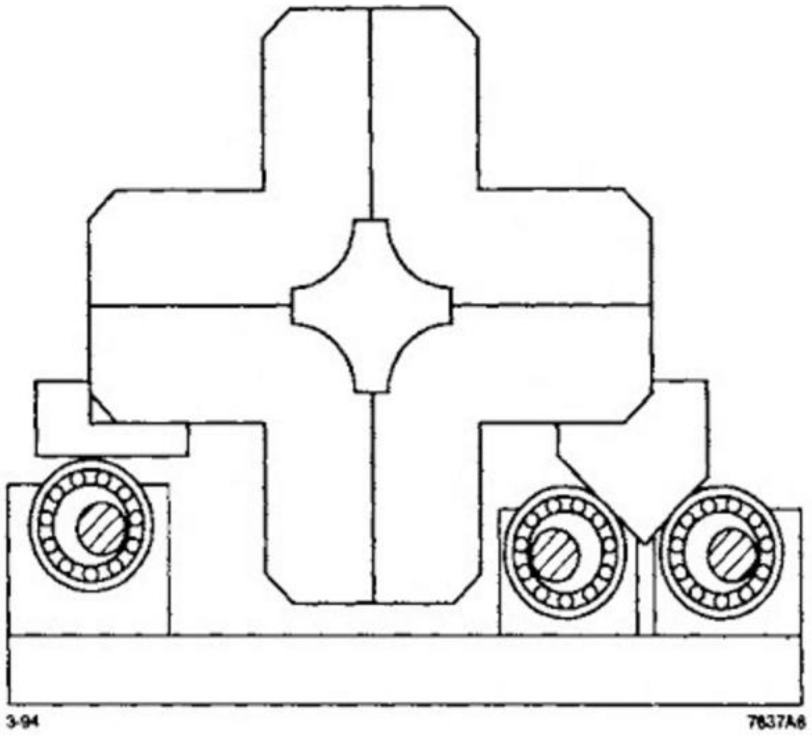


Push-push screw arrangement.

- 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.

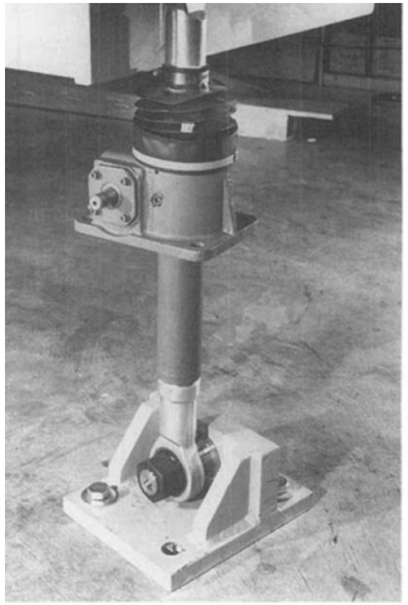
Standard means of adjustment

Roller cams

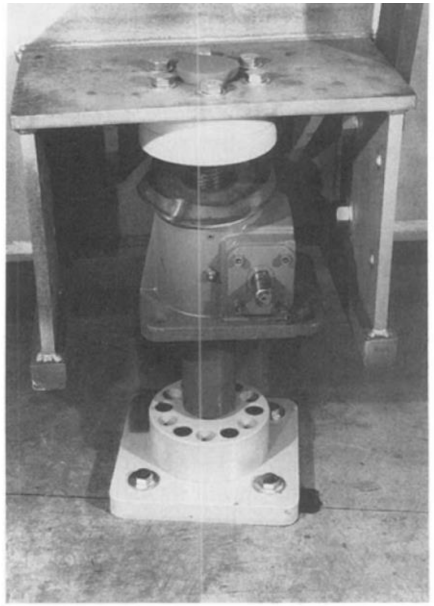


Magnet positioning mount with roller cams.

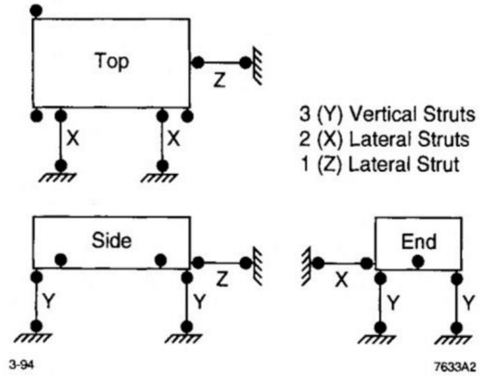
Struts



ALS 5-ton machine screw jack strut.



ALS 20-ton machine screw jack strut.



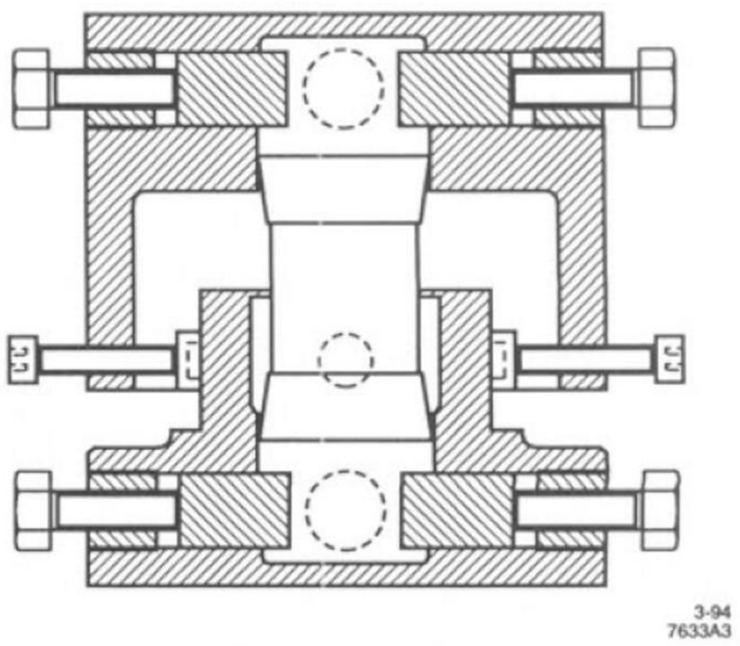
Kinematic suspension.

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

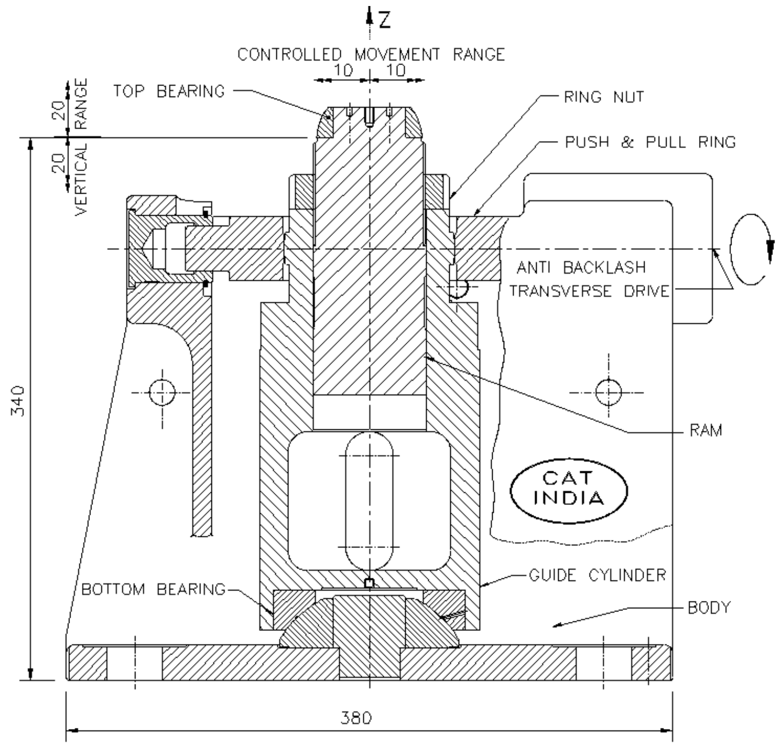
[Ruland2]

Standard means of adjustment

Polyurethane jack



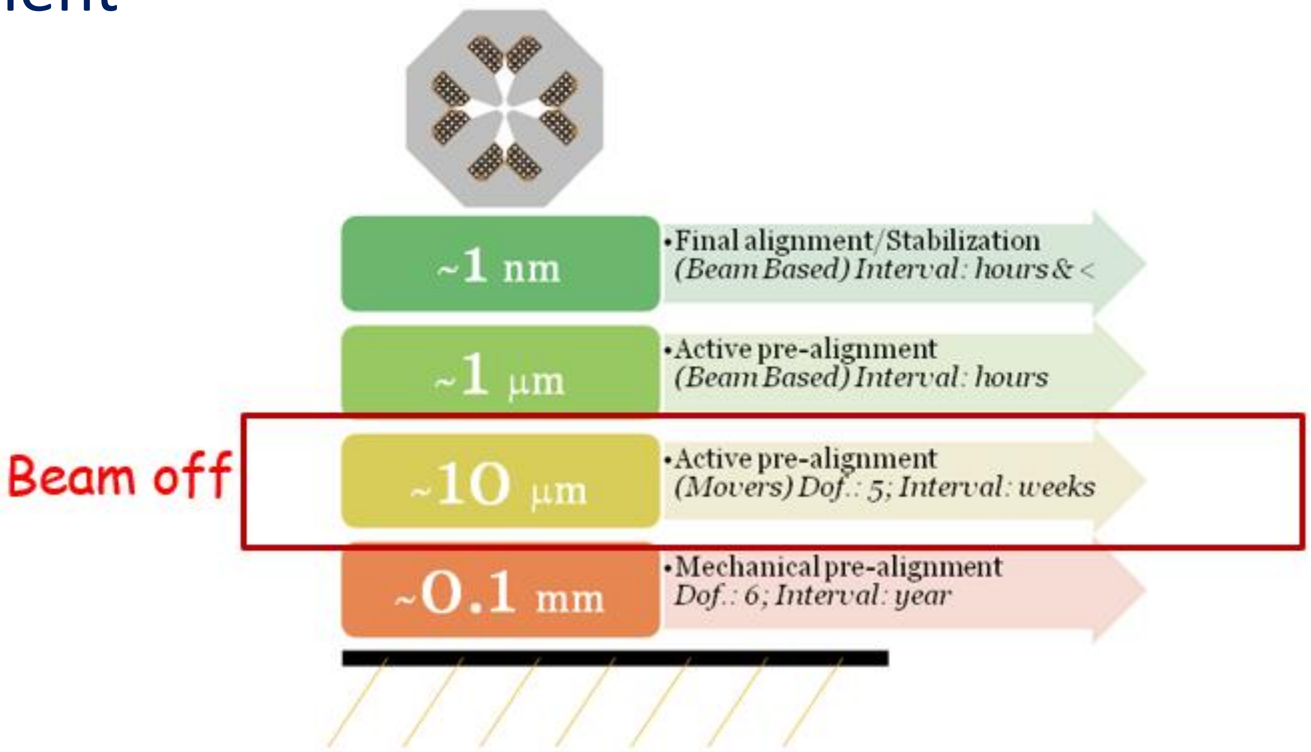
«Indian» LHC jack



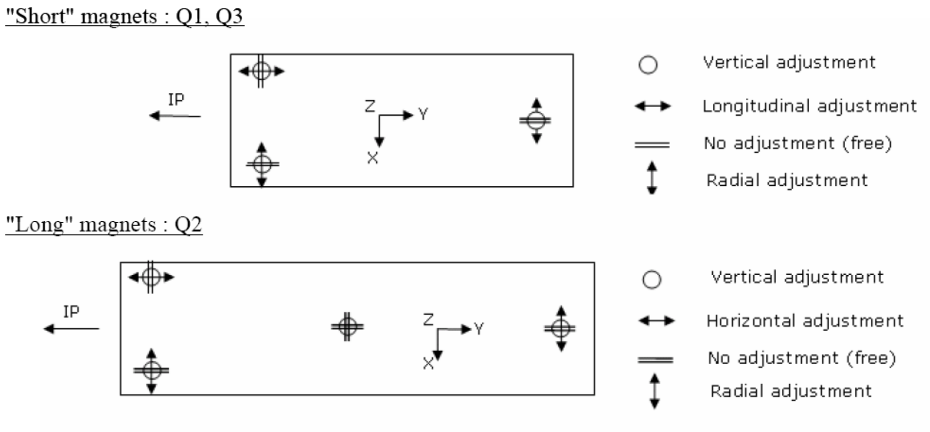
Motorized jacks

Different cases:

- Remote alignment in severe environment
- Active pre-alignment

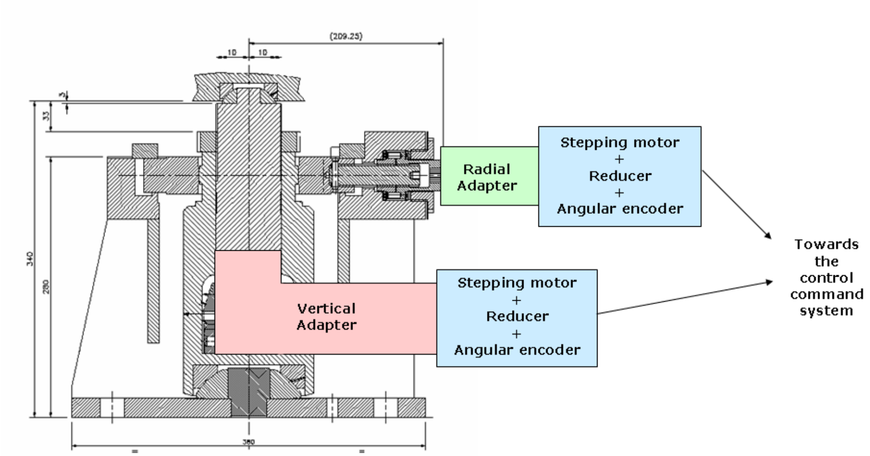


LHC motorized jacks

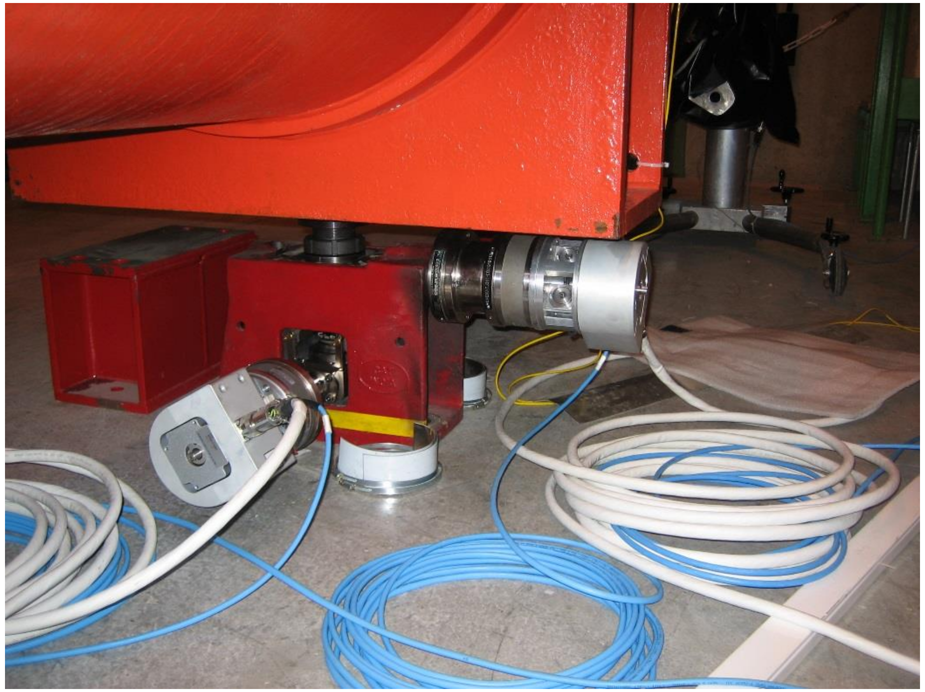


Jack configuration in the LHC

Polurethane pastille

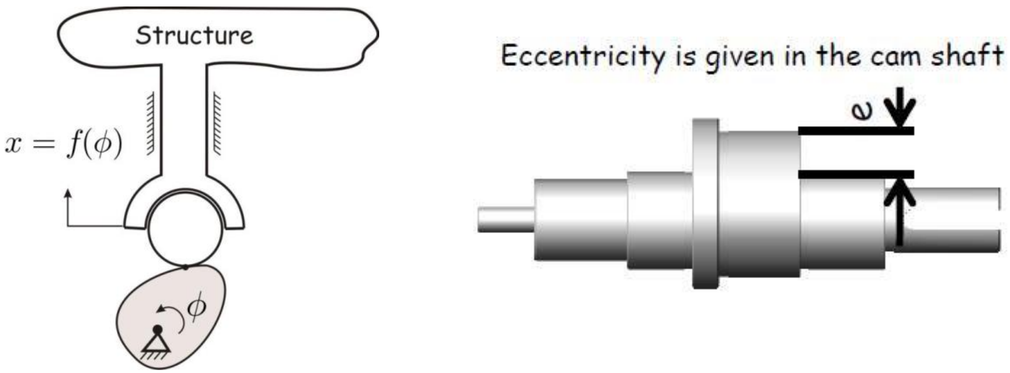


Motorization concept of the LHC jack

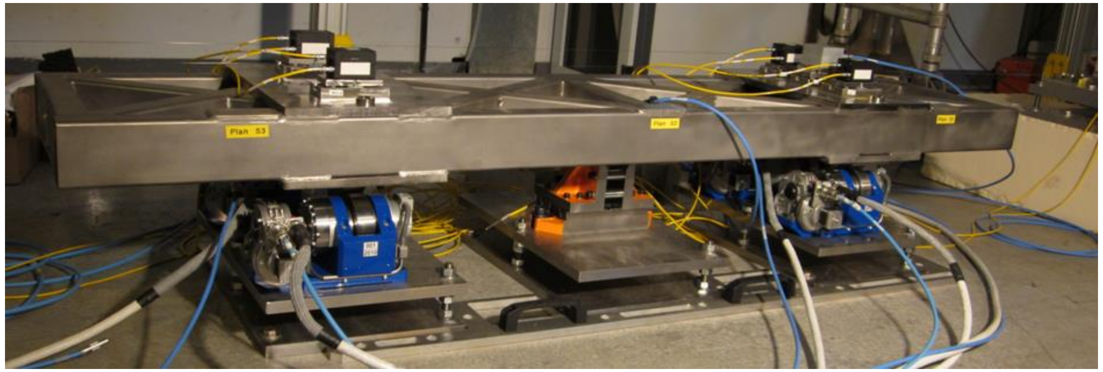


LHC motorized jack

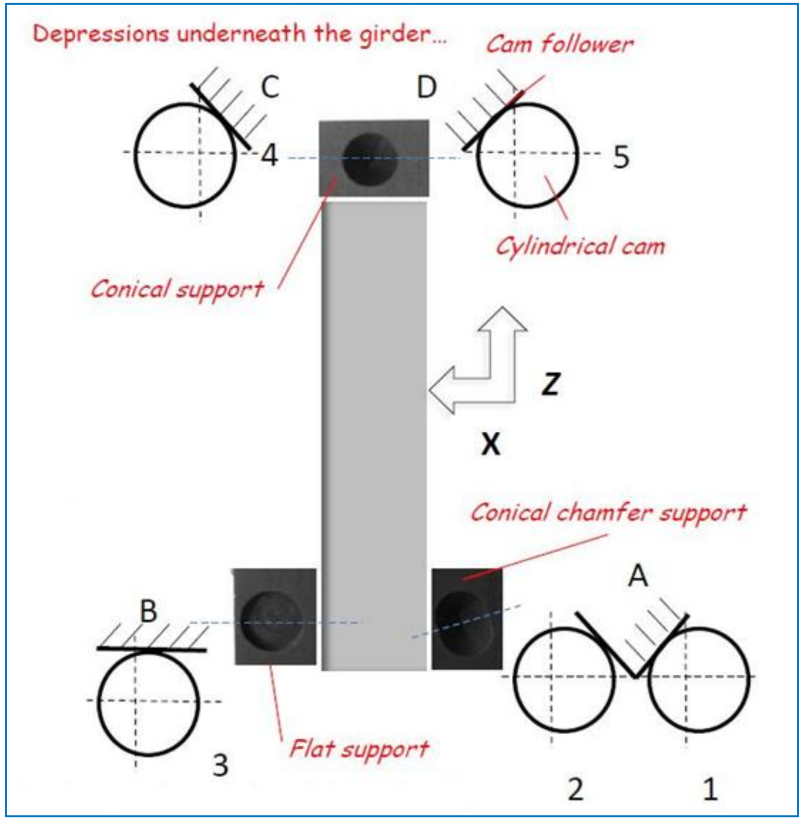
Cam movers



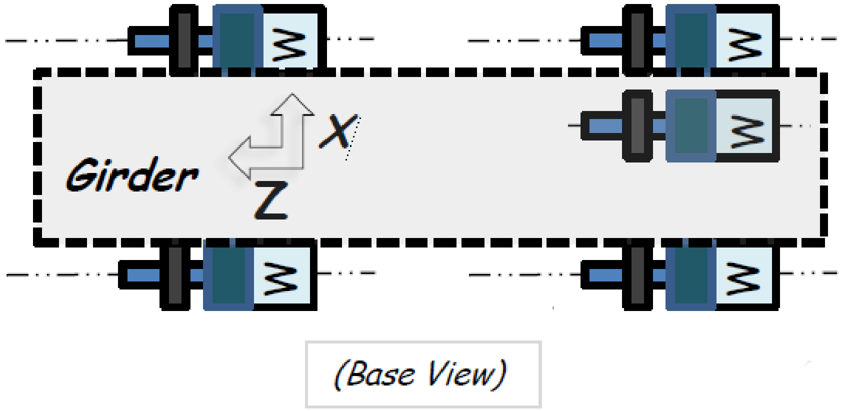
Cam movers concept



2m long girder for the qualification of cam movers at CERN



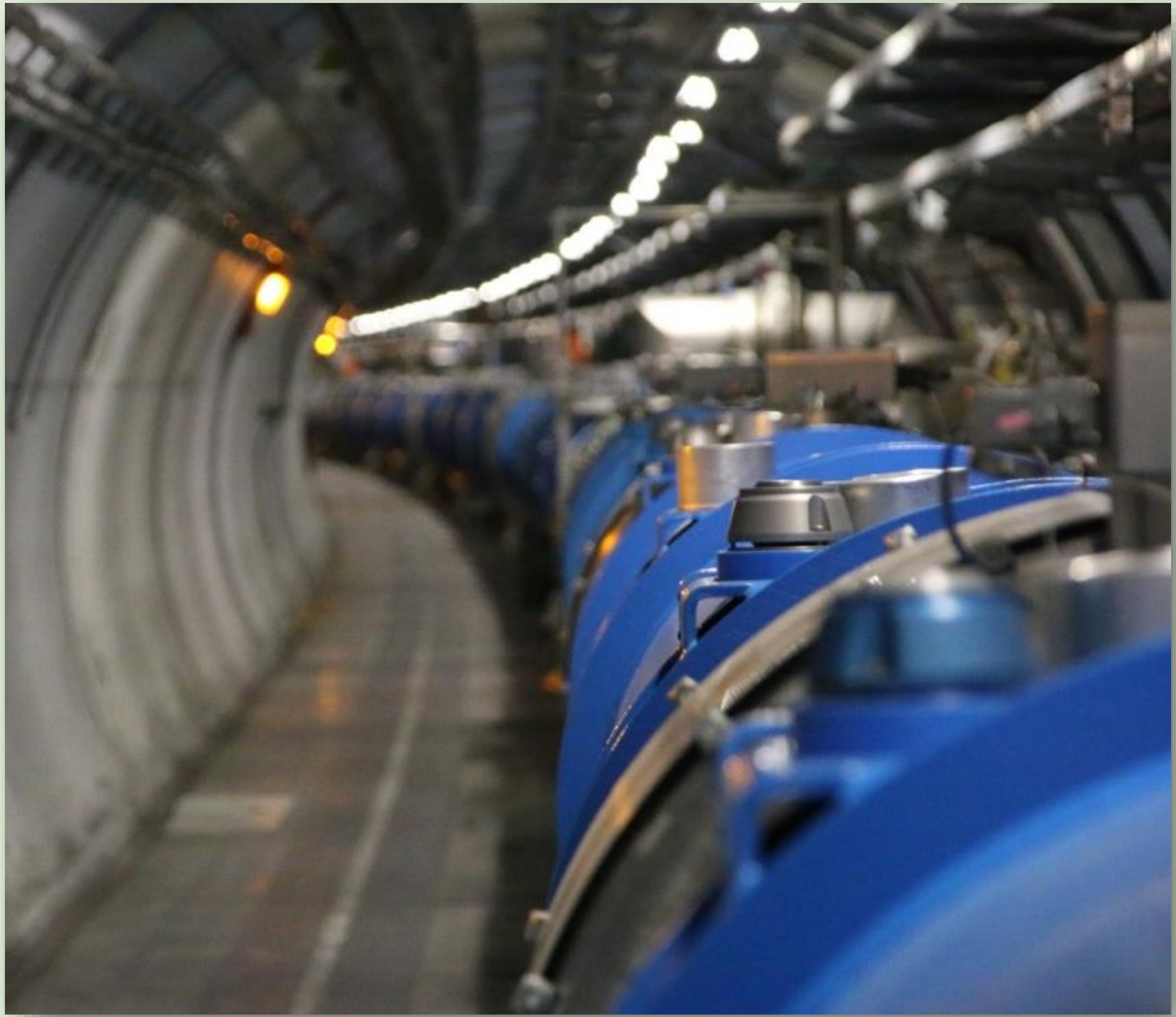
Cam configuration for 5 DOF displacements



