Joint Universities Accelerator School

SURVEY and ALIGNMENT in accelerators

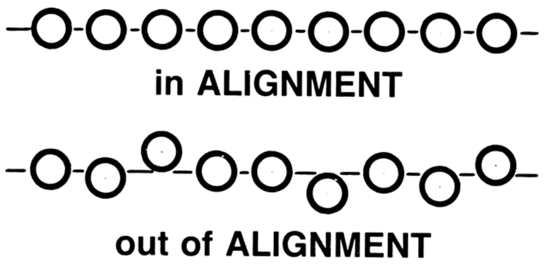
Jean-Christophe Gayde

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?

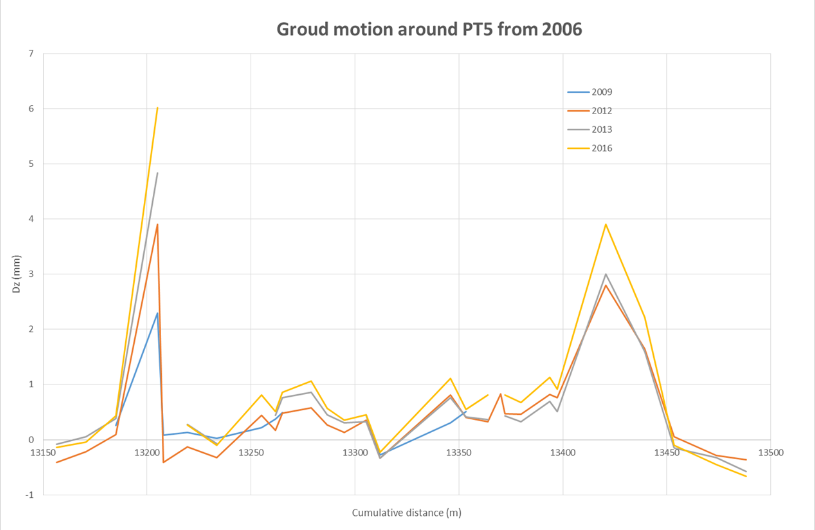
- According to the Oxford dictionary: “an arrangement in which two or more things are positioned in a straight line”
- In the context of particle accelerators, the “things” are: beam instrumentation & vacuum devices, magnets, RF components, etc.

Why aligning components?

- Earth on which accelerators are buit is in constant motion
- Mechanical constraints (Vacuum, t°, P, …..) generate “disruptions”
- Accelerators have to be kept aligned within given tolerances to make the beam pass through