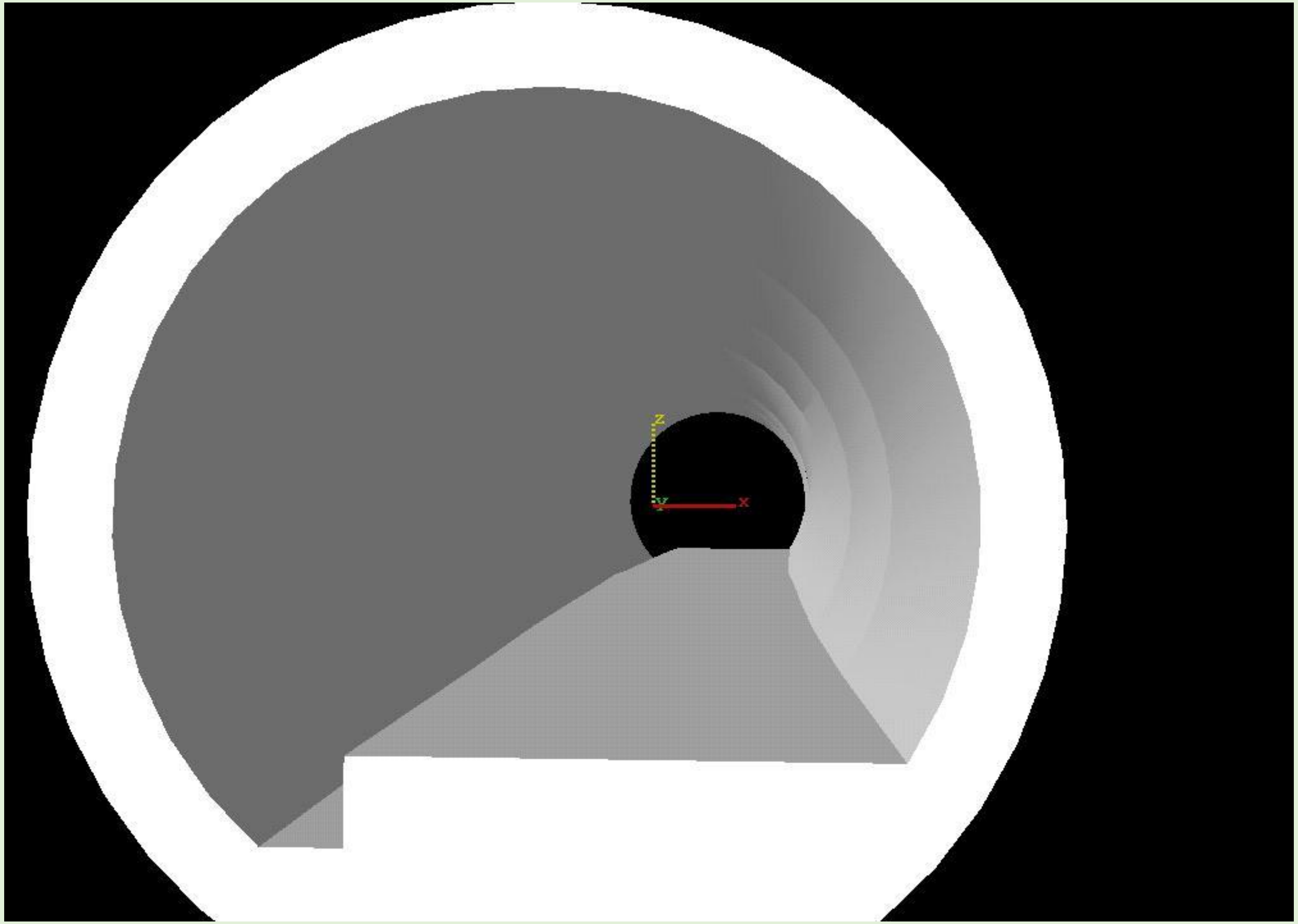
Motorization concept of the cam movers

[Kemppinen]

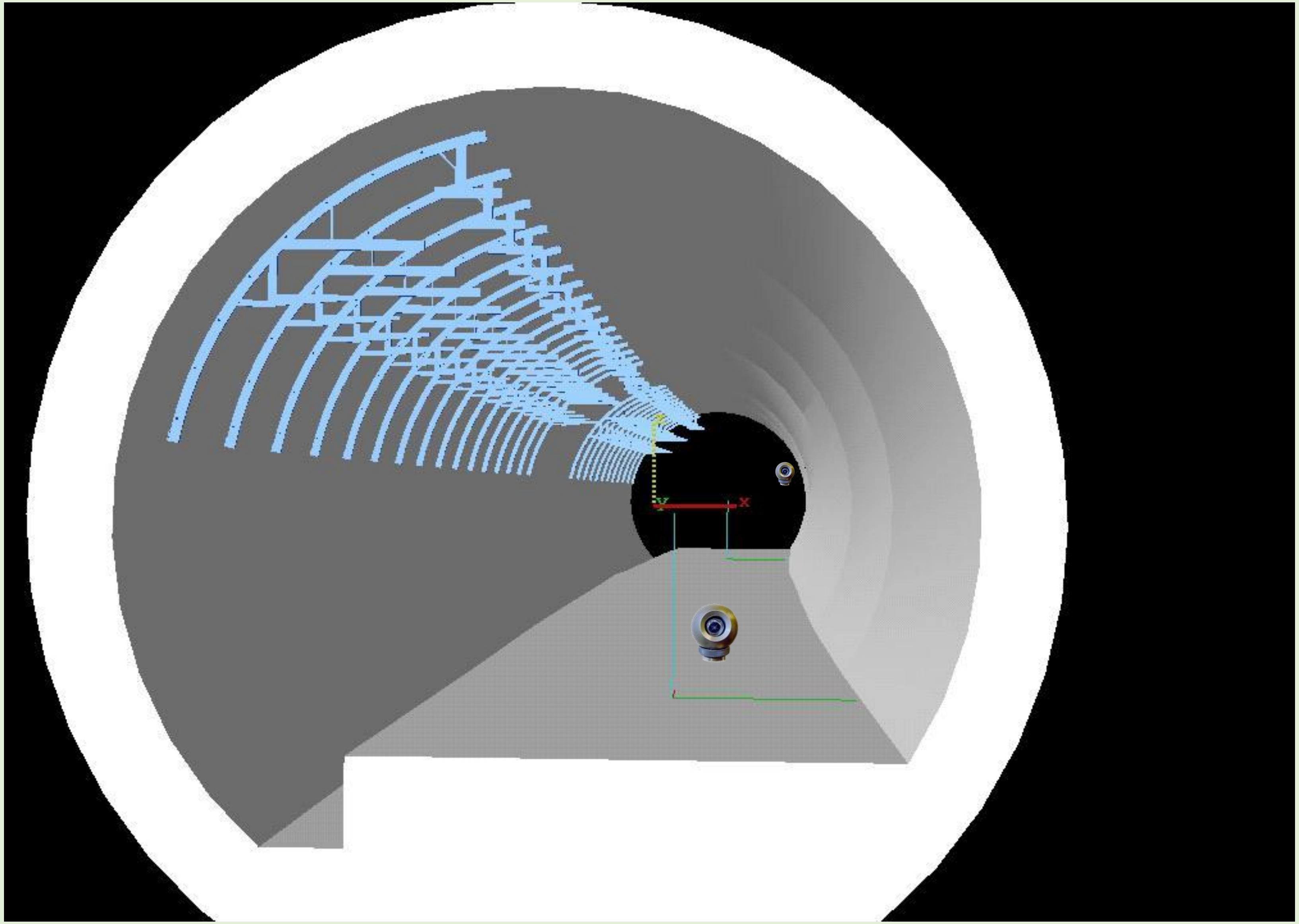
Case of the LHC



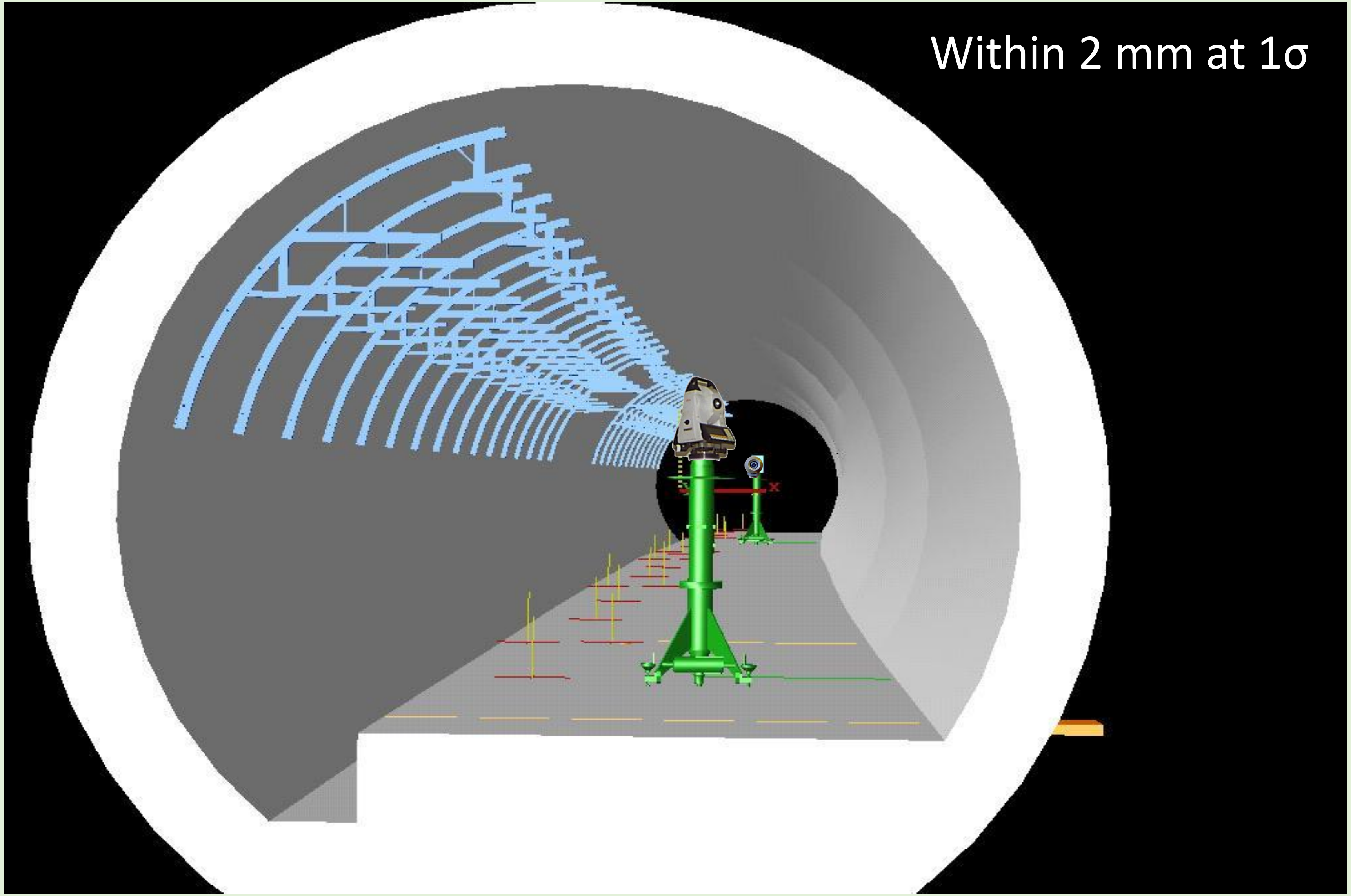
Tunnel empty



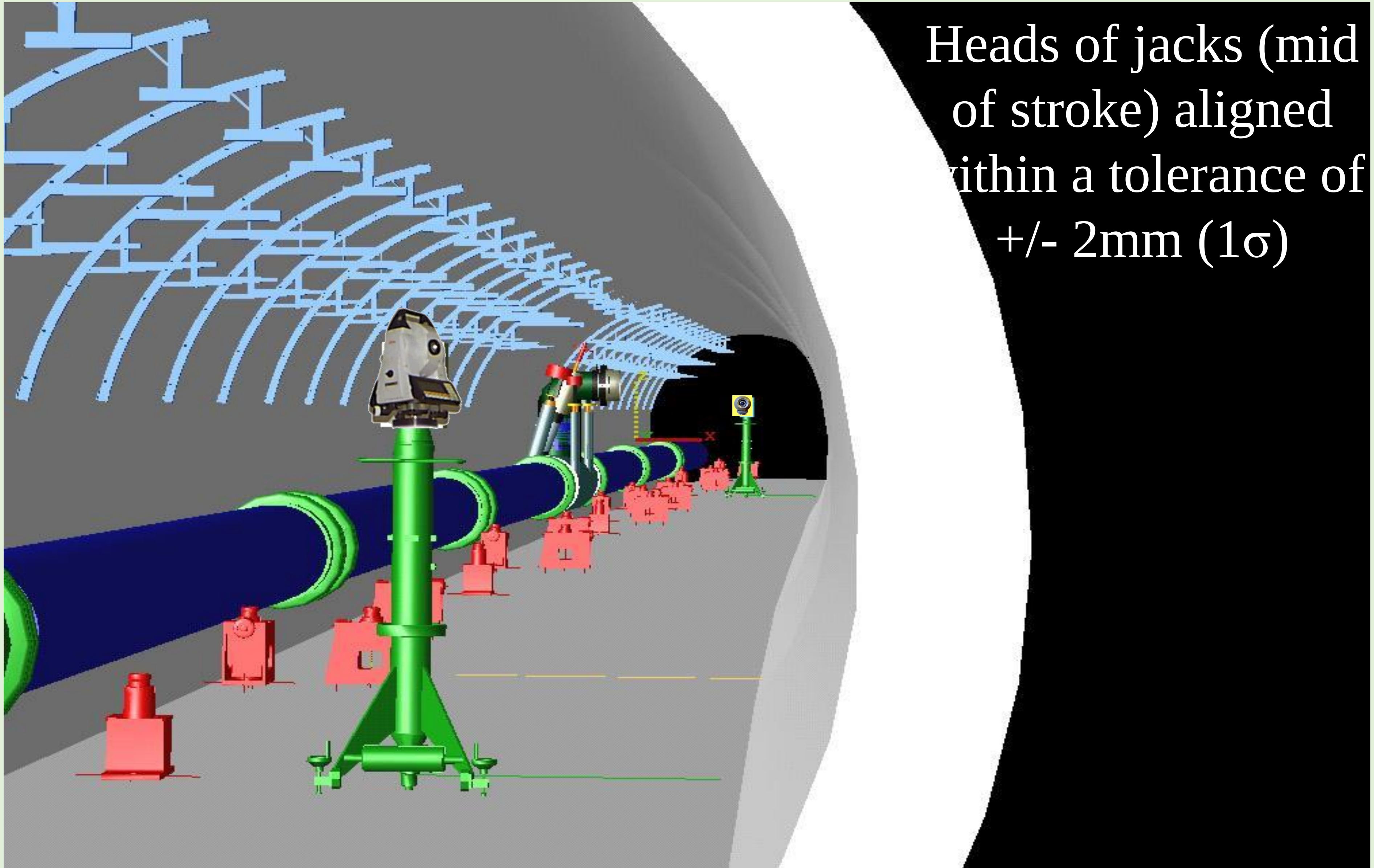
Determination of underground geodetic network



Marking on the floor

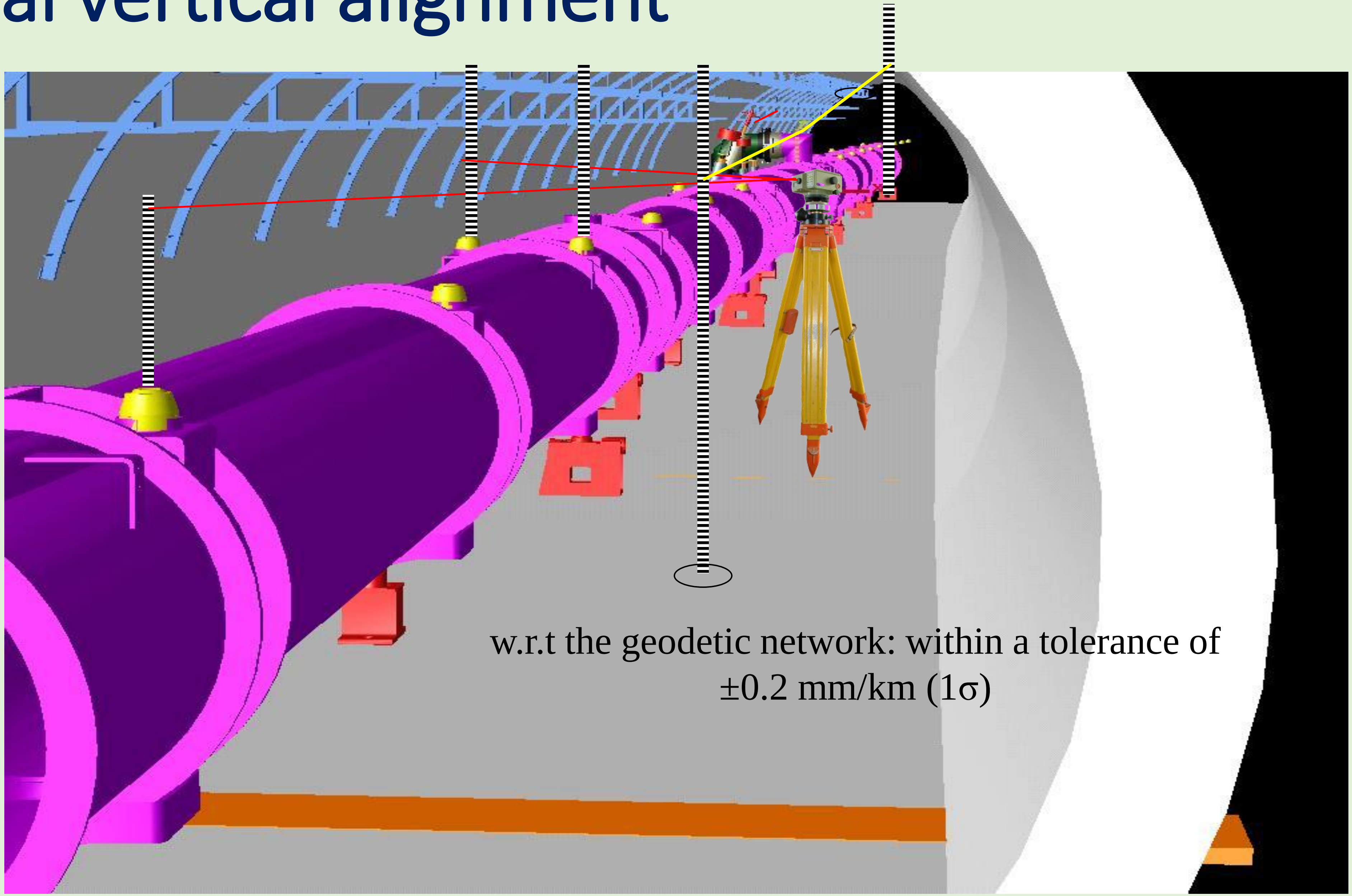


Positioning of jacks



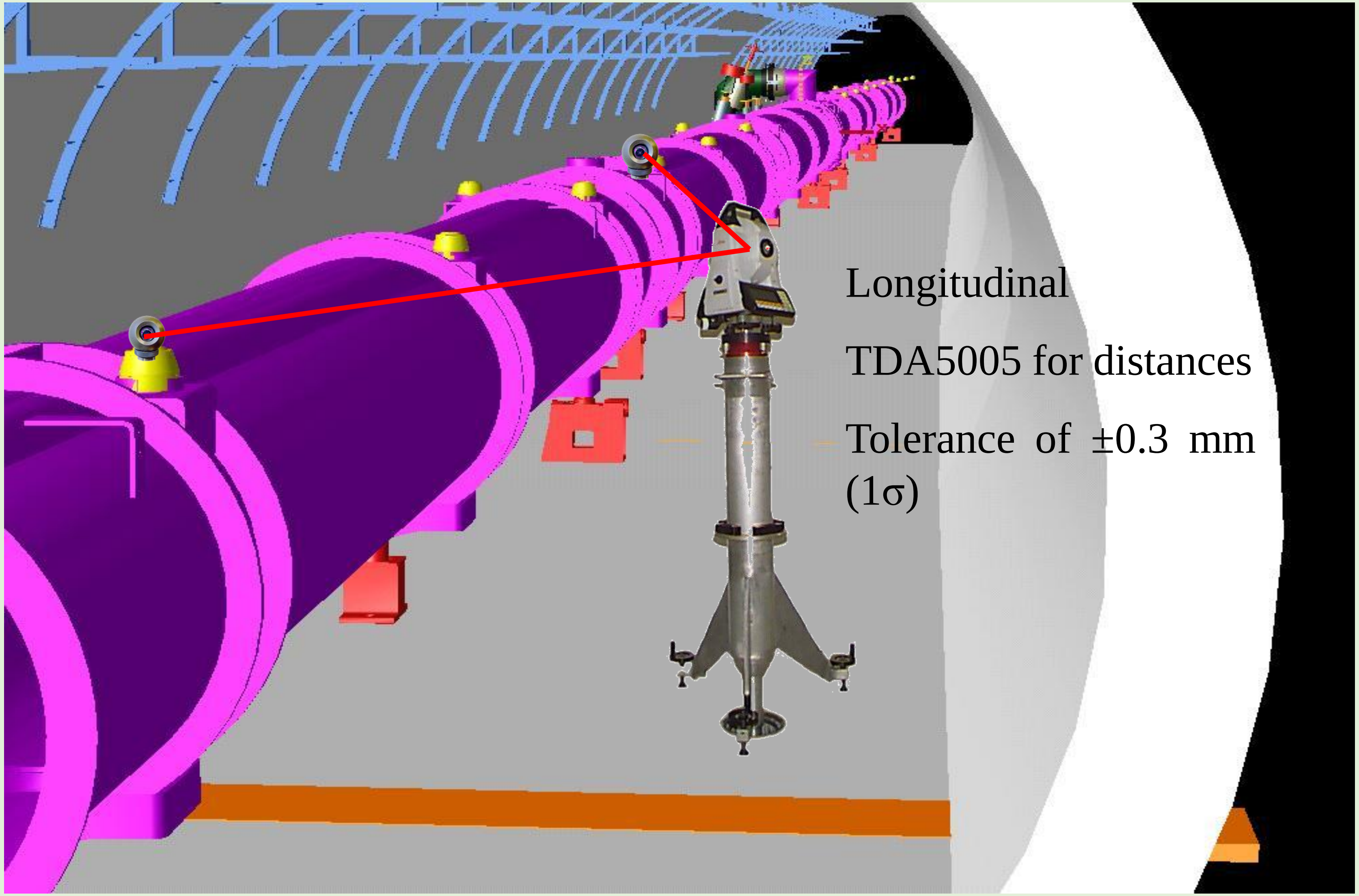
Heads of jacks (mid of stroke) aligned within a tolerance of +/- 2mm (1σ)

Initial vertical alignment



w.r.t the geodetic network: within a tolerance of ±0.2 mm/km (1σ)

Initial longitudinal alignment

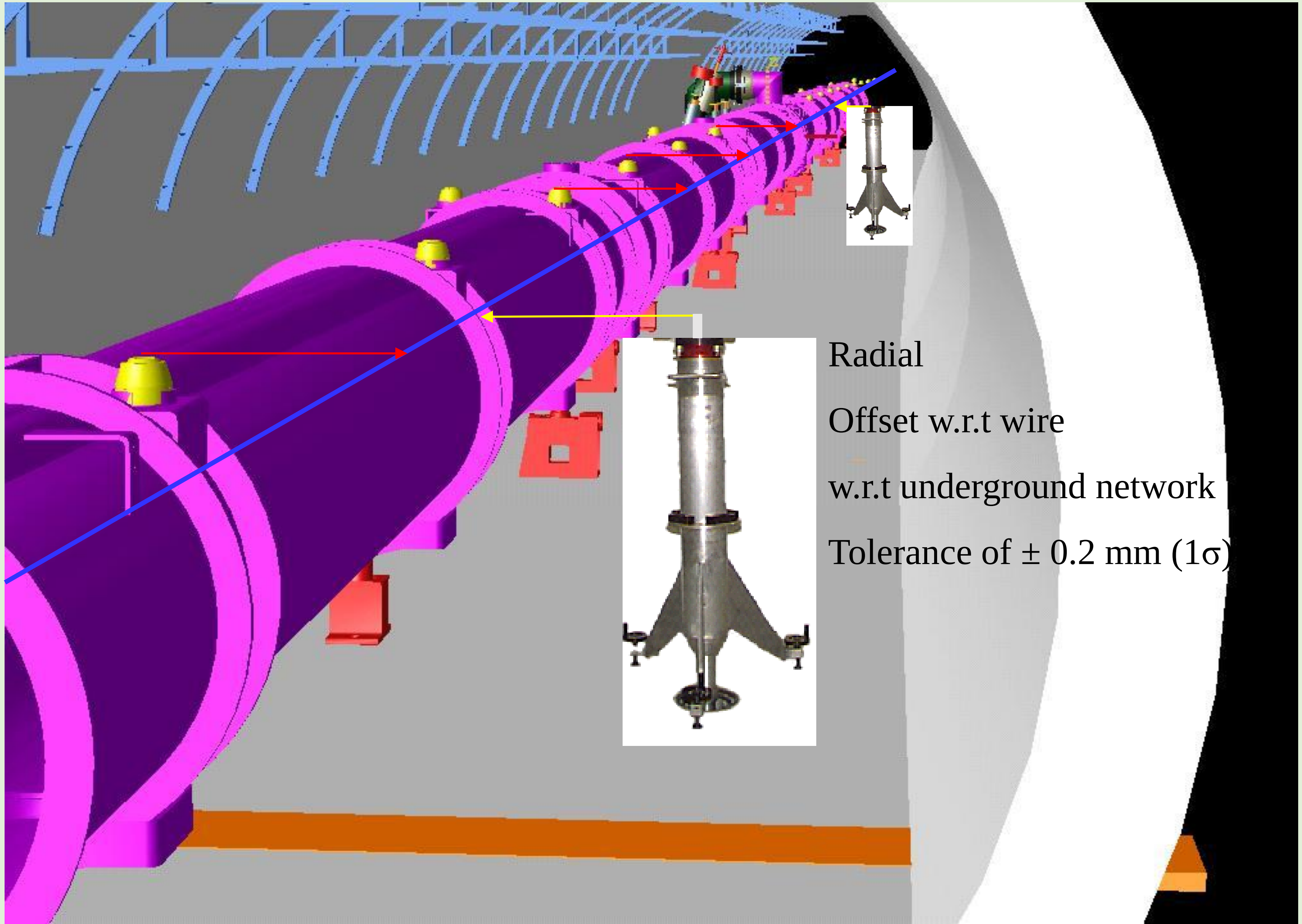


Longitudinal

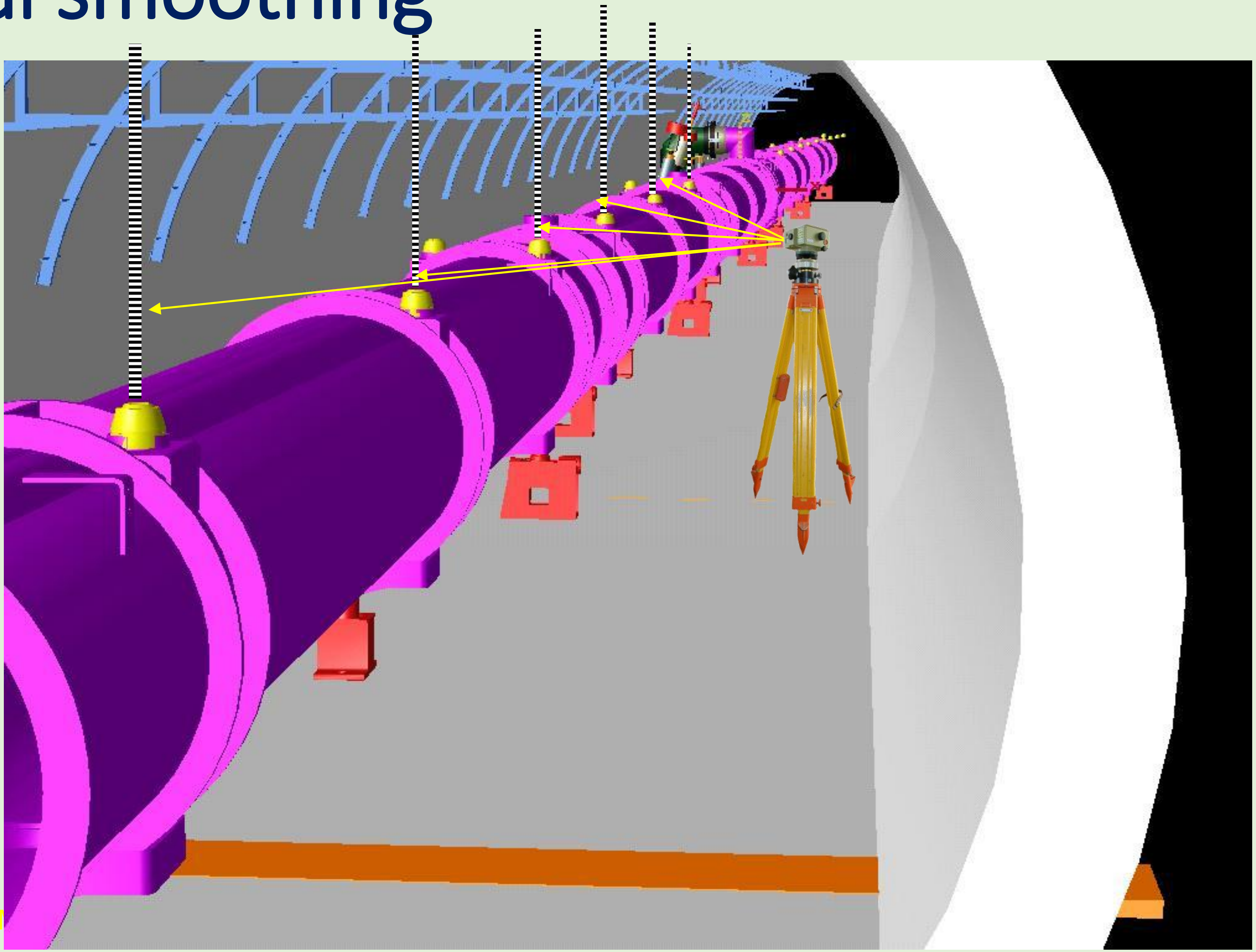
TDA5005 for distances

Tolerance of ±0.3 mm (1σ)

Initial longitudinal alignment

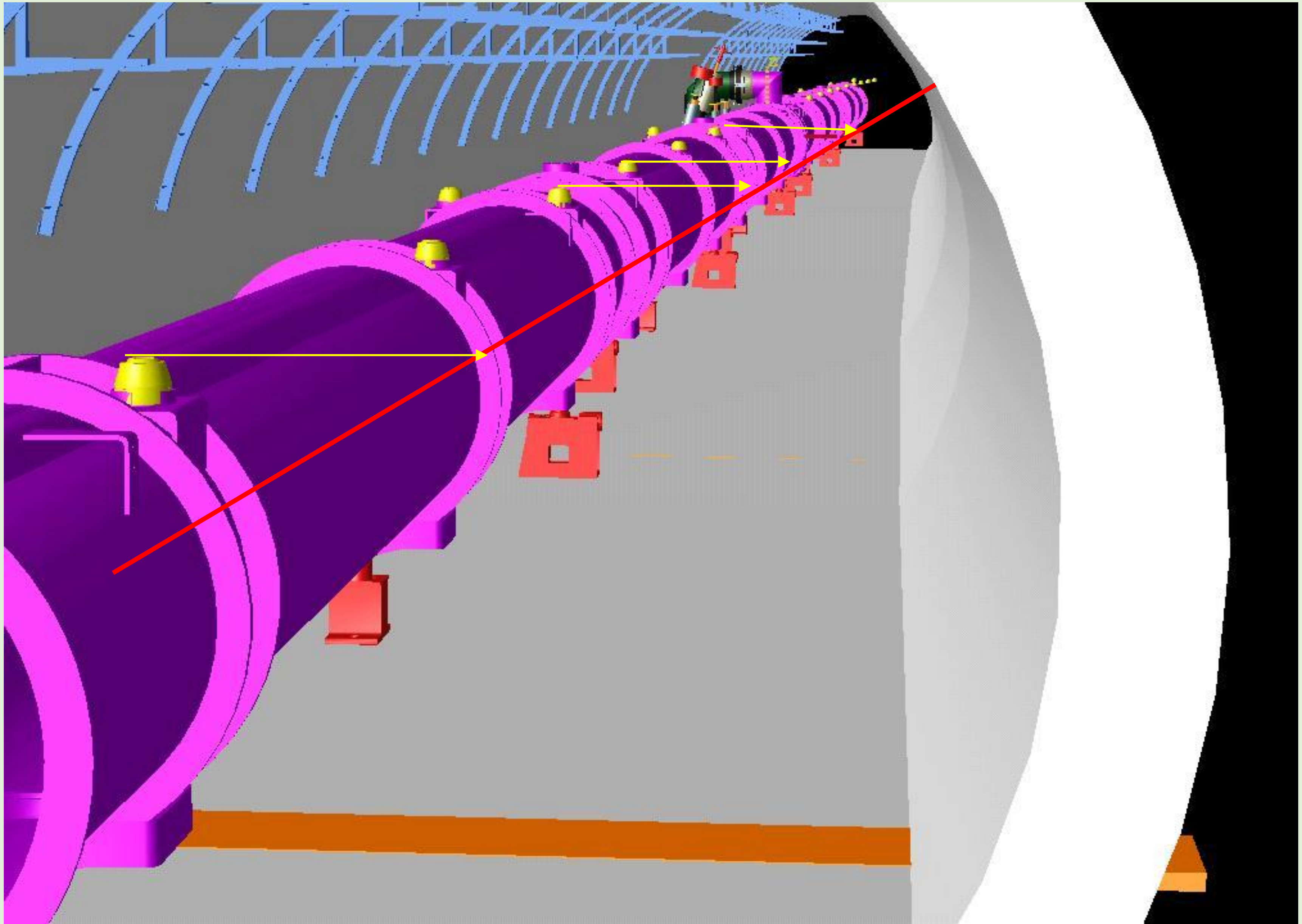


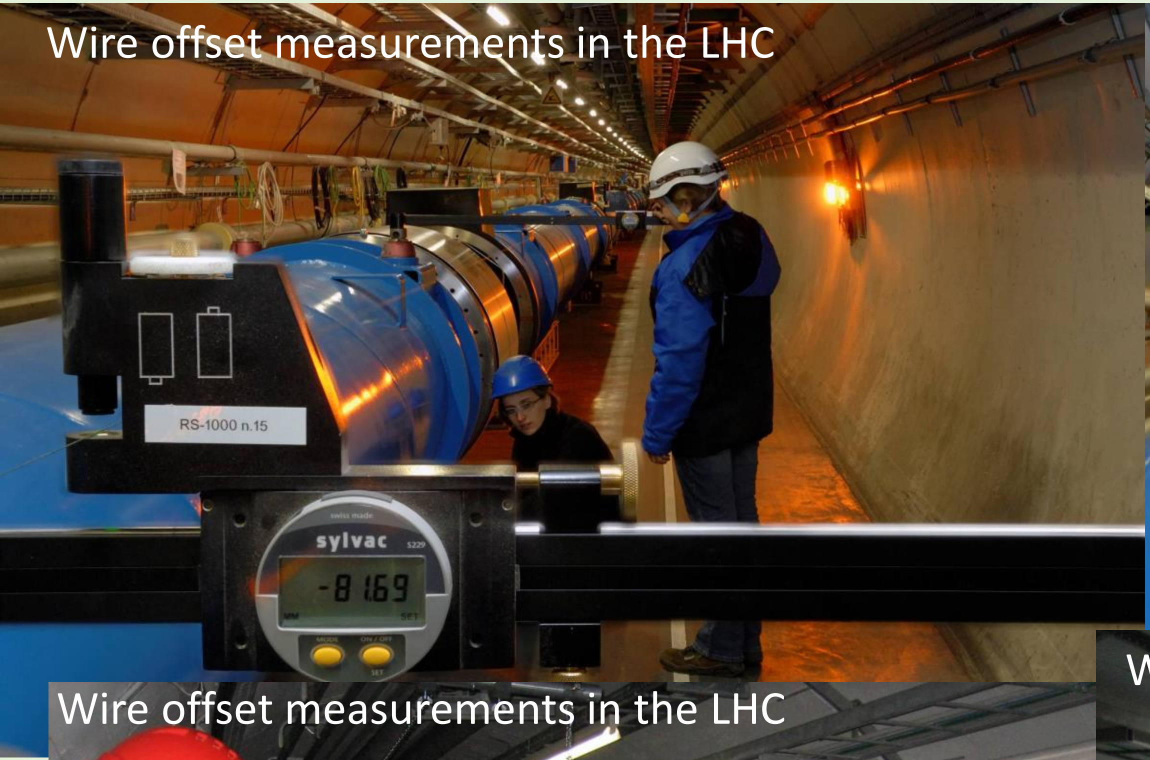
Vertical smoothing



D. M

Radial smoothing




Wire offset measurements in the LHC
RS-1000 n.15
sylvac
-8 1.69


Wire offset measurements in the LHC
10

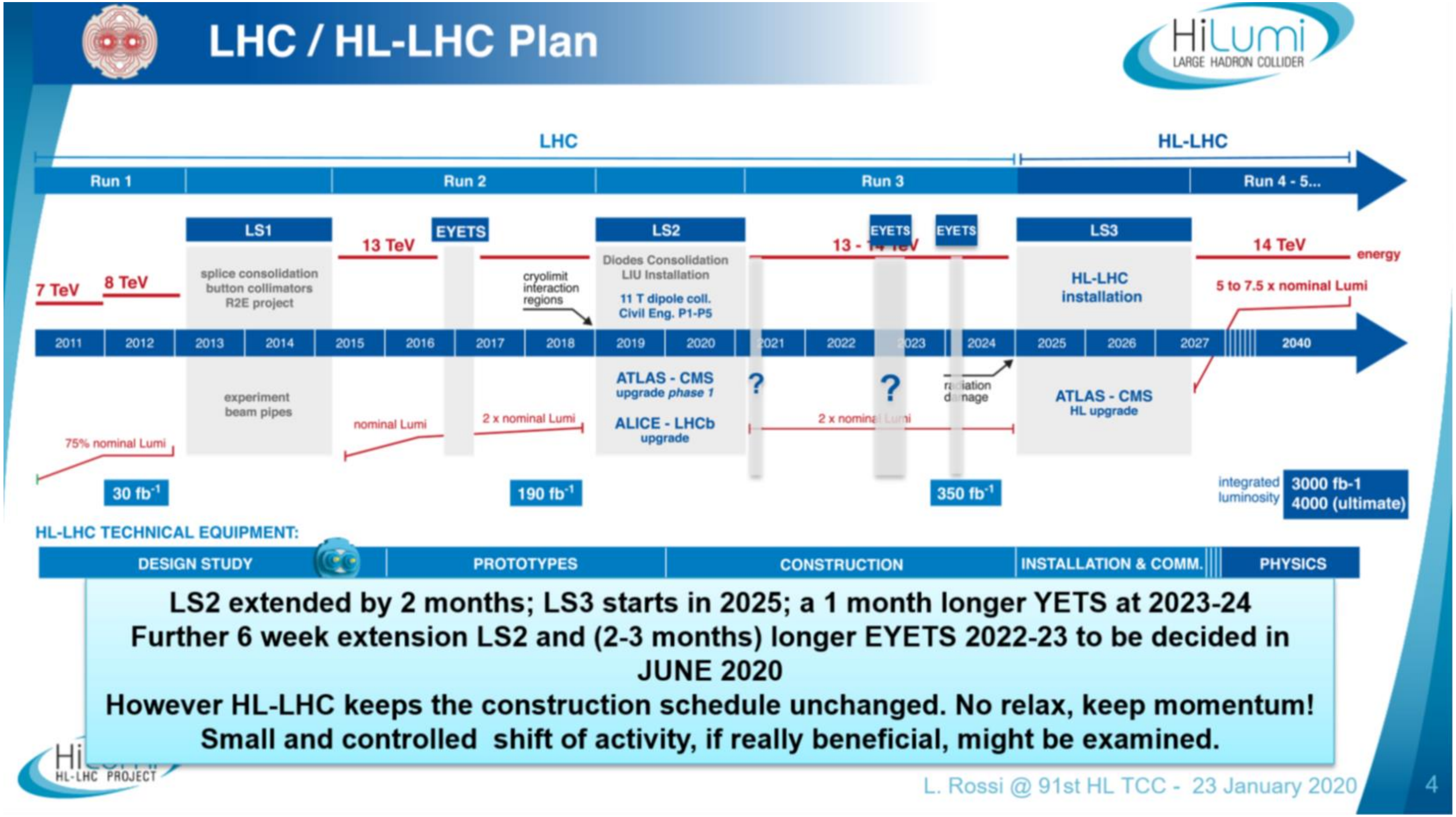

Wire offset measurements in the LHC


Wire protection pipe

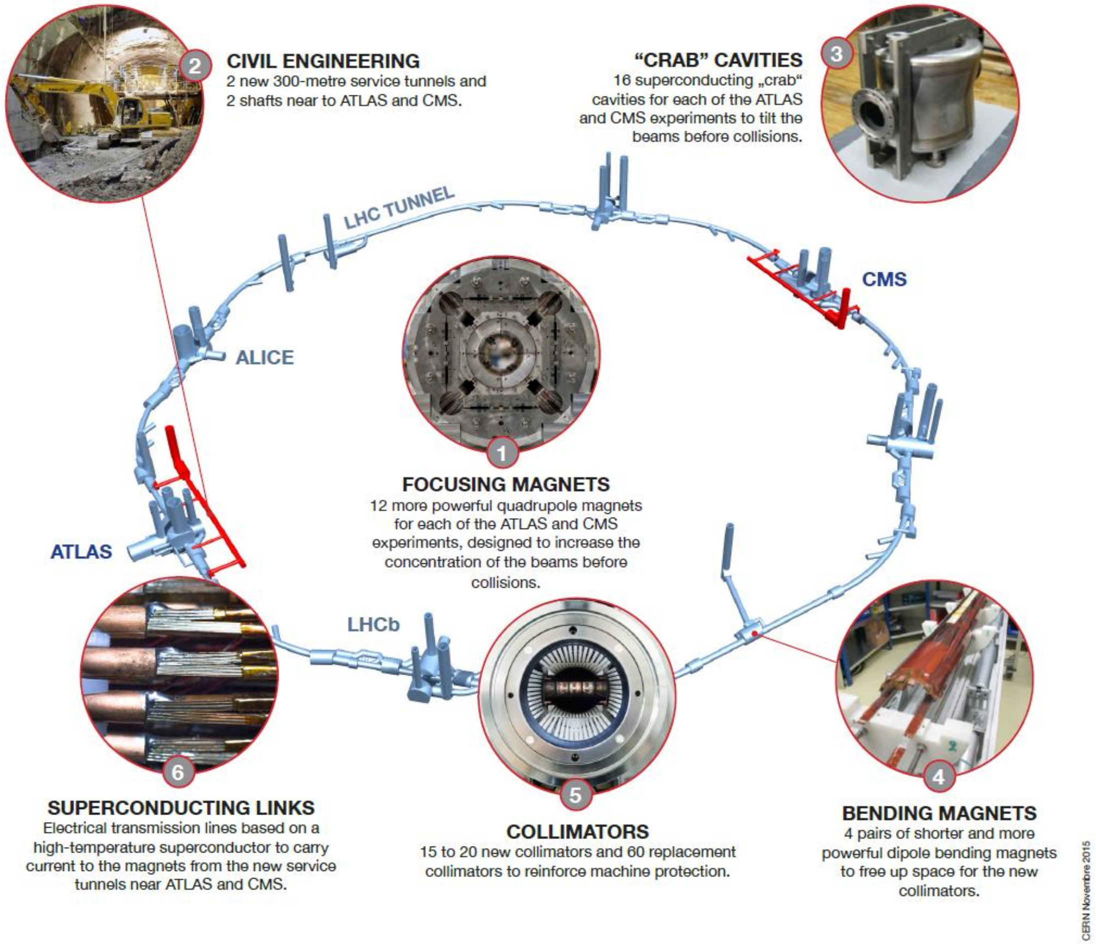
Current challenges on HL-LHC

- Internal monitoring of cold masses
- Full Remote Alignment

HL-LHC: introduction



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**
- ✓ **…**

2 new challenges on survey & alignment:

- ✓ Internal monitoring
- ✓ Full Remote Alignment System

Major intervention on more than 1.2 km of the LHC

HL-LHC: internal monitoring system

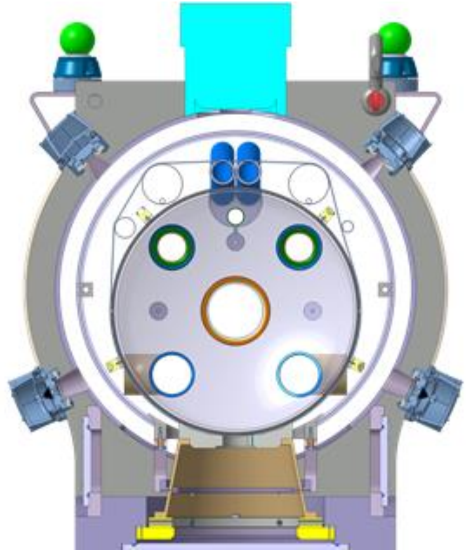
- From the LHC experience: we know at the micron level the position of the cryostat, but not what happens inside → difficult to correlate with beam.
- Displacements up to ± 0.5 mm (3σ) seen on the LHC dipoles after transport
- Strong interest from BE/ABP to know more accurately than in the LHC the longitudinal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

- 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

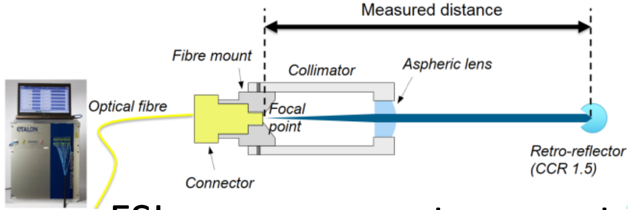
  - $\Delta Phase\ (meas.) = \frac{2\pi}{c} * L_M * \Delta\nu$
  - $\Delta Phase\ (\ ref.\ ) = \frac{2\pi}{c} * L_R * \Delta\nu$

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

The distance measurement is deduced from the ratio between the phase change induced in an interferometer reference and an interferometer measurement by frequency scanning



HL-LHC quadrupole cross-section



FSI measurement concept

FSI measurement

HL-LHC: internal monitoring system

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

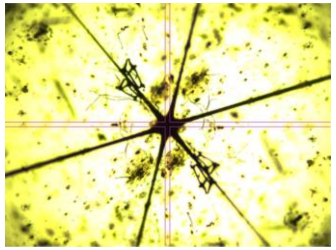
→

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

→

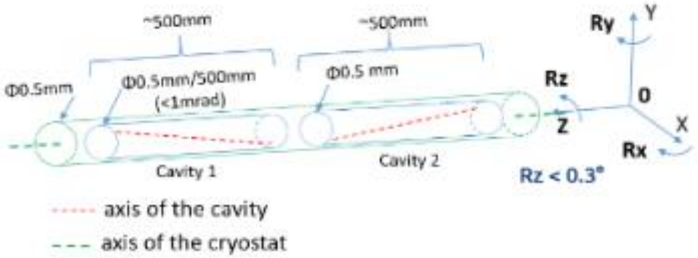
Validation on a test magnet (Dipole)
Validation of performance
- Accuracy and precision
- Long term stability
- Cryo-condensation issues

10 MGy

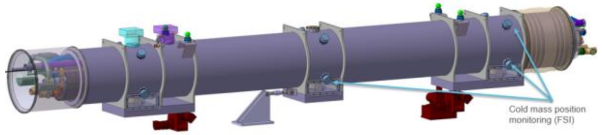


CCR after 10 MGy irradiation

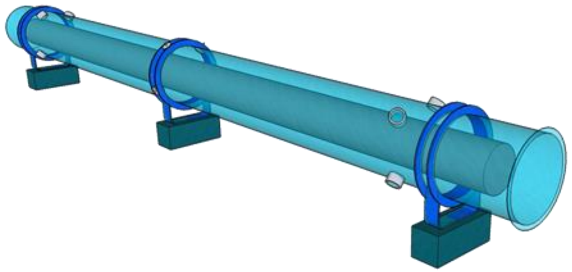
Crab cavity section



Crab cavities alignment requirements

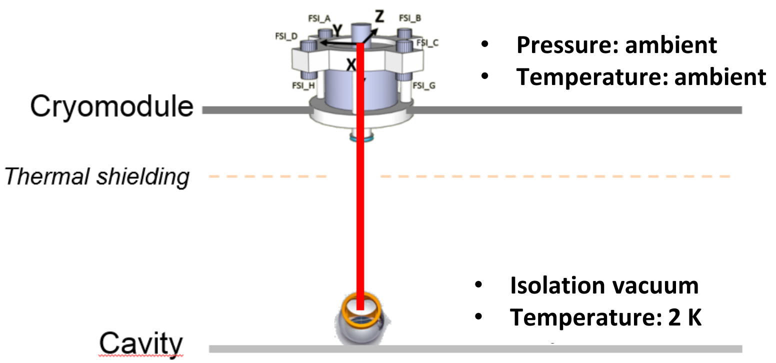


HL-LHC inner triplet

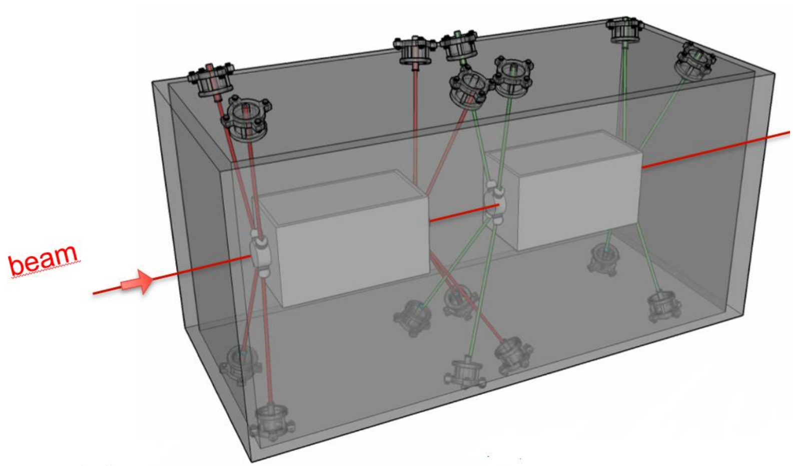


[Mainaud Durand2]

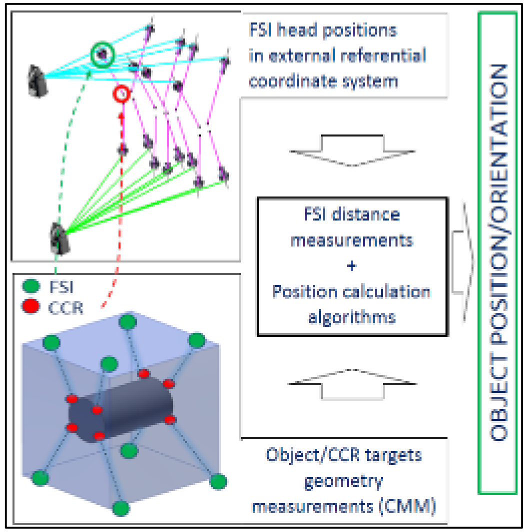
HL-LHC: internal monitoring system



FSI measurement concept



FSI measurement configuration in crab cavity cryostat



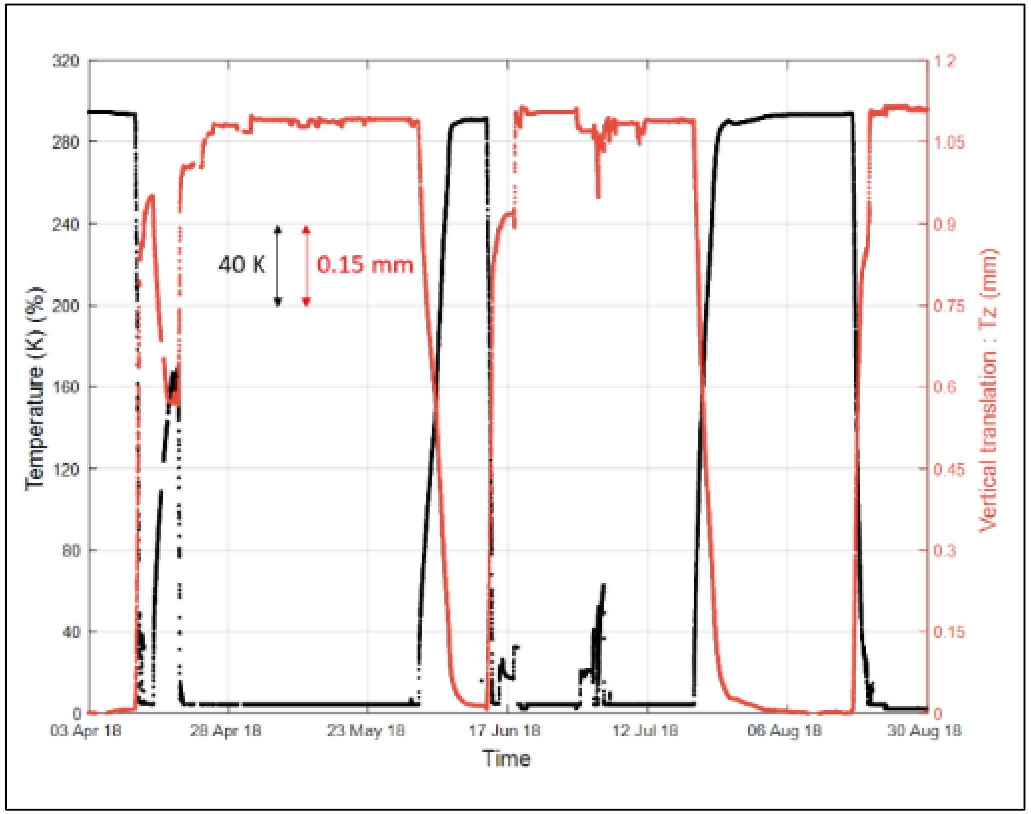
Feedthrough

CCR

[Rude]

HL-LHC: internal monitoring system

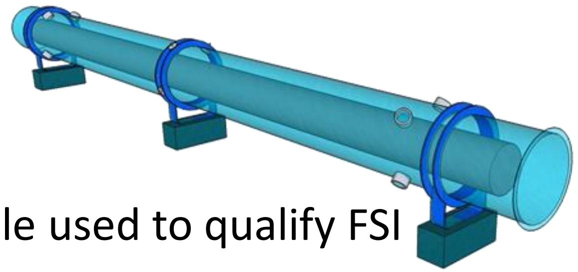
Crab cavity prototype installed in SPS



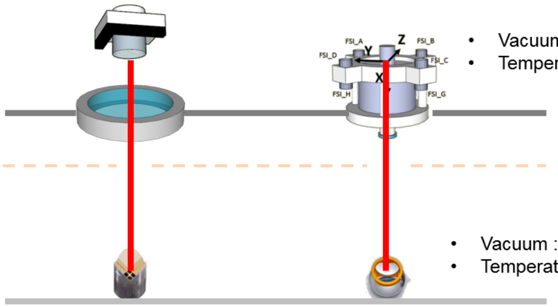
FSI measurements in the SPS prototype

- 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

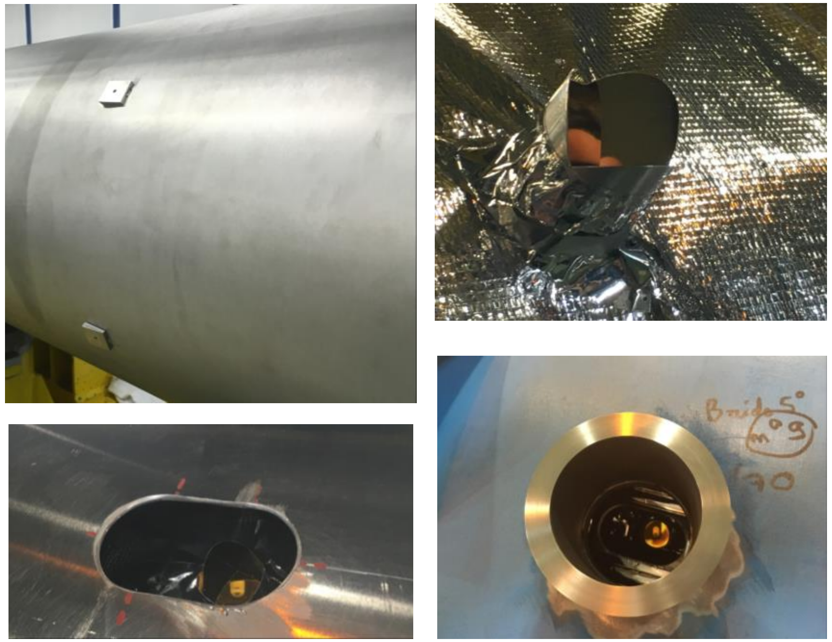
HL-LHC: internal monitoring system



Dipole used to qualify FSI

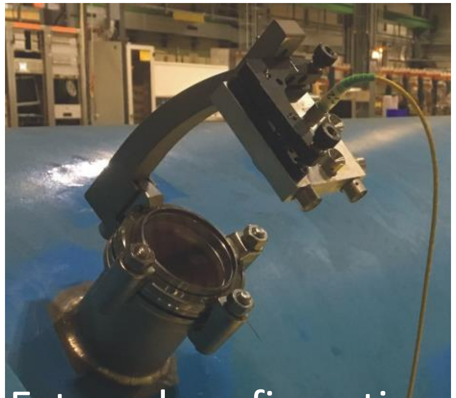


Measurement configuration

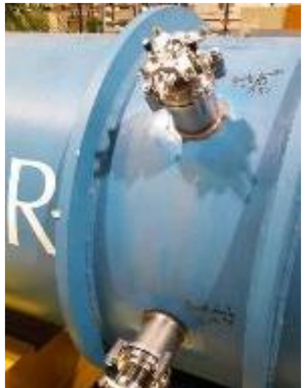


Installation steps of the FSI target

[Mainaud Durand3]



External configuration

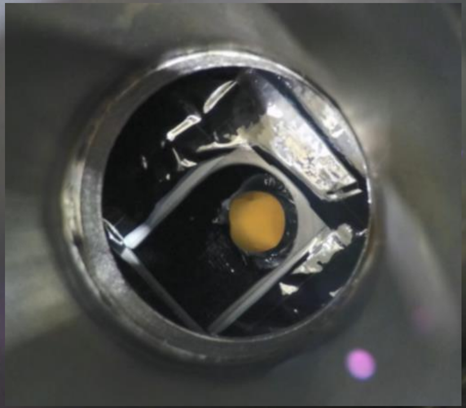


Feedthrough

Hollow prism

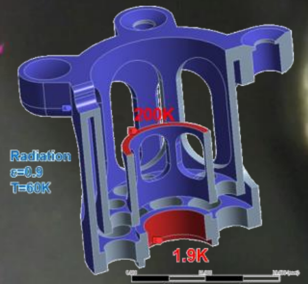
Ball Retro Reflector

HL-LHC: internal monitoring system

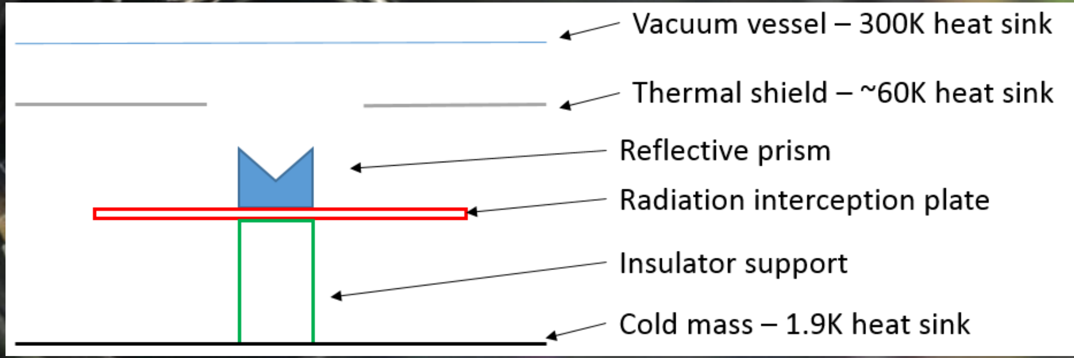


How can we achieve a "heating" of the probes up to ~200K ?

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").

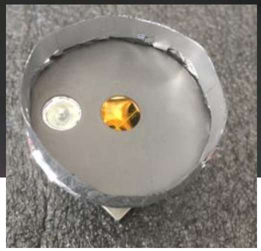


Thermal simulations

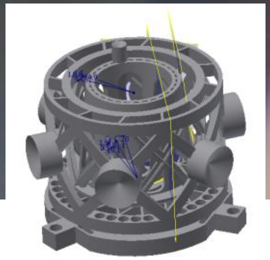


New concept of reflector support

[Micolon]

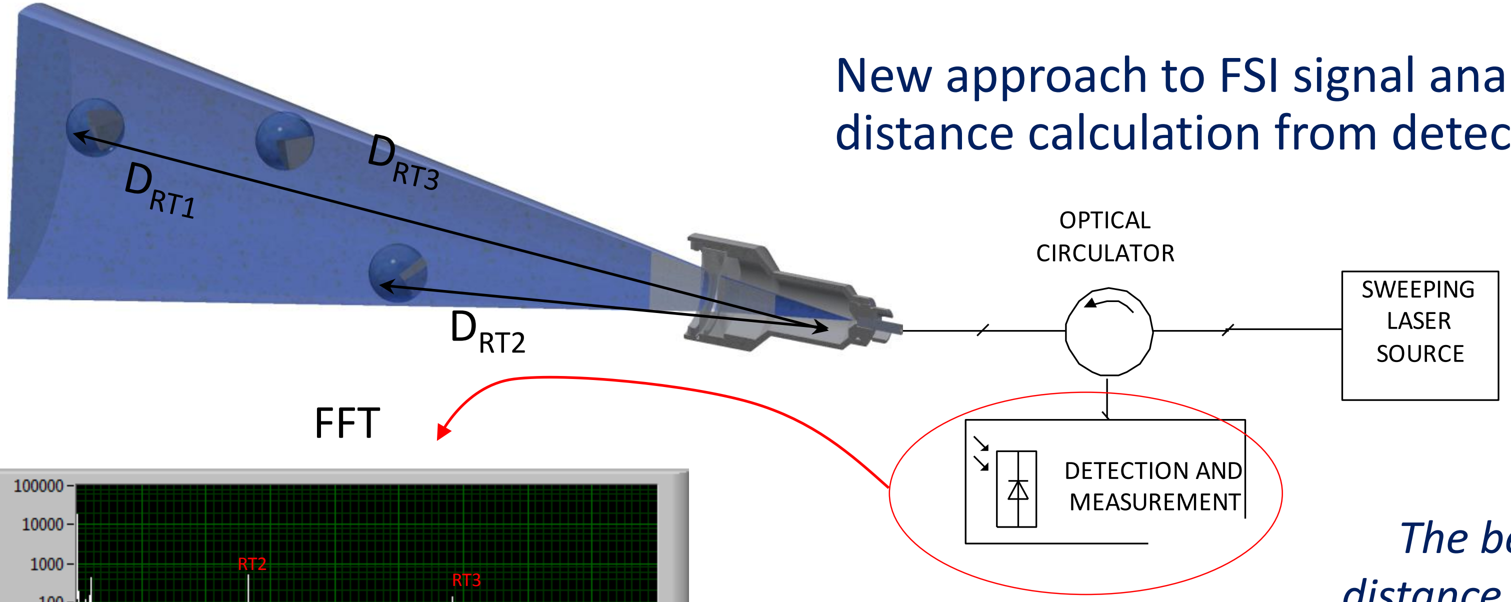

1st generation of isolated reflector support

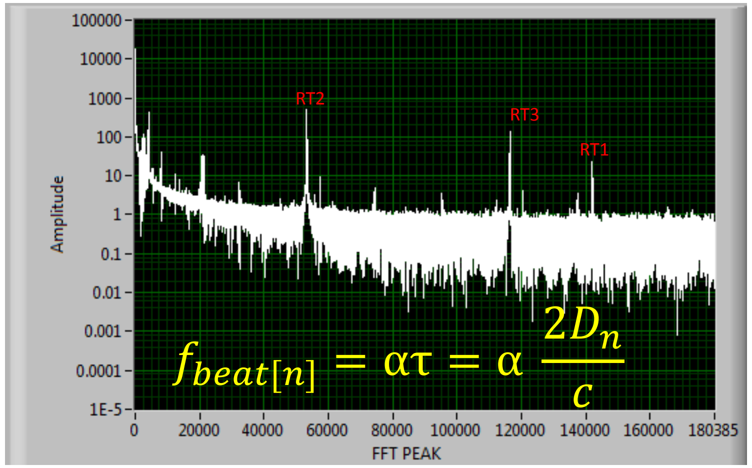



2nd generation of isolated reflector support

HL-LHC: internal monitoring system

New approach to FSI signal analysis – Fourier based distance calculation from detected beat frequencies





The beat frequency is proportional to the distance between the ferrule tip and the target if the laser sweeping speed is contant.

$$D_n = c\,\frac{f_{beat[m]}}{2\frac{d\nu}{dt}n}$$

Multi-target FSI

In-house Multi Target FSI concept

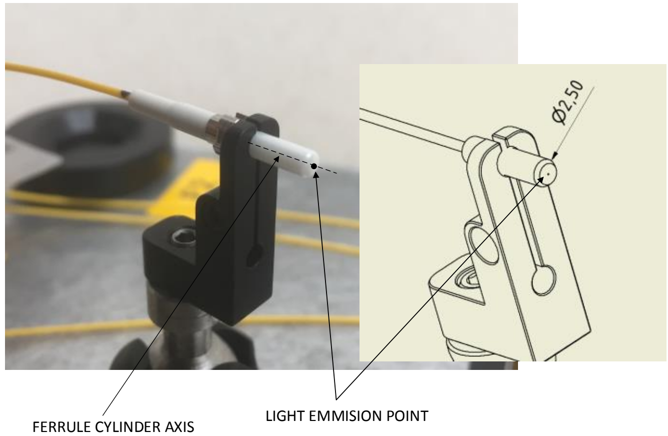
α – is a sweep rate of the laser ($\alpha = \frac{d\nu}{dt}$ - laser frequency change in time);

c – speed of light; n – refractive index of light transmission medium;

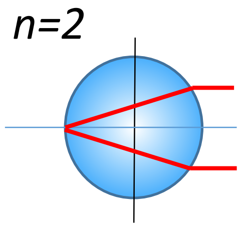
τ – time of flight of laser to the target

HL-LHC: internal monitoring system

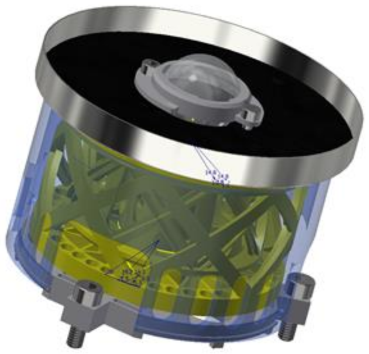
- Very robust measurement method – almost insensitive to the light intensity (high and very small power reflections visible over the noise background
- Possible to use low cost glass balls as a reflectors
- Possible to measure multiple targets within single laser scan
- Beam delivery optics can be very simple
- Possible to use with the collimated and divergent beams
- Simple and scalable Optics



Ferrule picture

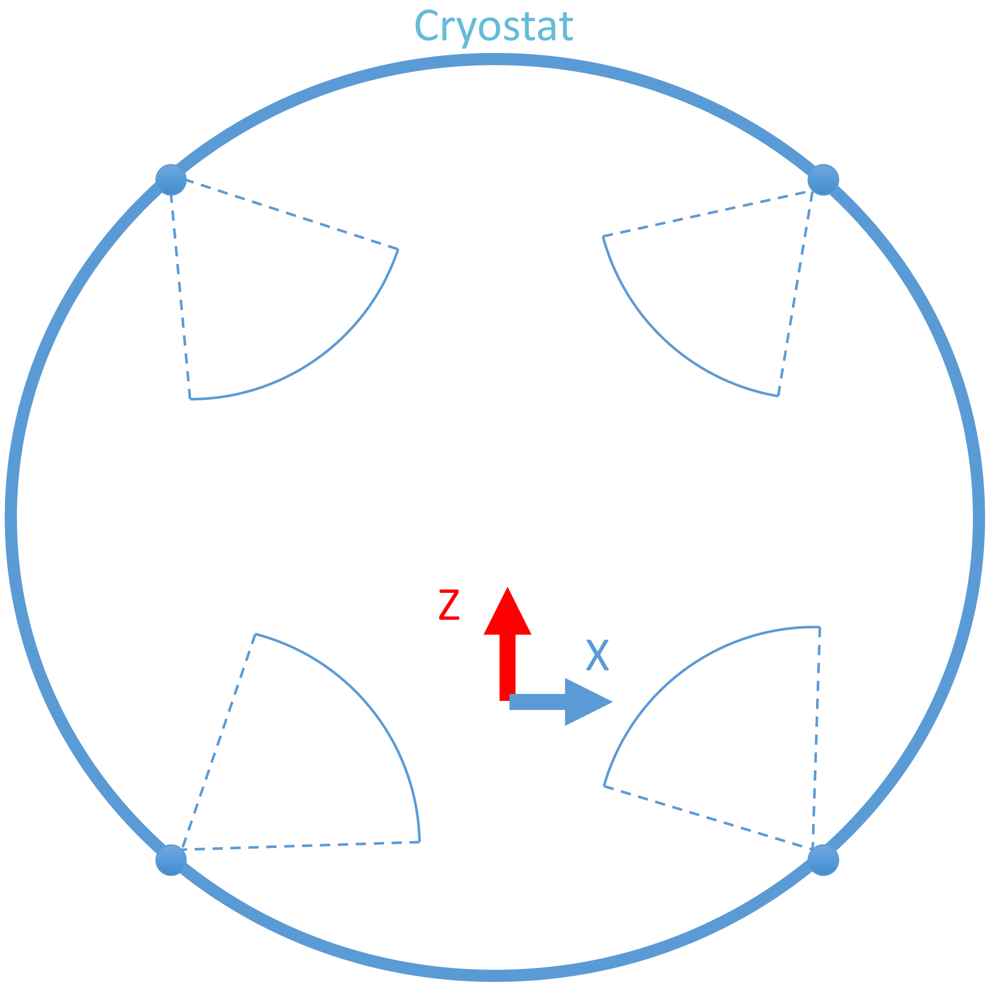


New reflector: glass ball

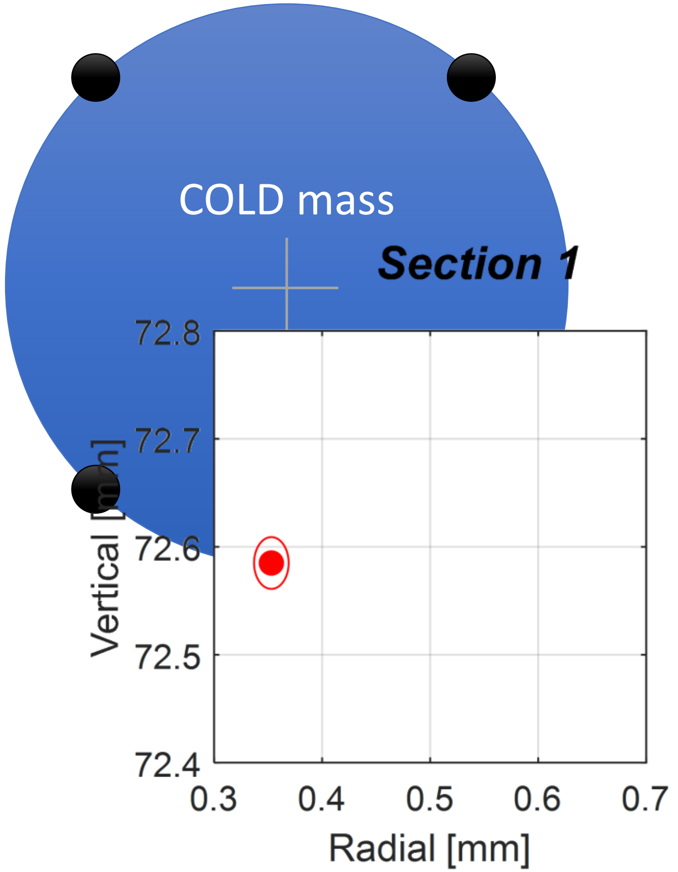


New reflector in its isolated support

HL-LHC: internal monitoring system

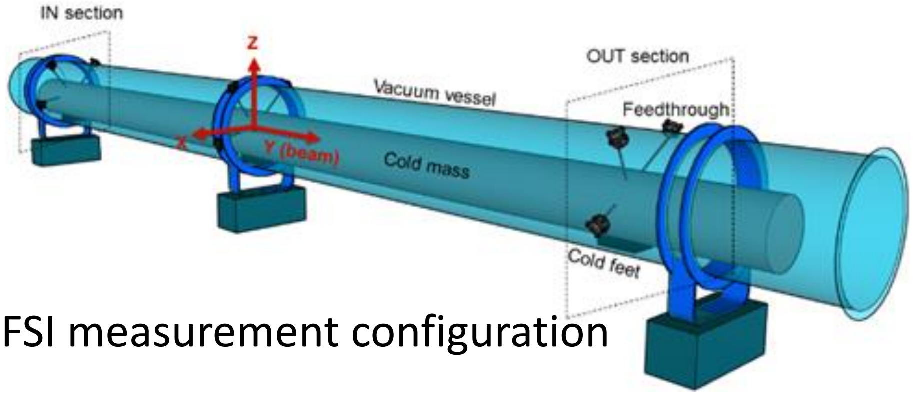


Coordinates determination using FSI distance measurements

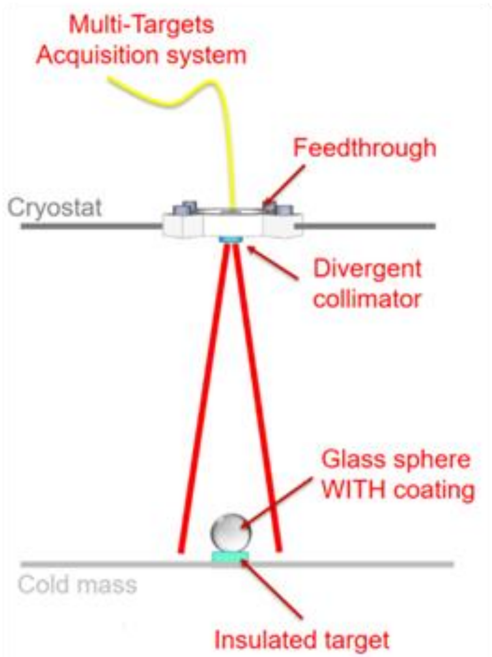


Point coordinates and associated uncertainty of measurement

HL-LHC: internal monitoring system



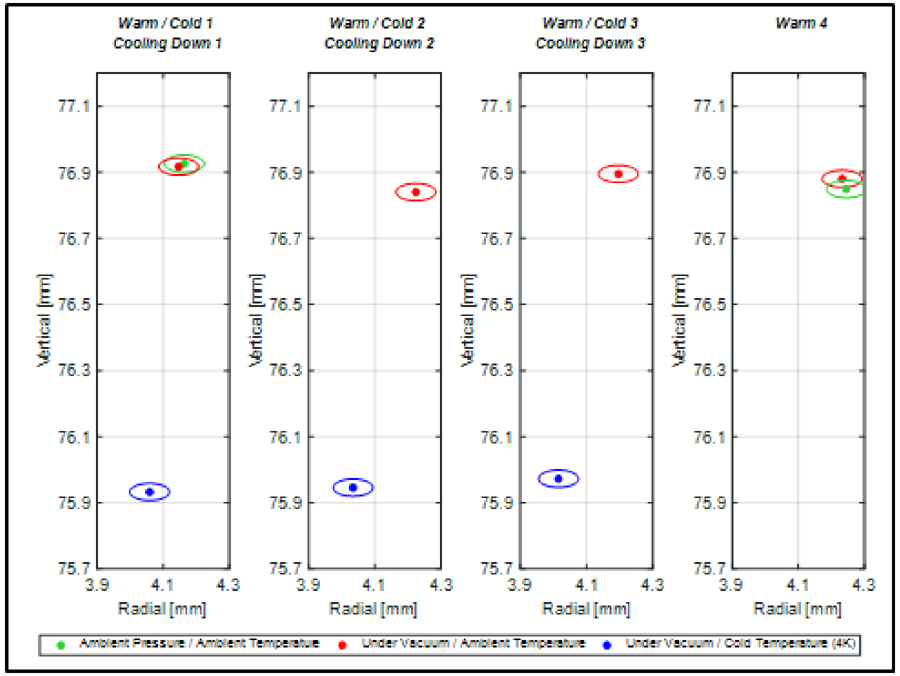
FSI measurement configuration



FSI measurement concept

Simplified feedthrough

Target support

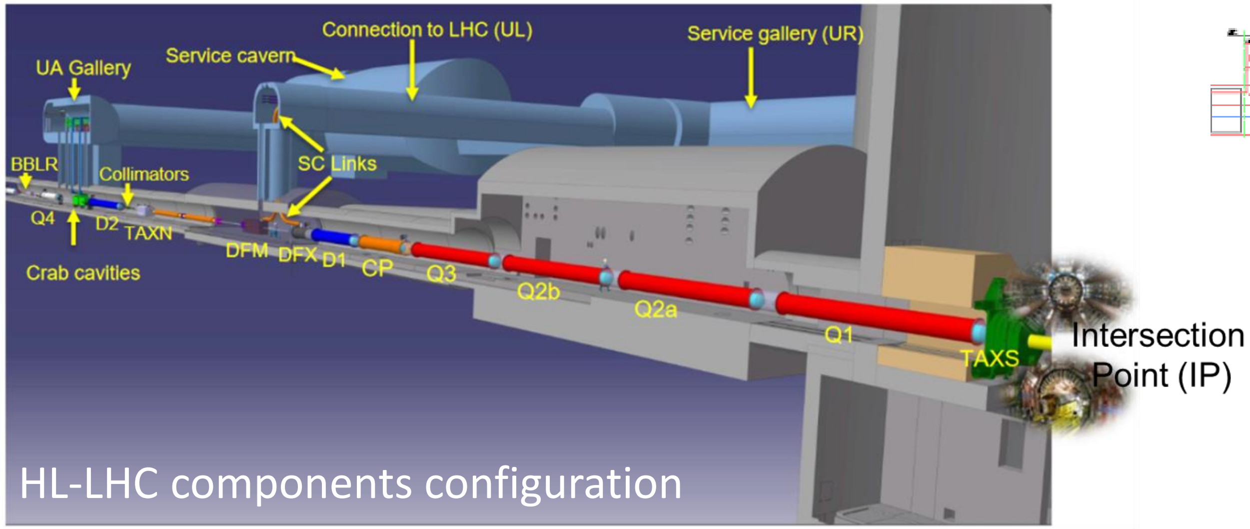


Coordinates after 3 thermal cycles

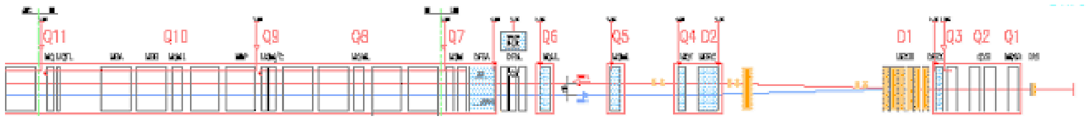
Accuracy of section determination

Direction	Accuracy (mm)
X : Radial [mm]	0.060
Y : Longitudinal [mm]	0.085
Z : Vertical [mm]	0.030

HL-LHC: Full Remote Alignment System



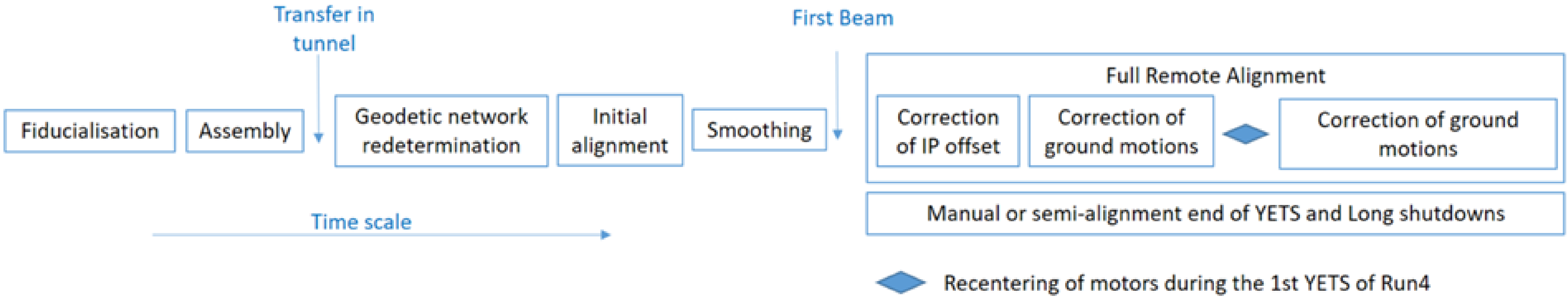
HL-LHC components configuration



The Full Remote Alignment System (FRAS) will allow aligning rigidly (as a block, simultaneously) and remotely from the CERN Control Centre, all the components from Q1 to Q5 on both sides of the IP within ± 2.5 mm.

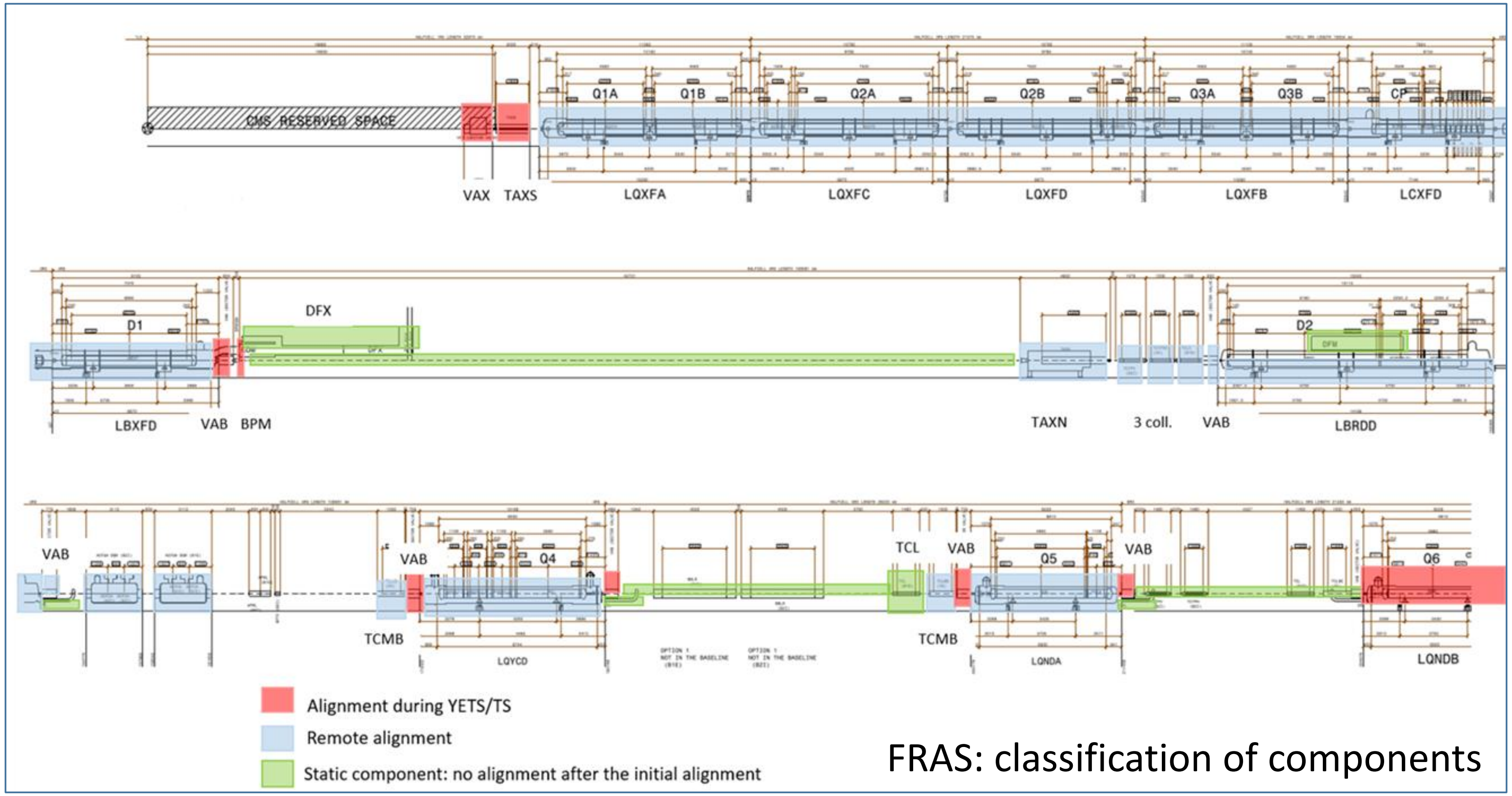
It will allow:

- An important reduction of the dose taken by surveyors
- A reduction in the mechanical misalignment, allowing to decrease the required correctors strength
- A gain in aperture for several components through the reduction of tolerances.



- The initial alignment of the new components in the tunnel w.r.t. the underground geodetic network.
- The smoothing of the new components along an “ideal” line from Q7 Left – Inner tracker detector – Q7 Right to make the first pilot beam pass through.
- After a few weeks of operation, as soon as enough luminosity will have been accumulated to check the real position of the IP, a rigid remote re-alignment of all components from Q5 Left to Q5 Right will be carried out according to the offsets seen in the inner tracker.
- During the first YETS of Run 4, all the motors will be recentered to benefit from the maximum stroke (if needed after the first months of operation), while the level of radiations is still low.
- The compensation of ground motion all along the following years, when needed, will be performed preferably during TS, as a machine requalification is required after each movement. Small machine movements (within a few tenths of a millimetre) could be allowed without requalification during the operation of a pilot beam.

HL-LHC: Full Remote Alignment System



Components in red and in green, compatible with a remote alignment
(enough aperture and flexibility of bellows)

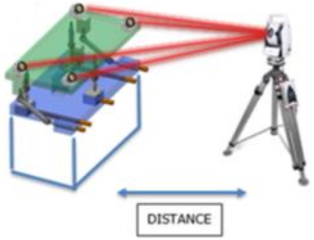
HL-LHC: Full Remote Alignment System

Solution proposed for the position determination

1. Measure the position of components using Laser tracker and permanent targets

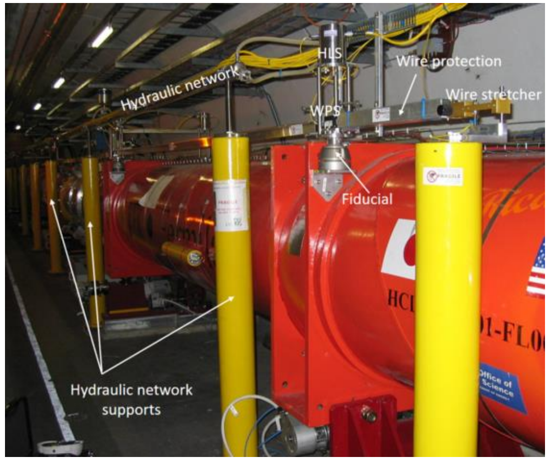
Laser tracker

Glass sphere



- ✓ Only at the end of YETS and LS
- ✓ In the tunnel

2. Measure the position using permanent sensors installed on the cryostat

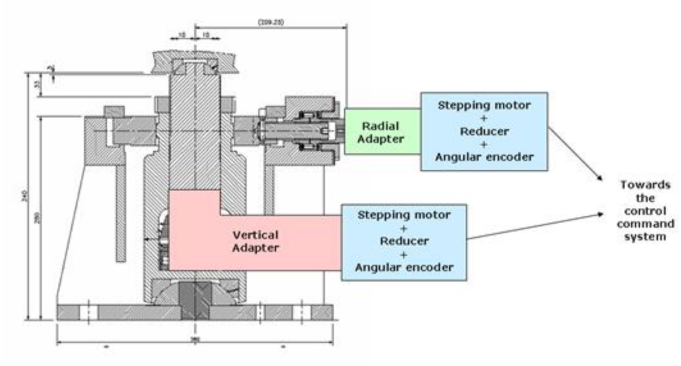


- ✓ Continuous and remote measurements
- ✓ From the CCC

HL-LHC: Full Remote Alignment System

Solution proposed for the adjustment solution

1. For components with a weight above 2t: jacks, with motorization when needed



2. For components with a weight below 2t: platforms, with motorization when needed

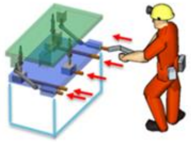


Fig. 8a. Manual adjustment: the operator turns adjustment knobs

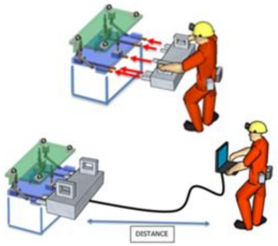


Fig. 8b. Semi/manual adjustment using temporary plug-in motors

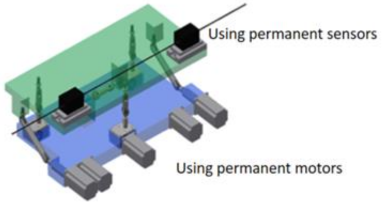
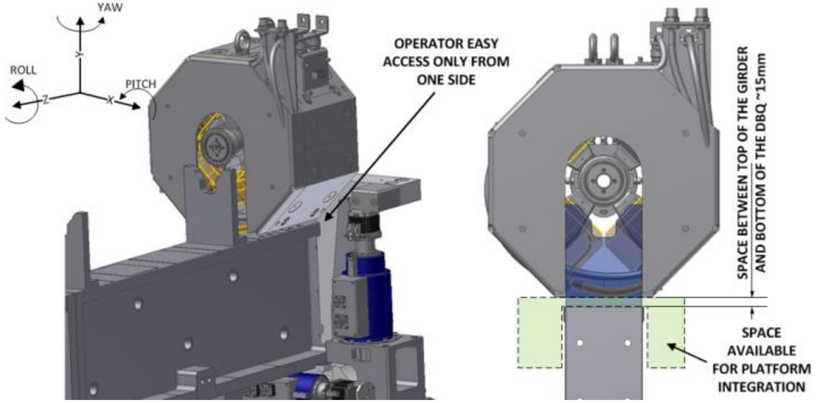


Fig. 8c. Remote alignment

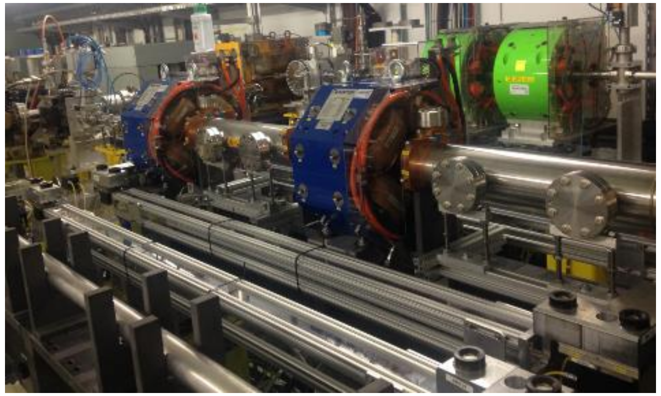
Adjustment possibilities using a platform

Full Remote Alignment System

«Standardized» adjustment platform



CLIC adjustment: space constrain



CLEAR components

Why a 5 DOF adjustment platform?

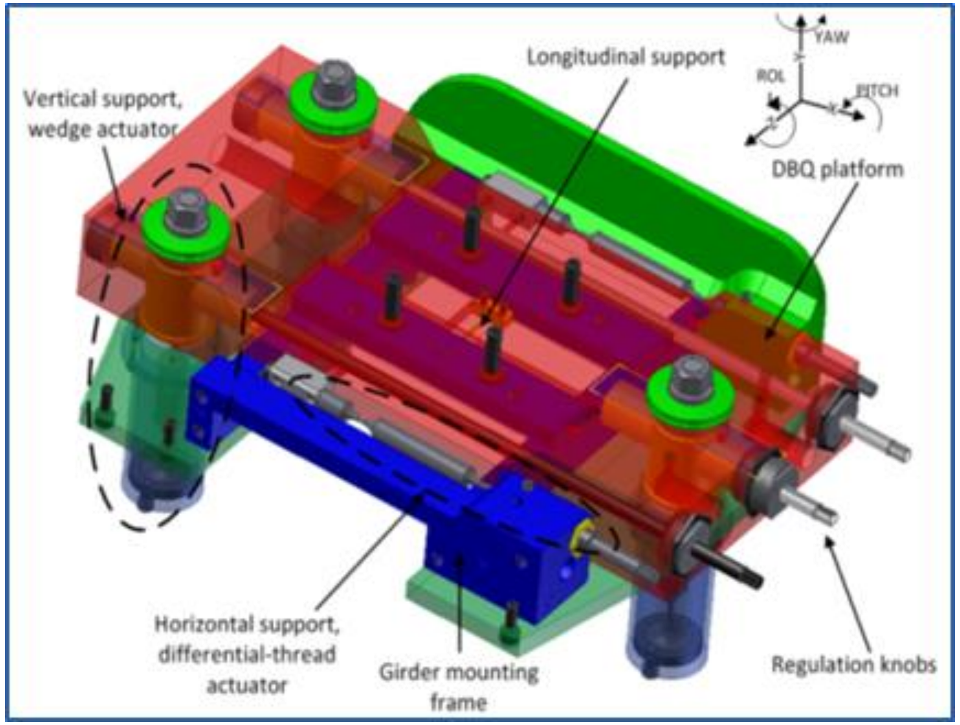
- More than 40 000 DB quadrupoles to be aligned 2 per 2 on a common support within a budget of error < 20 µm
- First tests used shims for the adjustment: the alignment took more than 1 day per quadrupole!
- Decision to develop a specific platform, with all adjustment knobs on the same side, in a limited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

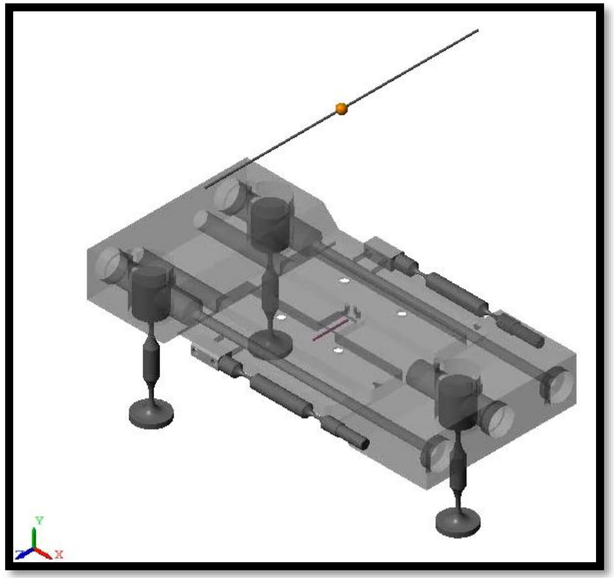
Requirements:

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

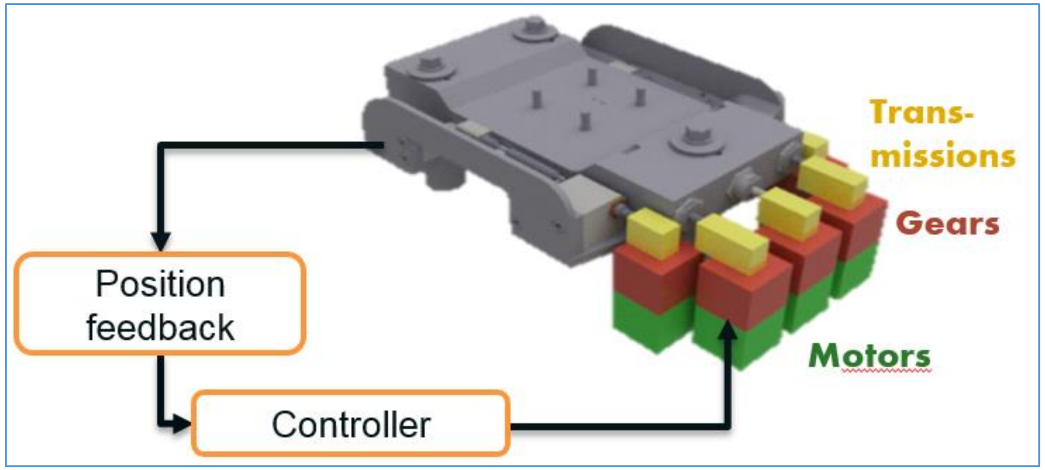
Full Remote Alignment System

«Standardized» adjustment platform





Kinematic of adjustment



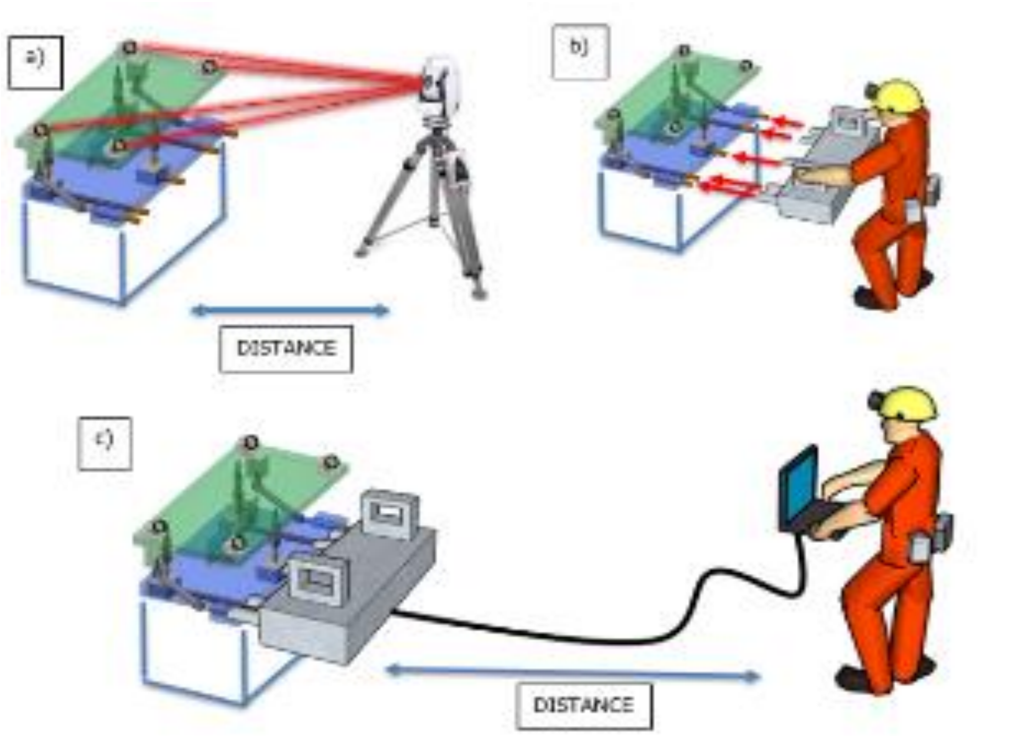
Control concept

Full Remote Alignment System

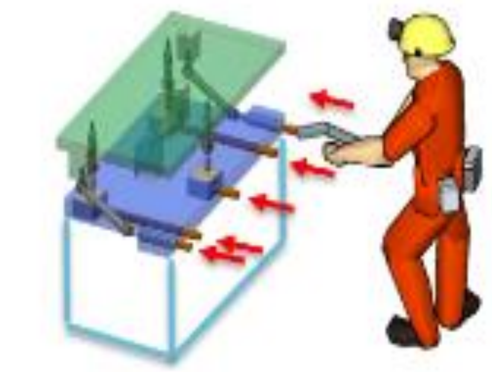
«Standardized» adjustment platform with plug-in motors

Full Remote Alignment System

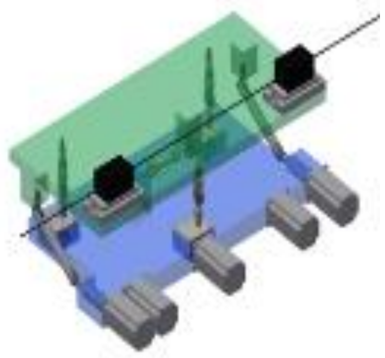
«Standardized» adjustment platform



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.



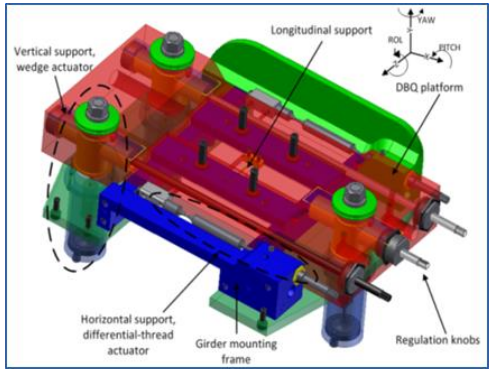
Universal adjustment platform – manual operation concept

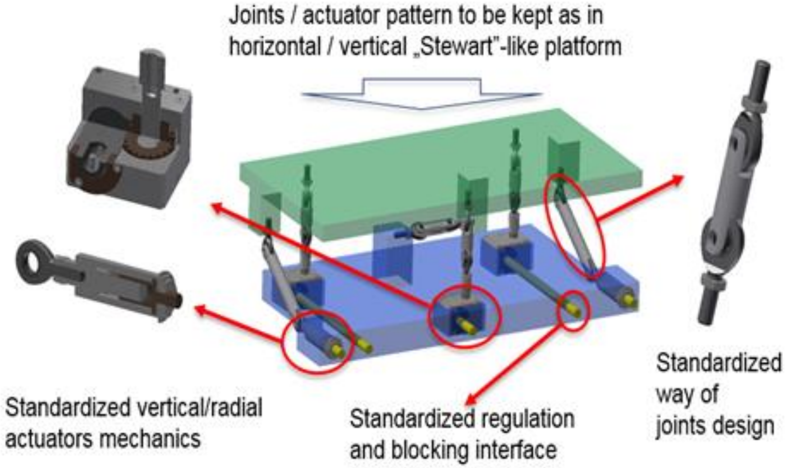


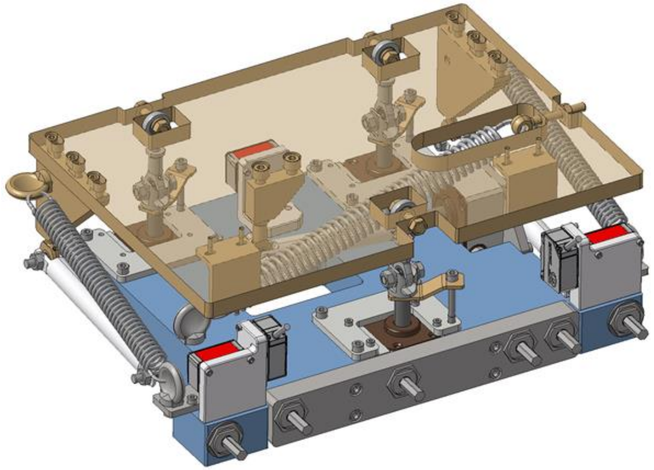
Universal adjustment solution - permanent motors version concept

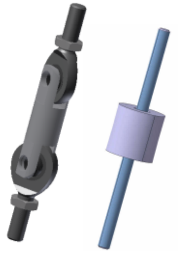
Full Remote Alignment System

«Standardized» adjustment platform

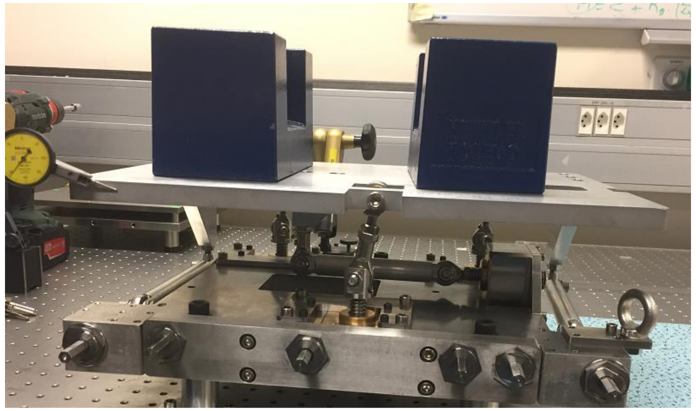








(1) (2)



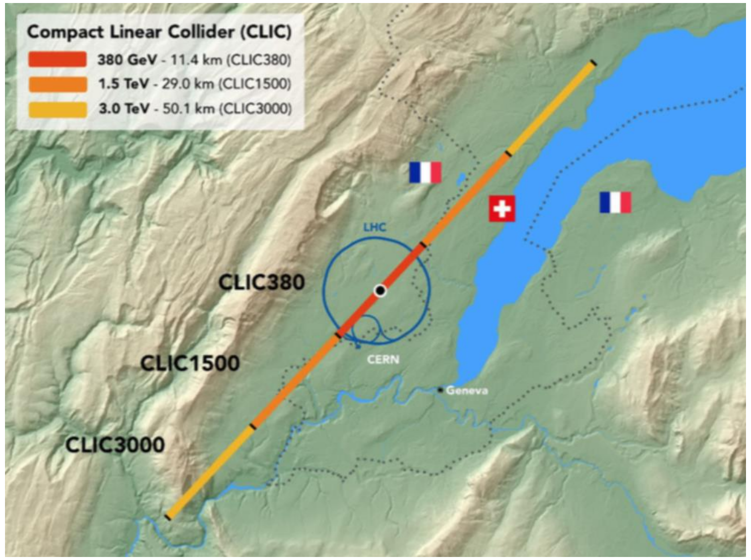
(1) Spherical joints
(2) Flexural joints: Nitinol joints and flexible shaft

R&D in survey & alignment:

Case of CLIC project
Case of FCC project
Other developments

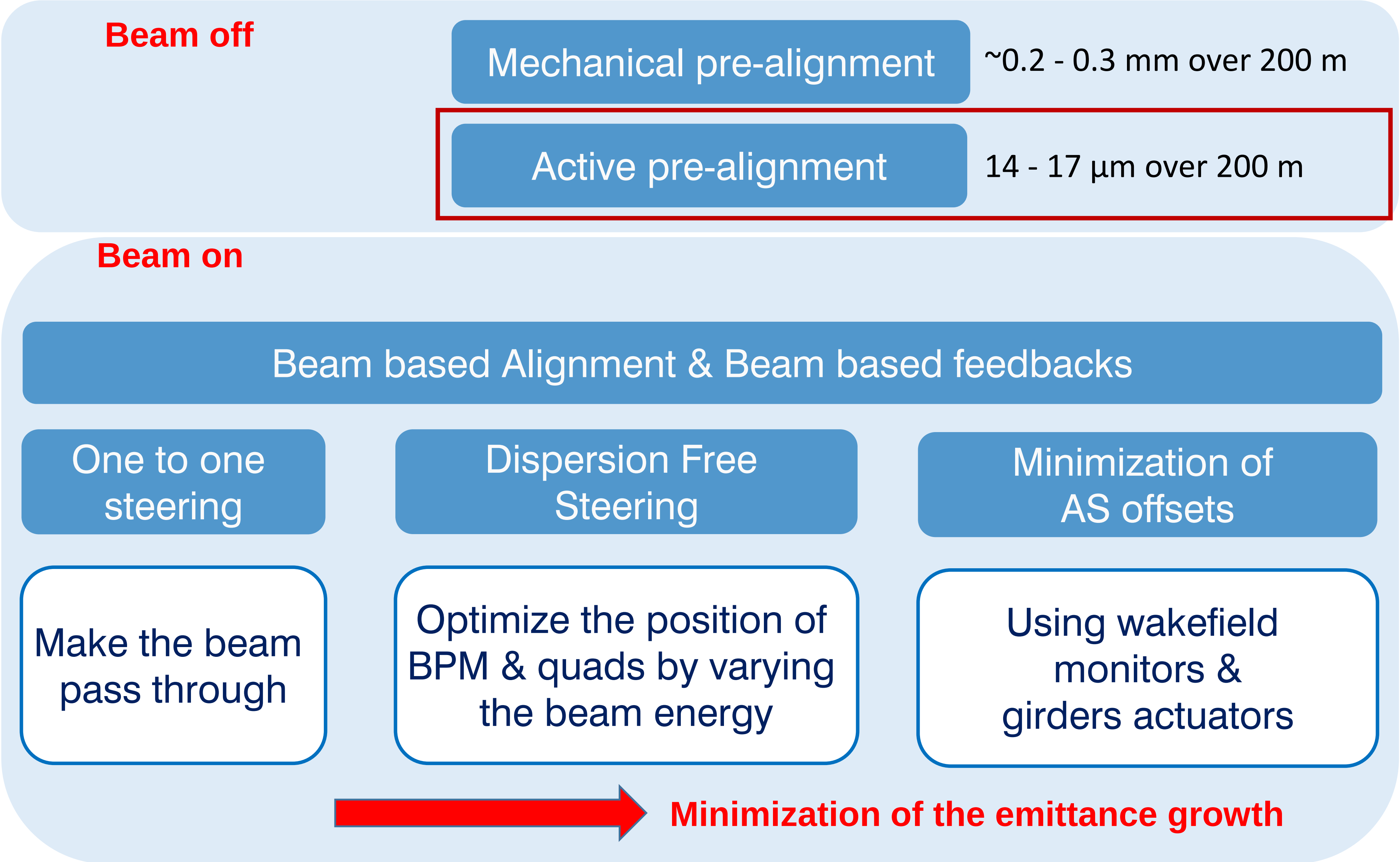
CLIC: introduction

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



Footprint of the CLIC

CLIC: introduction



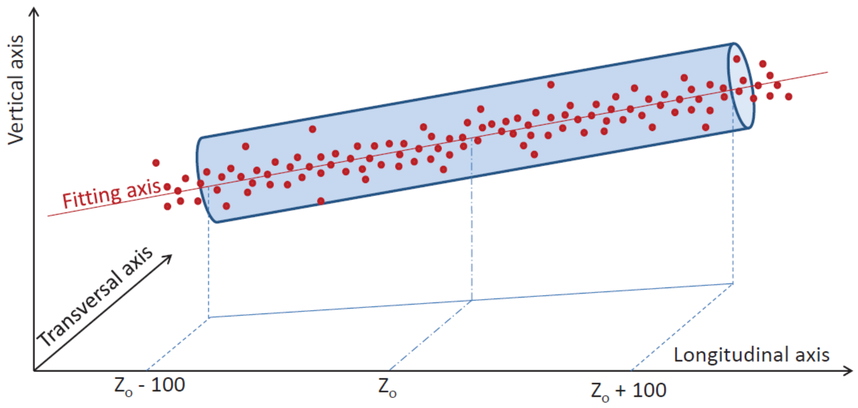
CLIC: introduction

- 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

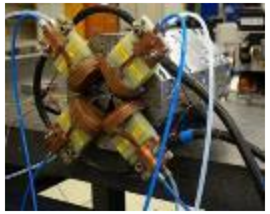


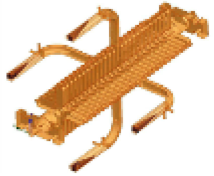
Along Main Linac: over sliding windows of 200 m

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

CLIC: introduction

Components to be aligned:





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

Strategy:

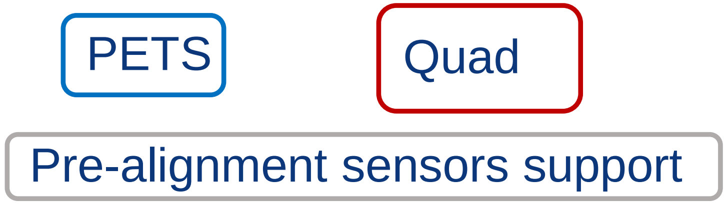
BPM | Quad

AS | AS | AS | AS

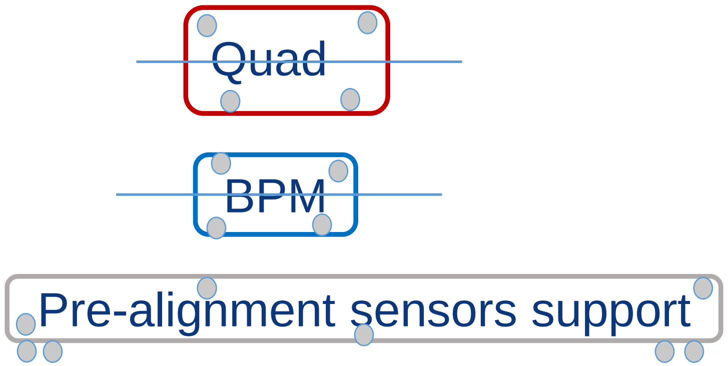
2 steps:

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

CLIC: alignment strategy

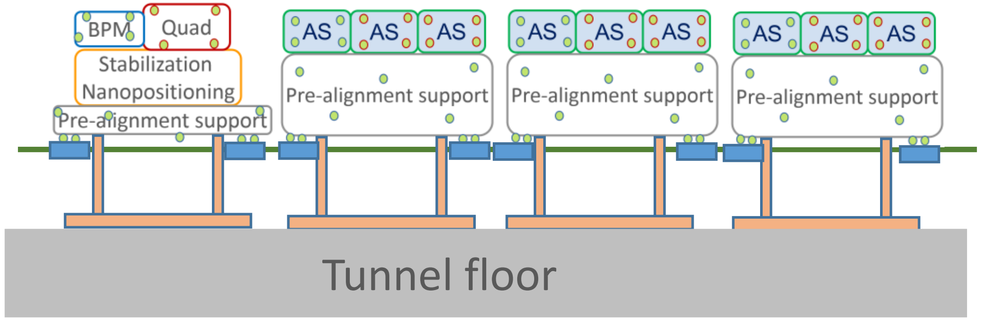


Fiducialisation:



Initial alignment:

Transfer in the tunnel:



[Mainaud Durand5]

PACMAN project

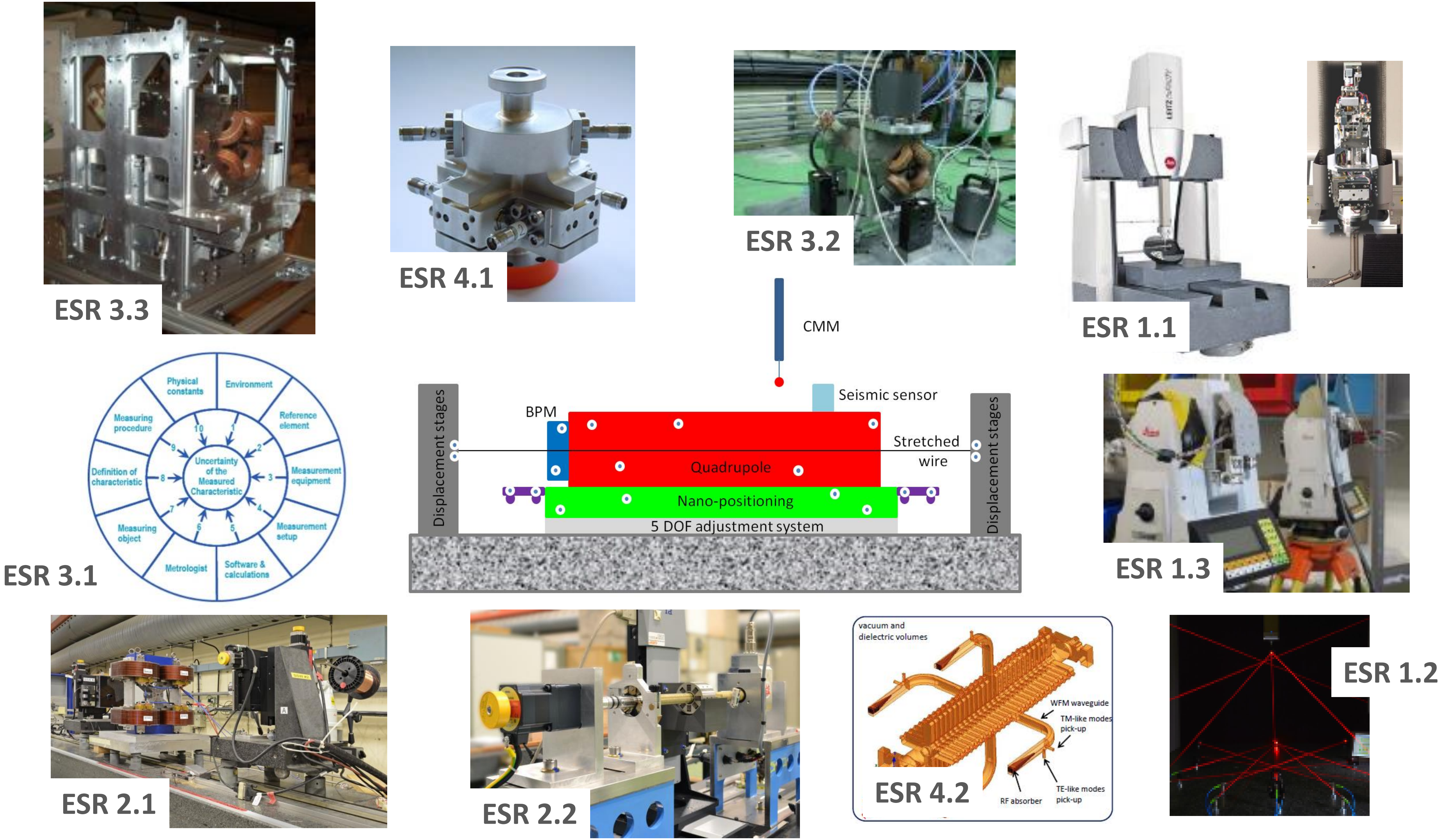
Web site: http://pacman.web.cern.ch/

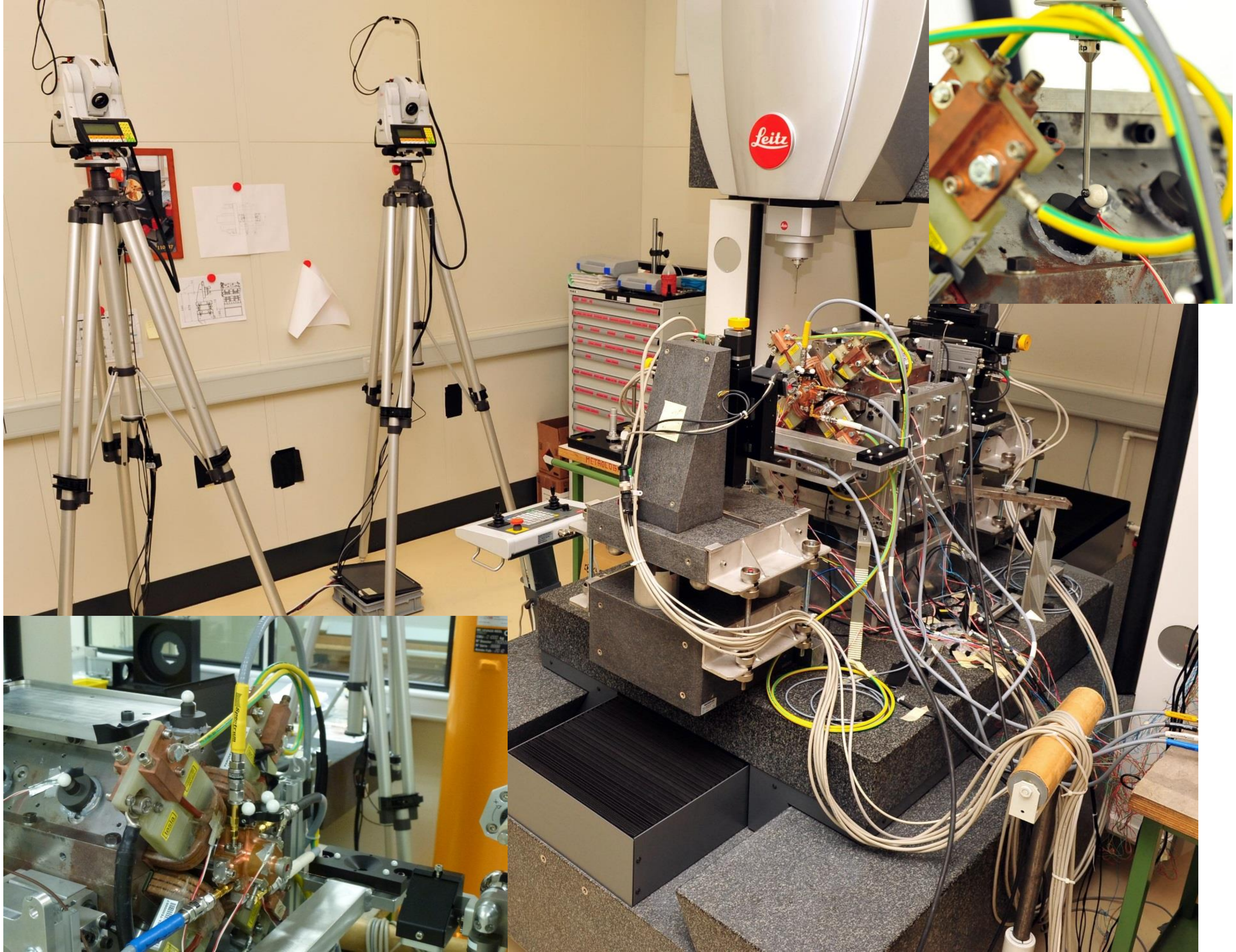
9 academic partners
8 industrial partners
4 years project: 1/09/2013 - 31/08/2017

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
Seismic sensor
BPM
Displacement stages
Stretched wire
Quadrupole
Nano-positioning
5 DOF adjustment system
Displacement stages
Physical constants
Environment
Measuring procedure
Reference element
Uncertainty of the Measured Characteristic
Definition of characteristic
Measurement equipment
Measuring object
Measurement setup
Metrologist
Software & calculations
ESR 3.1
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.

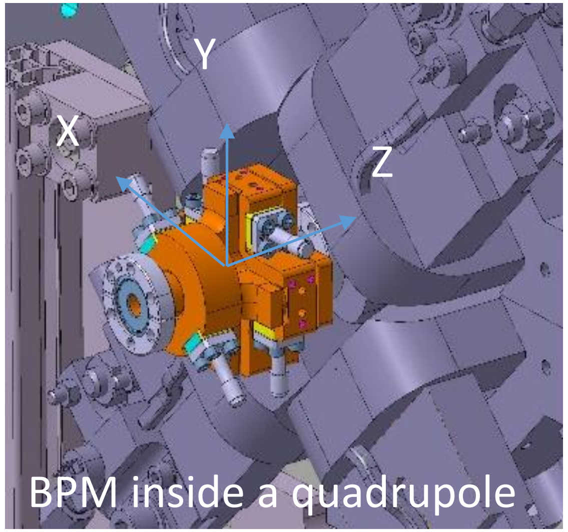


TABLE V. Mechanical, magnetic, and electric axes center offset.

	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

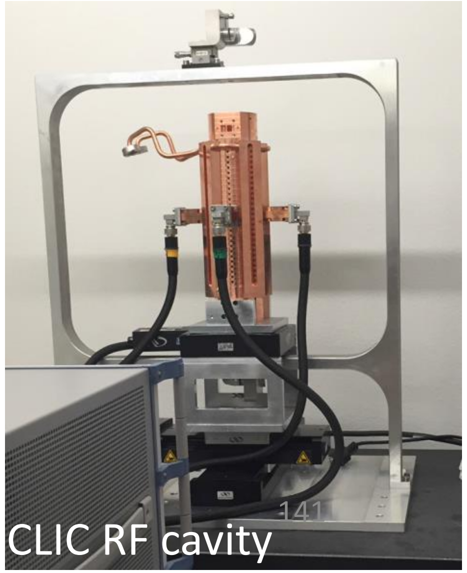
TABLE III. Offset between the mechanical axis and the magnetic axis at 126 A.

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]



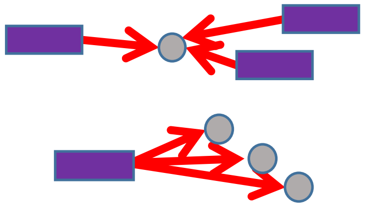
PACMAN: a few interesting results

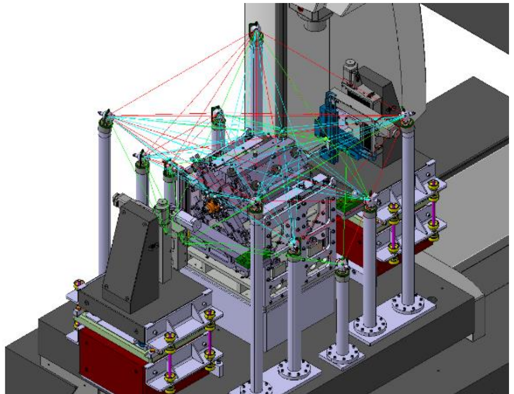
Determination of the position of the stretched wire, w.r.t. external targets:

3 methods:

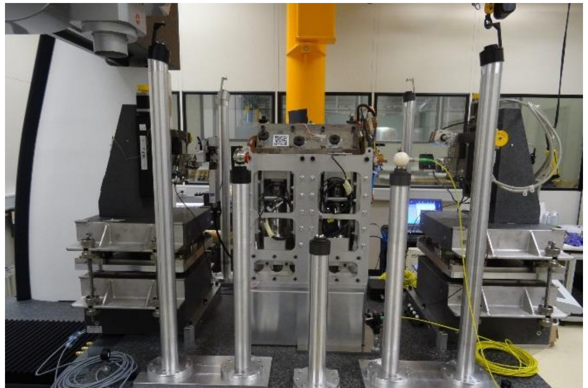
- Coordinate Measuring Machine measurements (+wire measured using confocal sensor plugged on the CMM head): uncertainty ~ 2 µm
- Frequency Scanning Interferometry (absolute distance measurements)
- Micro-triangulation (angle measurements)

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





Simulations on FSI config.



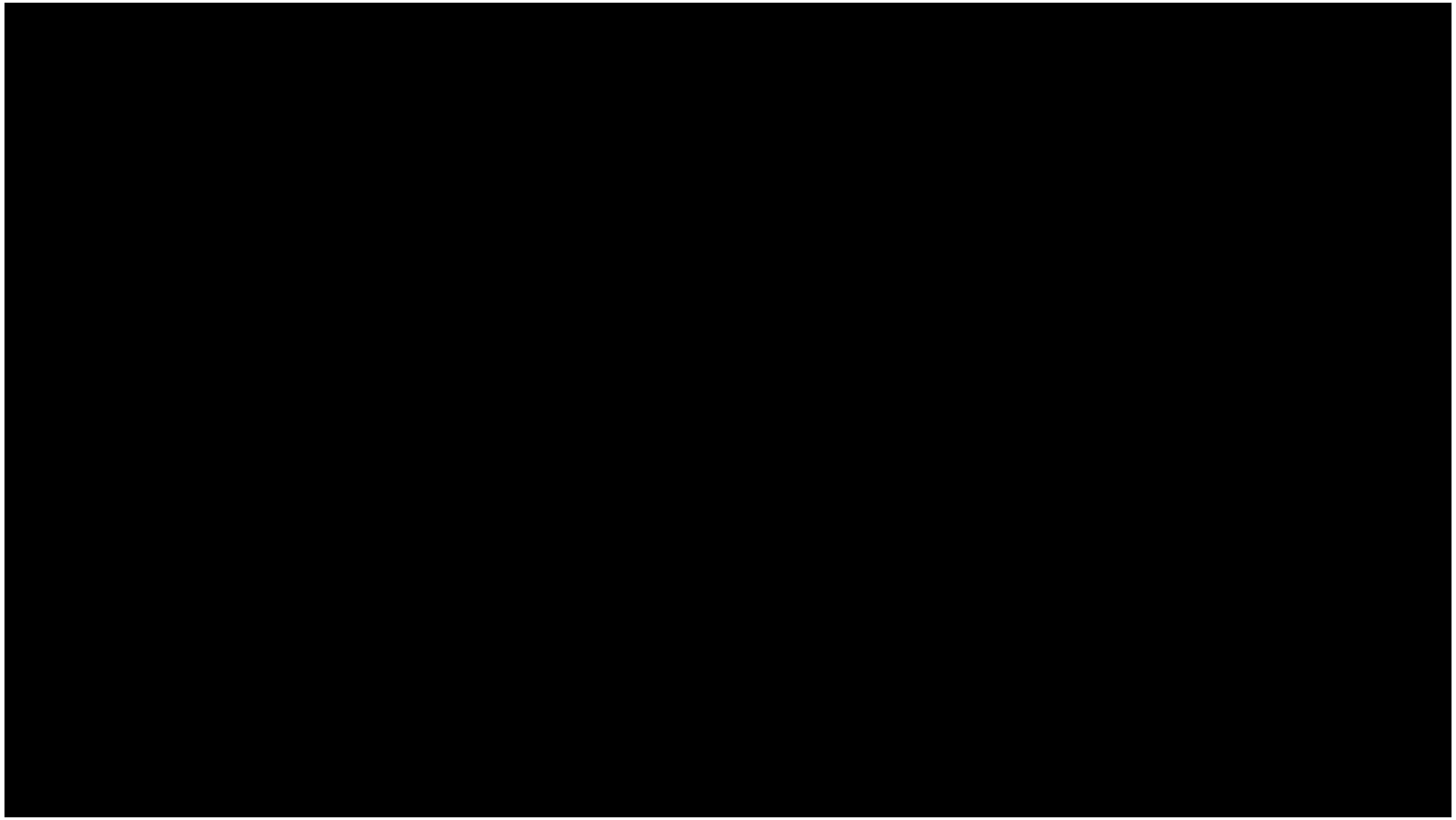
FSI config. in CMM

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

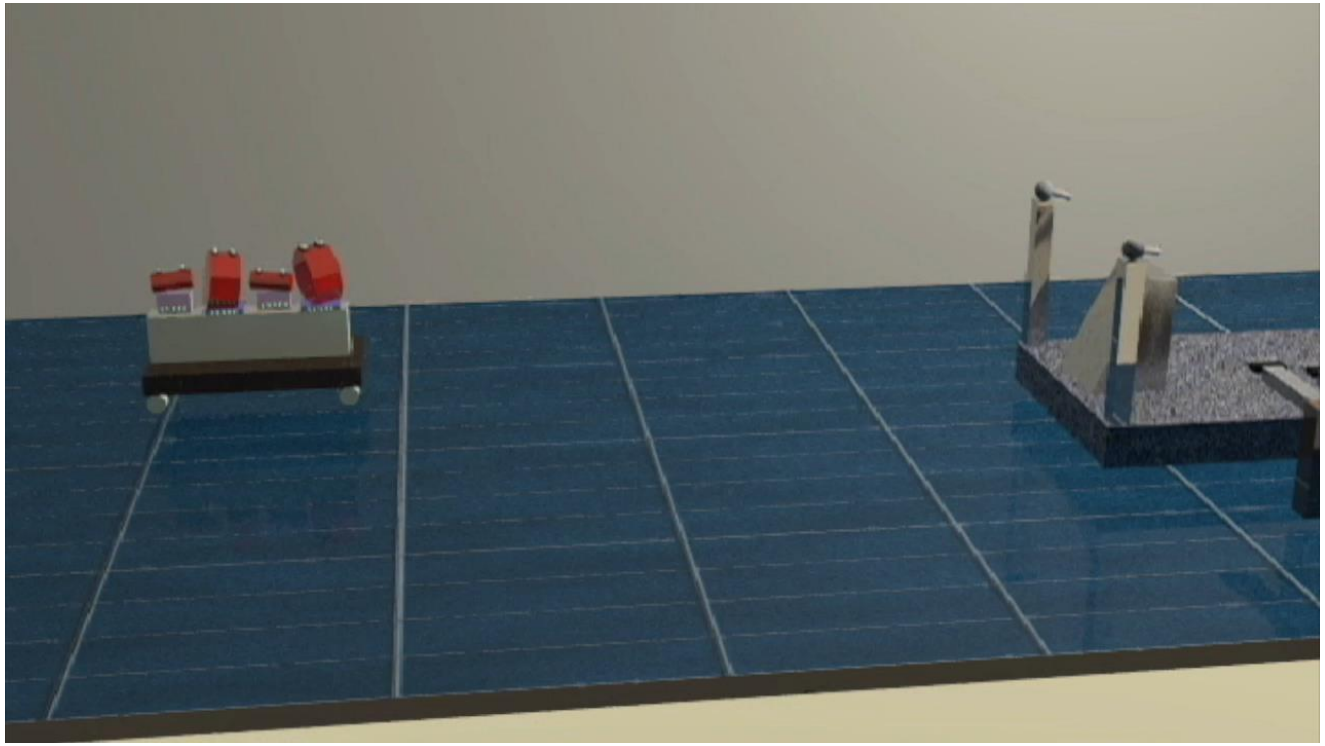
Strategy also applicable in the tunnel, after transport

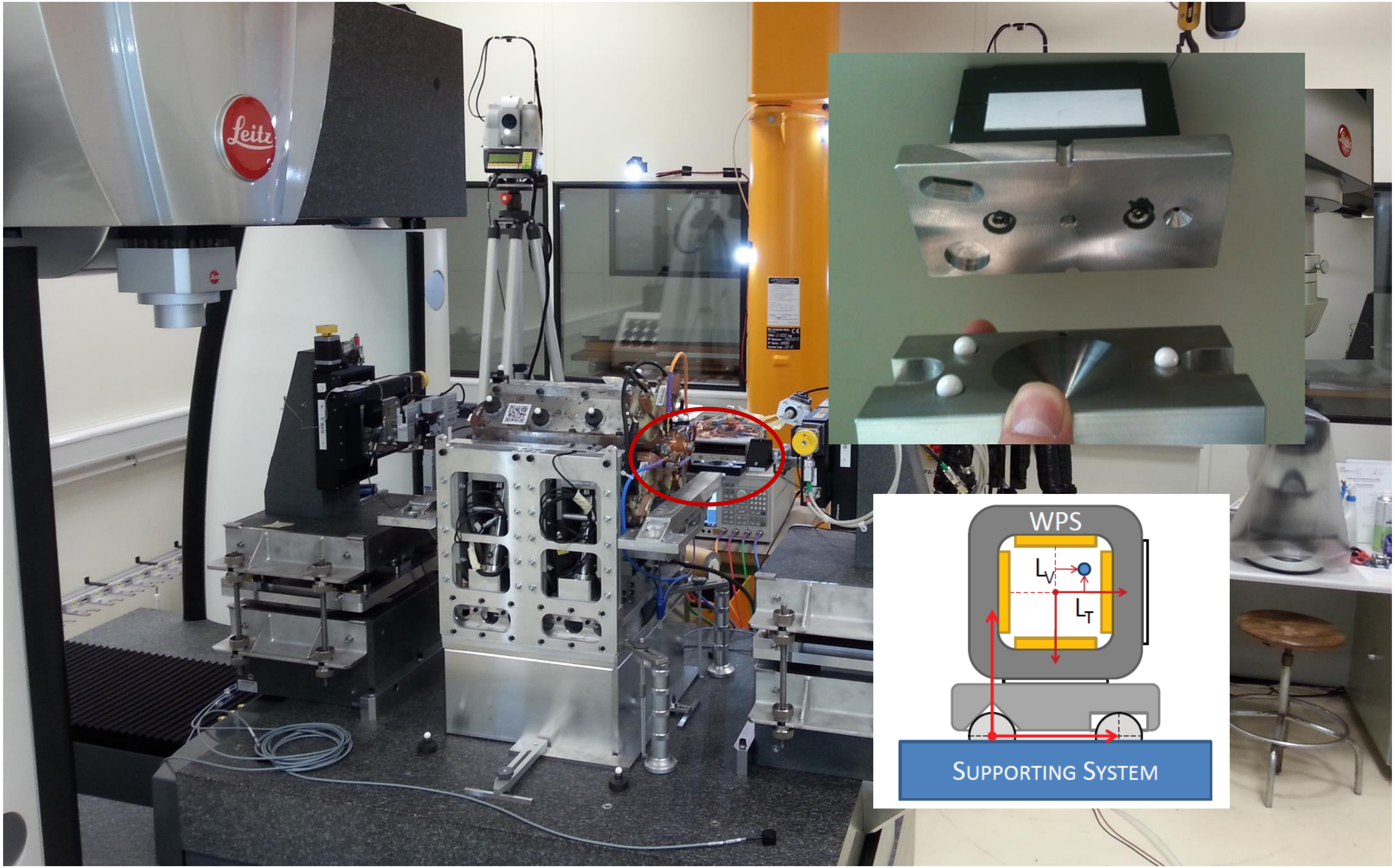
- All components individually fiducialised (PACMAN process using stretched wire)
- Alignment on a common support using plug-in system, knowing the position of the targets.



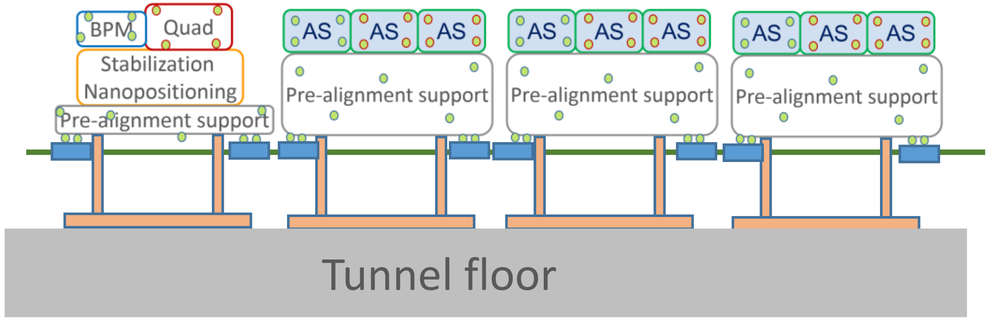
PACMAN: scenario 2

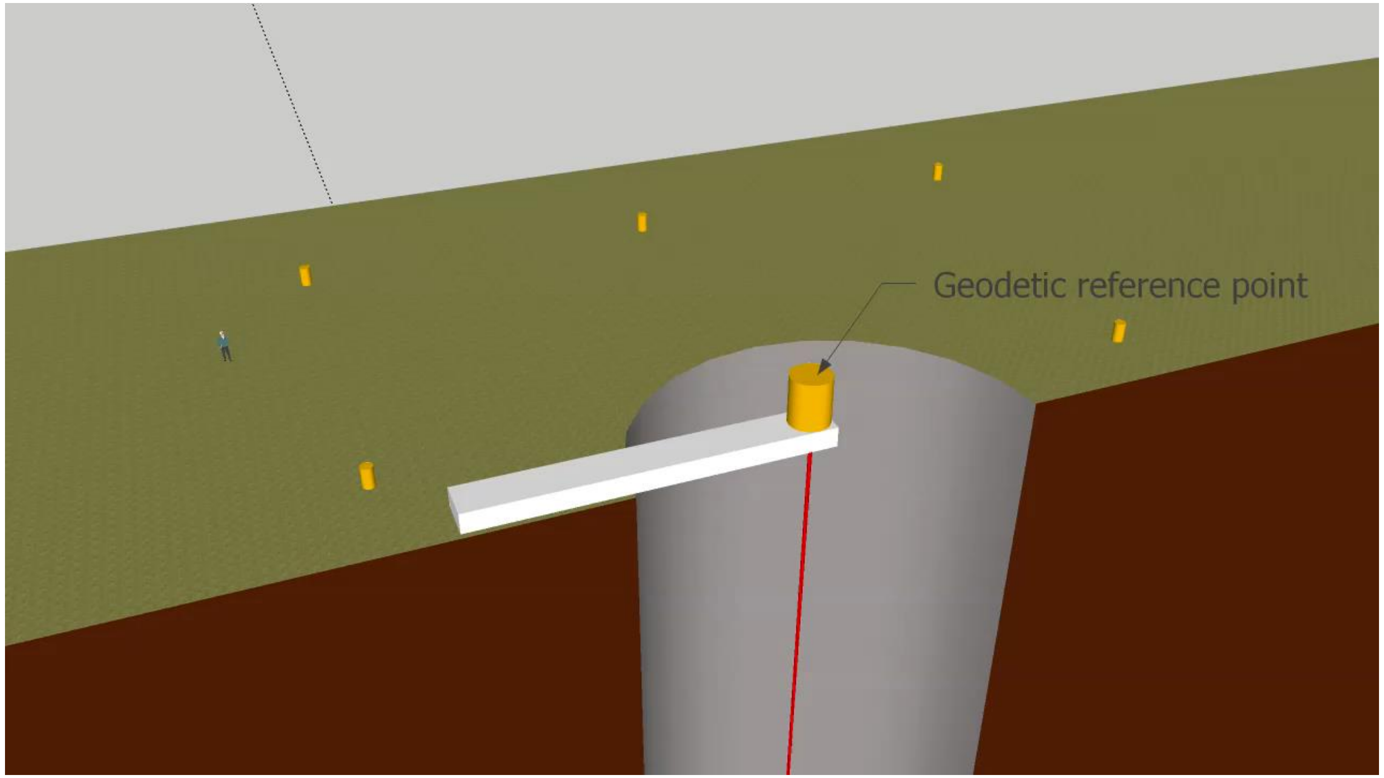
- All components installed roughly on a common support
- Installation of a stretched wire to align all the components reference axes at a theoretical position on the common support (PACMAN process + 5 DOF adjustment system)
- Determination of the position of the alignment targets once all the components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




Leitz
WPS
LV
LT
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)	5	10 (TBC)	5	10 (TBC)	5
Fiducials to pre-alignment sensor interface	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

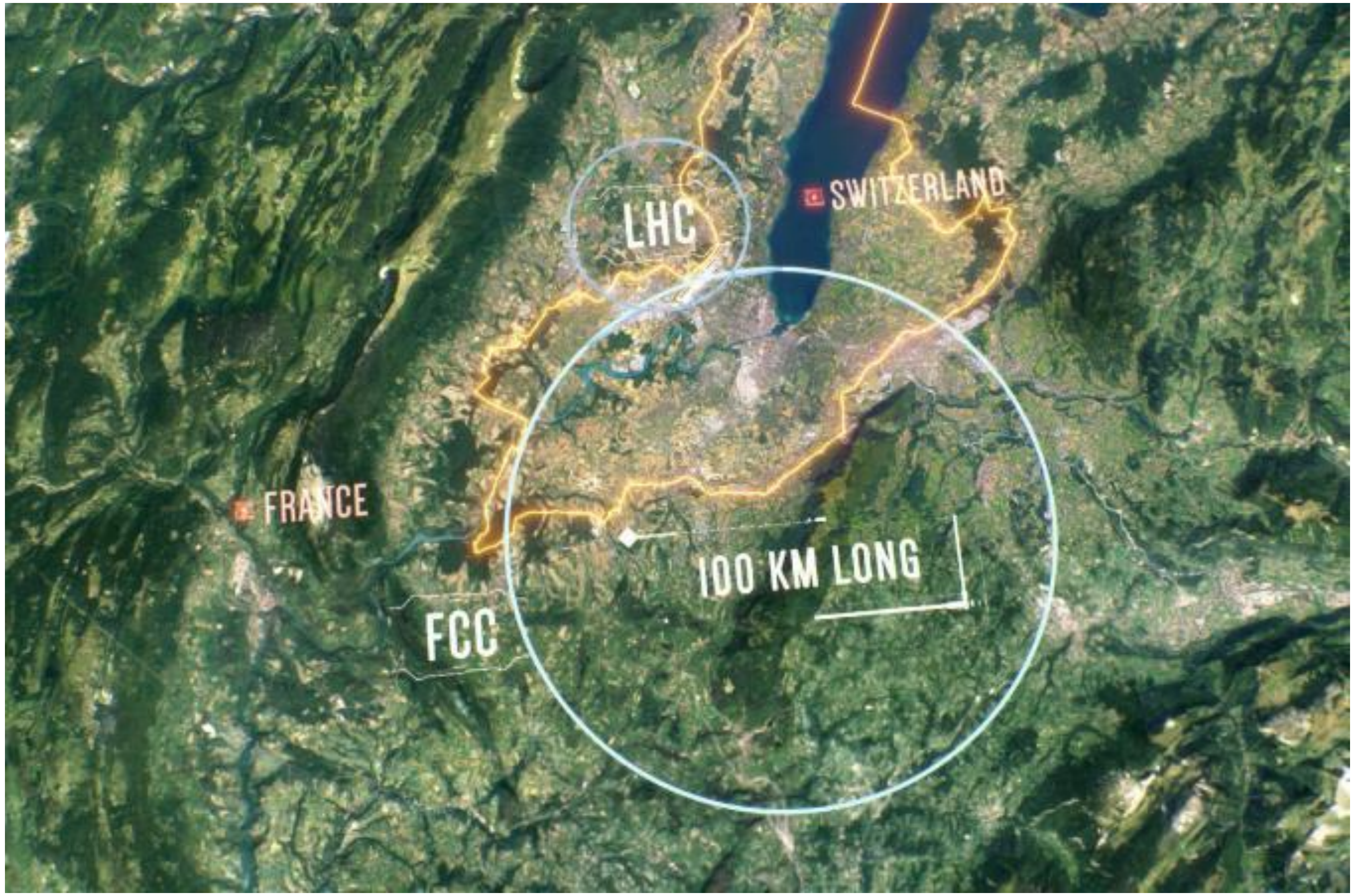
Common with HL-LHC

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)



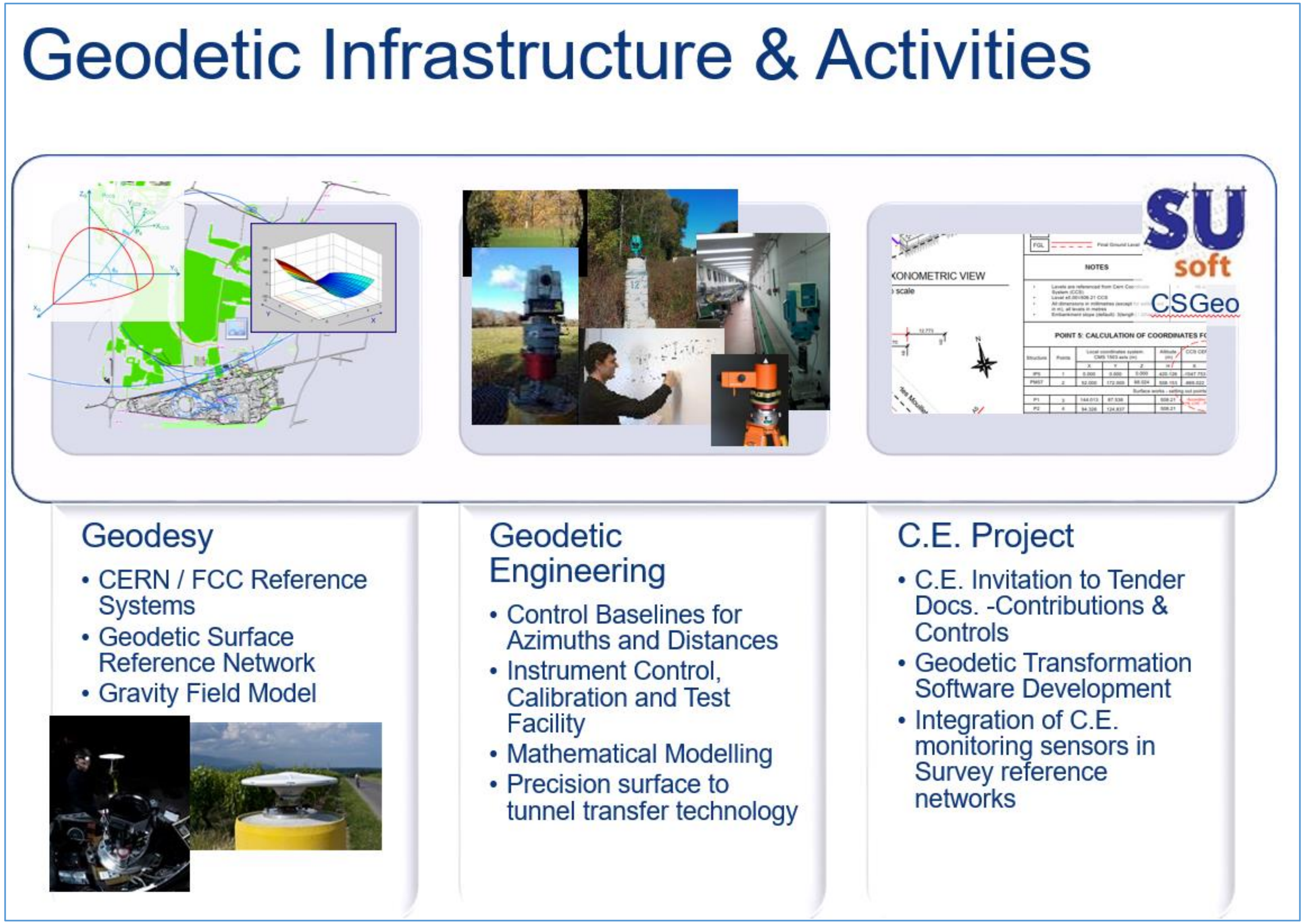
FCC alignment

- 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 ?

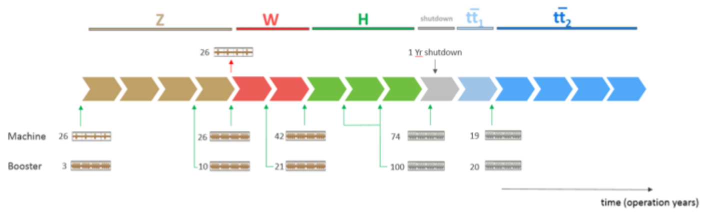
FCC alignment



FCC alignment

FCC-ee Operational Constraints

FCC-ee Operation Timeline



A. Niemi

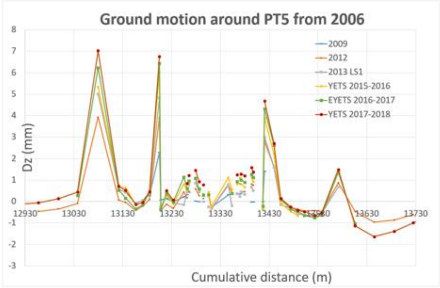
shutdown	no. cryomodules	length of shutdown
shutdown 1	–	12 weeks
shutdown 2	–	12 weeks
shutdown 3	10 CM	12 weeks
shutdown 4	26 CM	20 weeks
shutdown 5	21 CM	14 weeks
shutdown 6	42 CM	18 weeks
shutdown 7	30 CM	15 weeks
shutdown 8	30 CM	15 weeks
long shutdown	104 CM	1 year
shutdown 11	39 CM	17 weeks
shutdown 12	–	–
shutdown 13	–	–
shutdown 14	–	–

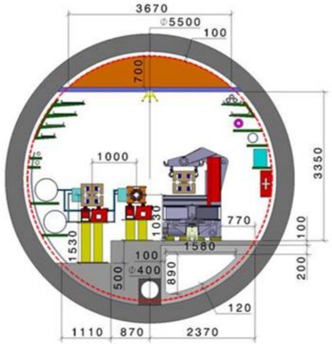
- Winter Shutdown
  - 12 to 20 wks

  20 days Machine Development / yr
- 11 days for Technical Stops
- Long Shutdown after 9 years

Other Constraints

- Significant tunnel / ground motion possible (>1 mm / year in LHC)
- Maintenance Access
  - Beamline elements
  - Position Monitoring and Alignment System





FCC alignment

Provisional Survey Working Parameters
Interpretations & Assumptions! To Confirm!!

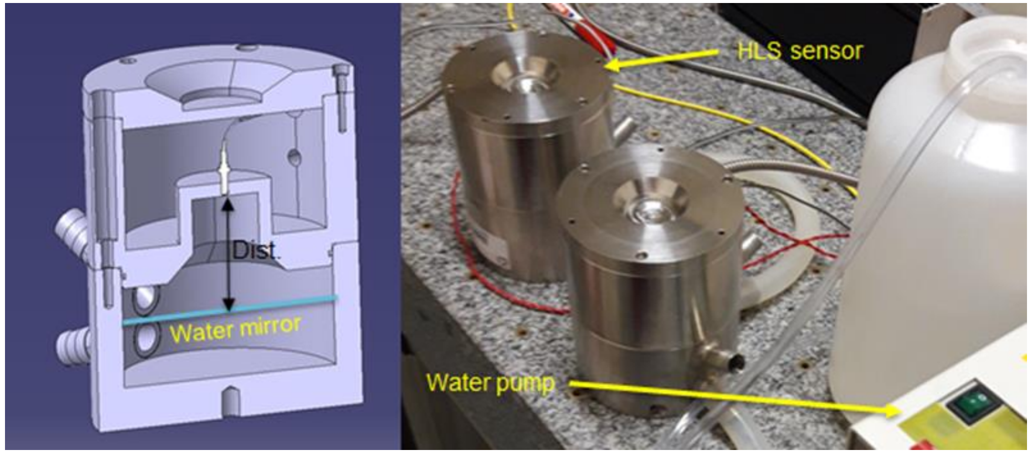
- Tunnel Alignment Precision Requirement
  - Main Ring: ~30 μm @ 1σ
  - Booster Ring: ~50 μm @ 1σ
- Quadrupoles and Sextupoles
  - Assembled on a Single Girder
- Frequent position monitoring required
- Re-alignment/Smoothing at least 1 / year
  - Main Beam arcs => ~12000 beamline modules
  - Booster arcs => ~10000 beamline modules

Provisional Survey Working Parameters
Interpretations & Assumptions! To Confirm!!

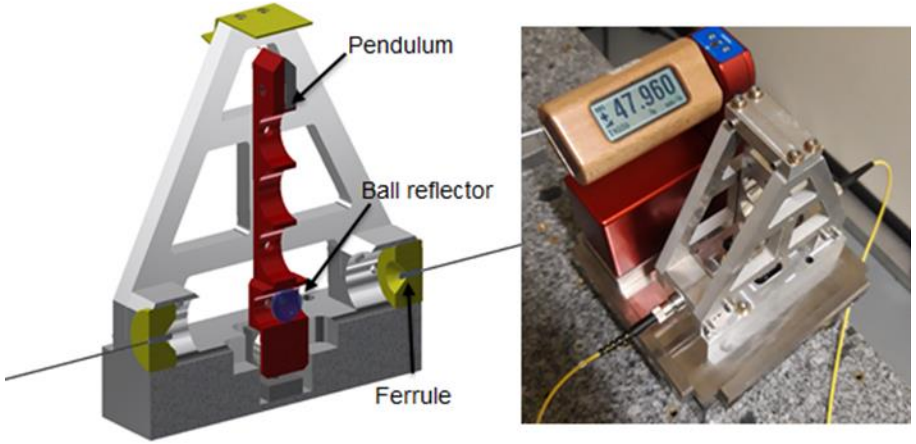
- Limited time for Survey tunnel activities
  - During both installation and operation
- Maintenance Access
  - Cannot disturb any Survey Tunnel Reference Infrastructure
- CDR Position Monitoring and Alignment Solution
  - Based on design for CLIC
  - Consequences for Accelerator Installation
  - Consequences for Geodesy

We have to develop a new generation of alignment sensors and actuators making the remote alignment of accelerators affordable.

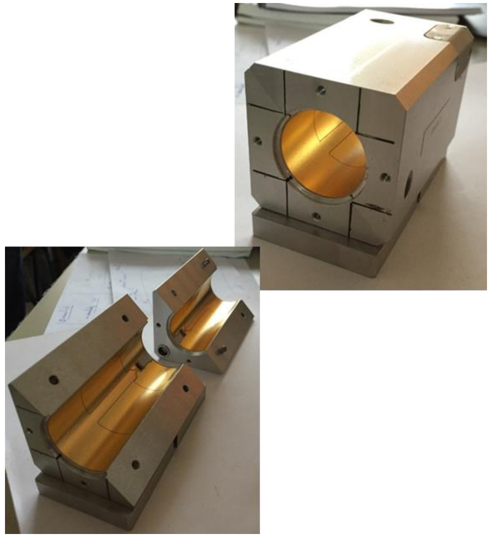
Other R&D

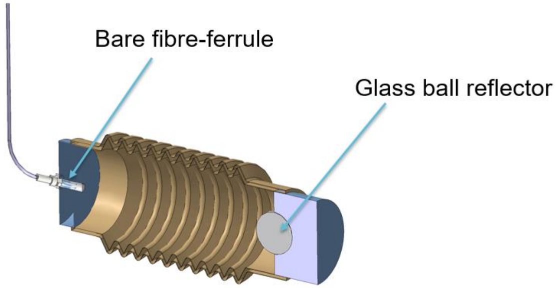


FSI-based HLS



FSI-based inclinometer


Capacitive based WPS



Short distance FSI

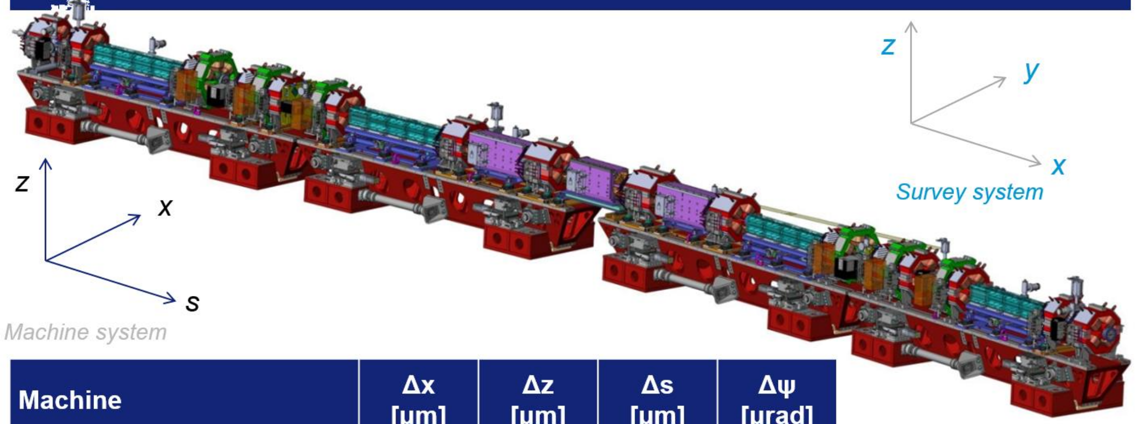

Long distance FSI

Study case: ESRF

What is the alignment strategy for :

- A synchrotron (Ø = 270 m), including:
- 129 girders
- 1000 magnets

ALIGNMENT TOLERANCES



Machine	Δx [µm]	Δz [µm]	Δs [µm]	Δψ [µrad]
Long. Varying field dipoles	>100	>100	1000	500
High gradient quadrupoles, Combined function dipoles	60	60	500	200
Medium gradient quads	100	85	500	500
Sextupoles	70	50	500	1000
Octupoles	100	100	500	1000

D. Martin Alignment EBS, IWAA2018 Fermilab Chicago USA

The European Synchrotron | ESRF

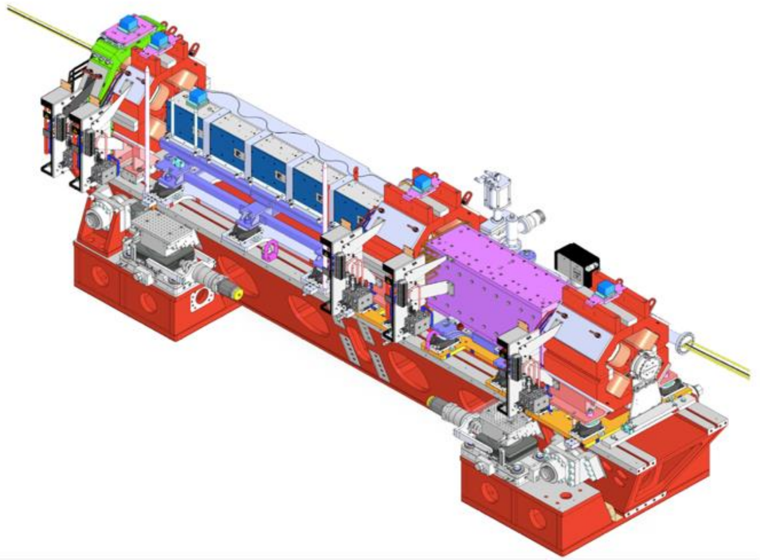
All info from this (very interesting) presentation:

Alignment of the ESRF Extremely Brilliant Source (EBS)
IWAA2018 Fermilab
David Martin ESRF

ESRF | The European Synchrotron

Study case: ESRF

EVERYTHING IS ASSEMBLED ON GIRDERS

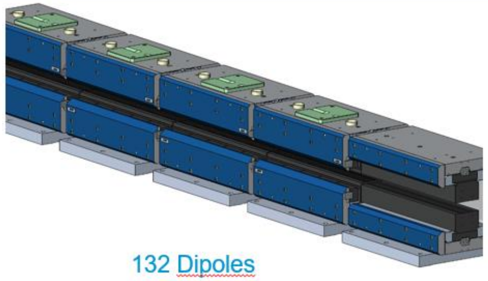


Four girders per cell :
- Magnet supports
- Magnets
- Vacuum equipment
- Diagnostics

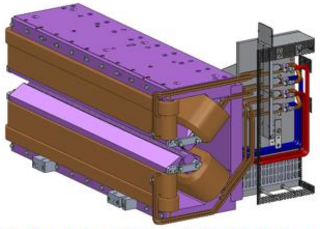
128 girders

6T empty
12-13T fully equipped

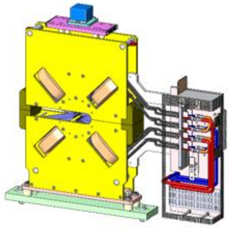
MAGNETS



132 Dipoles

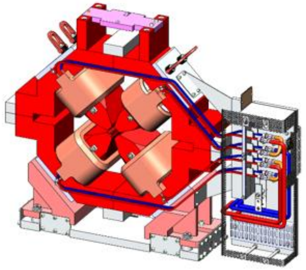


100 Combined function-quadrupoles

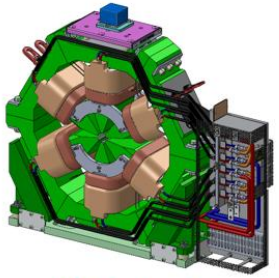


66 Octupoles

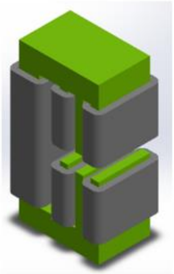
More than 1000 Magnets have been manufactured



524 Quadrupoles
(132 HG, 392 MG)



196 Sextupoles



98 Correctors

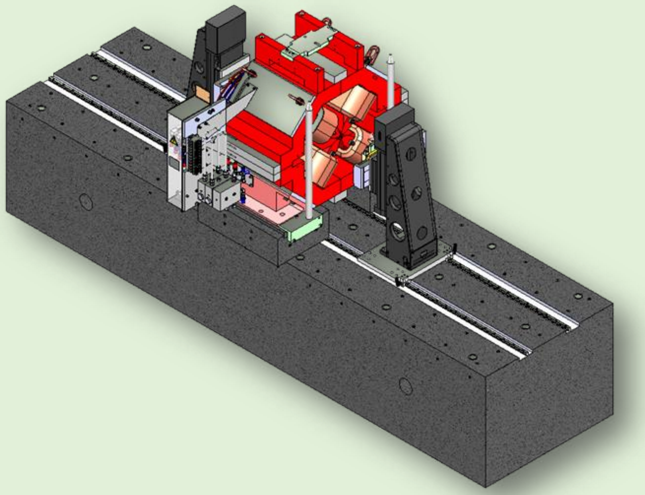
Study case: ESRF

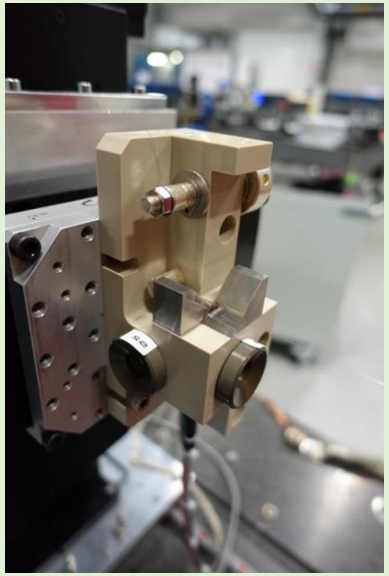
FIDUCIALISATION UNCERTAINTY

	Ux [µm]	Uy [µm]	Uz [µm]
Laser Tracker			
Wire position	13	17	22
Measurement	9	10	9
Repeatability	3	3	12
Magnet measurements		7	7
Magnetic Fiducialisation	*13*	*22*	*27*
Magnet Shim Determination			*29*
Total	**13**	**22**	**40**

We combine all of these errors/uncertainties to determine the fiducialisation uncertainty contribution.

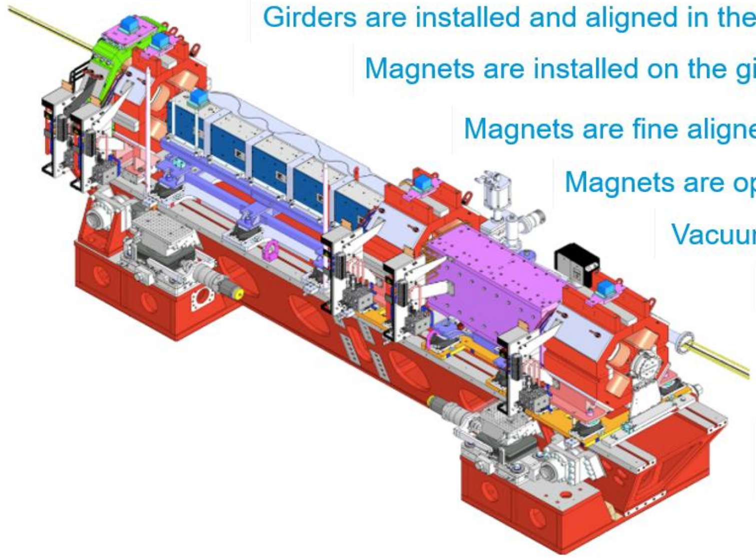
This is just one of many contributions to the overall alignment uncertainty…





Study case: ESRF

GIRDER ASSEMBLY



- Girders are installed and aligned in the horizontal plane
- Magnets are installed on the girder 0.5 mm
- Magnets are fine aligned 0.05 mm
- Magnets are opened
- Vacuum string is installed
- BPMs aligned 0.1 mm
- Magnets are closed
- Fine magnet alignment check and survey

ALIGNMENT OF THE GIRDER AND MEASUREMENT OF PLANARITY

The girders are aligned horizontally, the planarity is measured, and the local girder coordinate system established.

Study case: ESRF

MAGNETS ARE INSTALLED ON THE GIRDER AND ALIGNED

The magnets are installed on the girders and aligned to their nominal positions

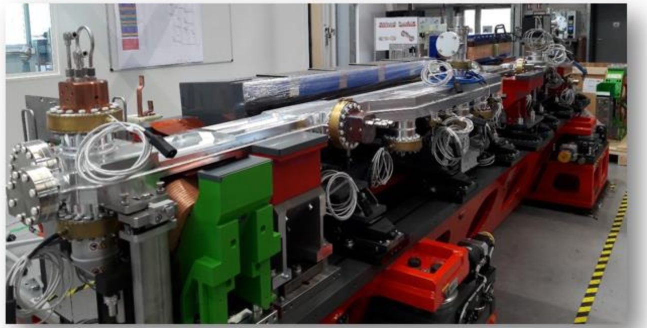
THE MAGNETS ARE OPENED AND THE VACUUM STRING IS INSTALLED.

The magnets are opened and the vacuum string is installed*

**Not shown here, the vacuum chambers are installed, aligned and baked out in the adjacent vacuum lab.*

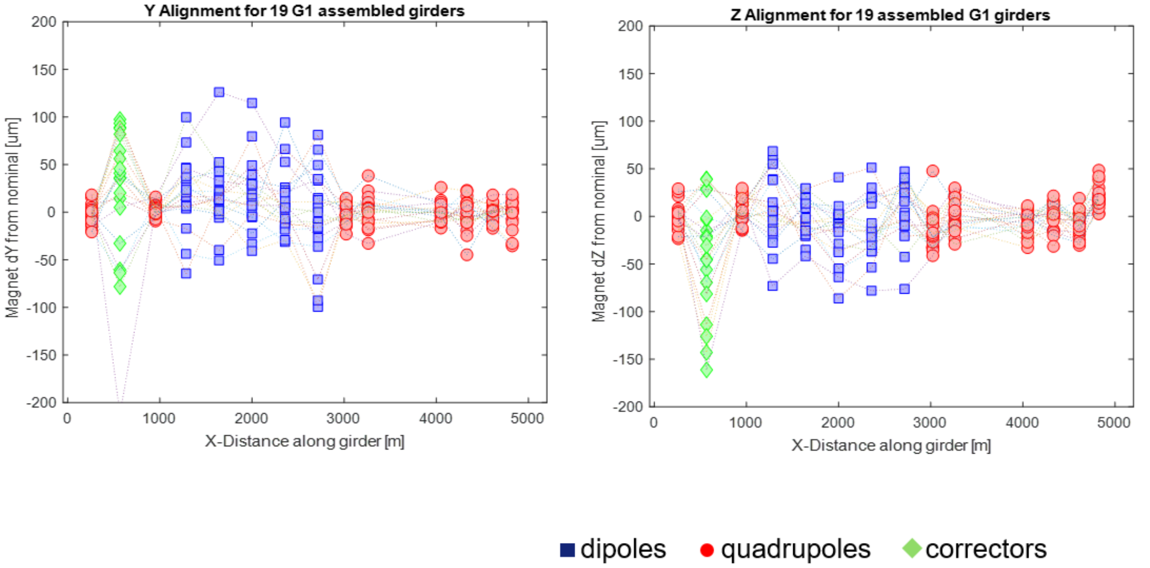
Study case: ESRF

THE VACUUM STRING IS ALIGNED AND THE FINAL ALIGNMENT MADE



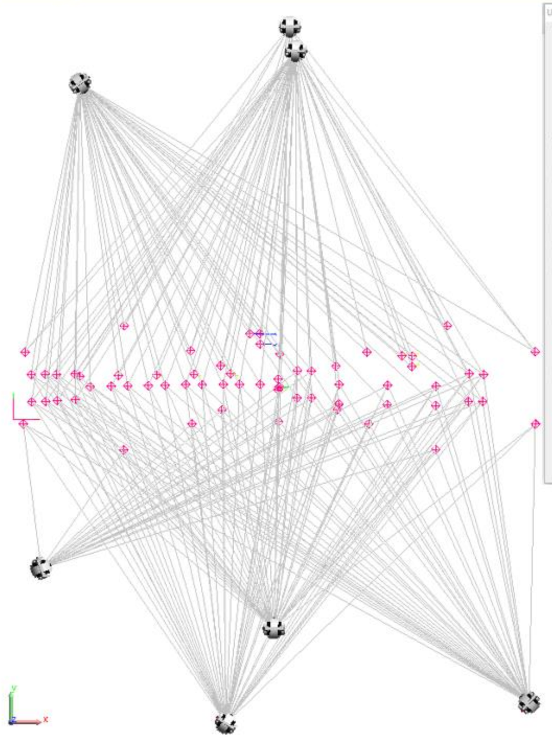
The vacuum chambers/BPMs are aligned, the magnets closed and the final alignment survey is made

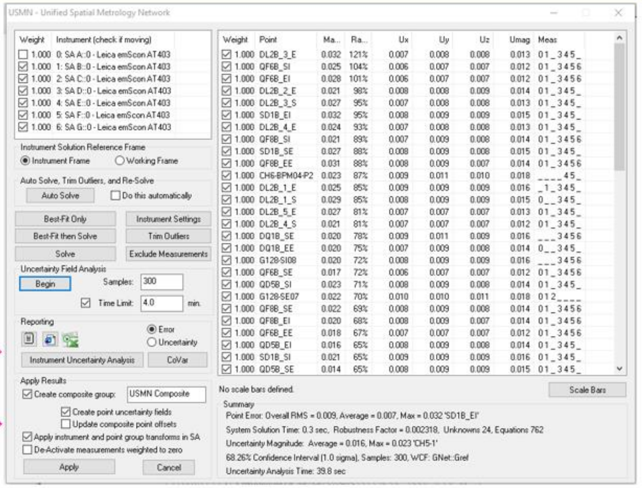
ALIGNMENT SUMMARY FOR 19 ASSEMBLED G1 GIRDERS



Study case: ESRF

GIRDER ALIGNMENT UNCERTAINTY





	Ux [µm]	Uy [µm]	Uz [µm]
Measurements	6	7	6
Transformation to nominal	126	24	25
Optimal Positioning		14	17
Total	**126**	**39**	**21**

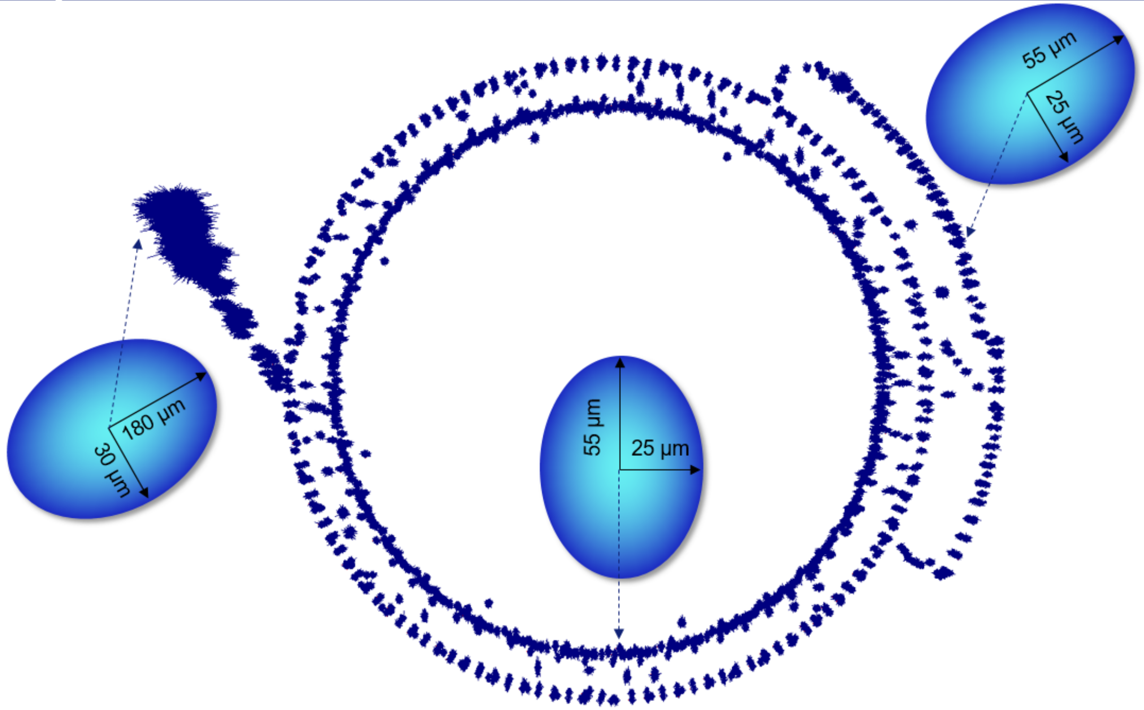
THE ESRF SURVEY NETWORKS

AT401/402/403
Laser Tracker

Angles ± 5 µm + 6 µm/m
Distance ±10 µm
ASME B89.4.19-2006 MPE

Study case: ESRF

EX2 NETWORK UNCERTAINTY



ESTIMATED INSTALLED UNCERTAINTIES

Final magnet alignment uncertainties for the EBS machine are currently estimated to be:

	Ux [µm]	Uy [µm]	Uz [µm]
Fiducialisation	13	22	40
Girder Rectitude	38	8	8
Magnet Opening/Closing	8	5	7
Alignment on girder	126	29	31
Transport	20	20	20
*Alignment in tunnel**	*25*	*15*	*15*
*Measurement in tunnel***	*26*	*55*	*30*
Total	**139**	**71**	**64**

** Estimated from existing networks not measured*
*** These values will certainly evolve downward*

Recall required tolerances:

Machine	Δy [µm]	Δz [µm]	Δx [µm]
Long. Varying field dipoles	>100	>100	1000
High gradient quadrupoles, Combined function dipoles	60	60	500
Medium gradient quads	100	85	500
Sextupoles	70	50	500
Octupoles	100	100	500

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, even before the official green light of the project.

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.

Conclusion

For the next generation of colliders, we need to develop robust, performant and low cost alignment sensors, optimizing also associated cables.

We will need to automatize standard operation, due to the limited access in the tunnel, important number of components to be marked, pre-aligned, etc.

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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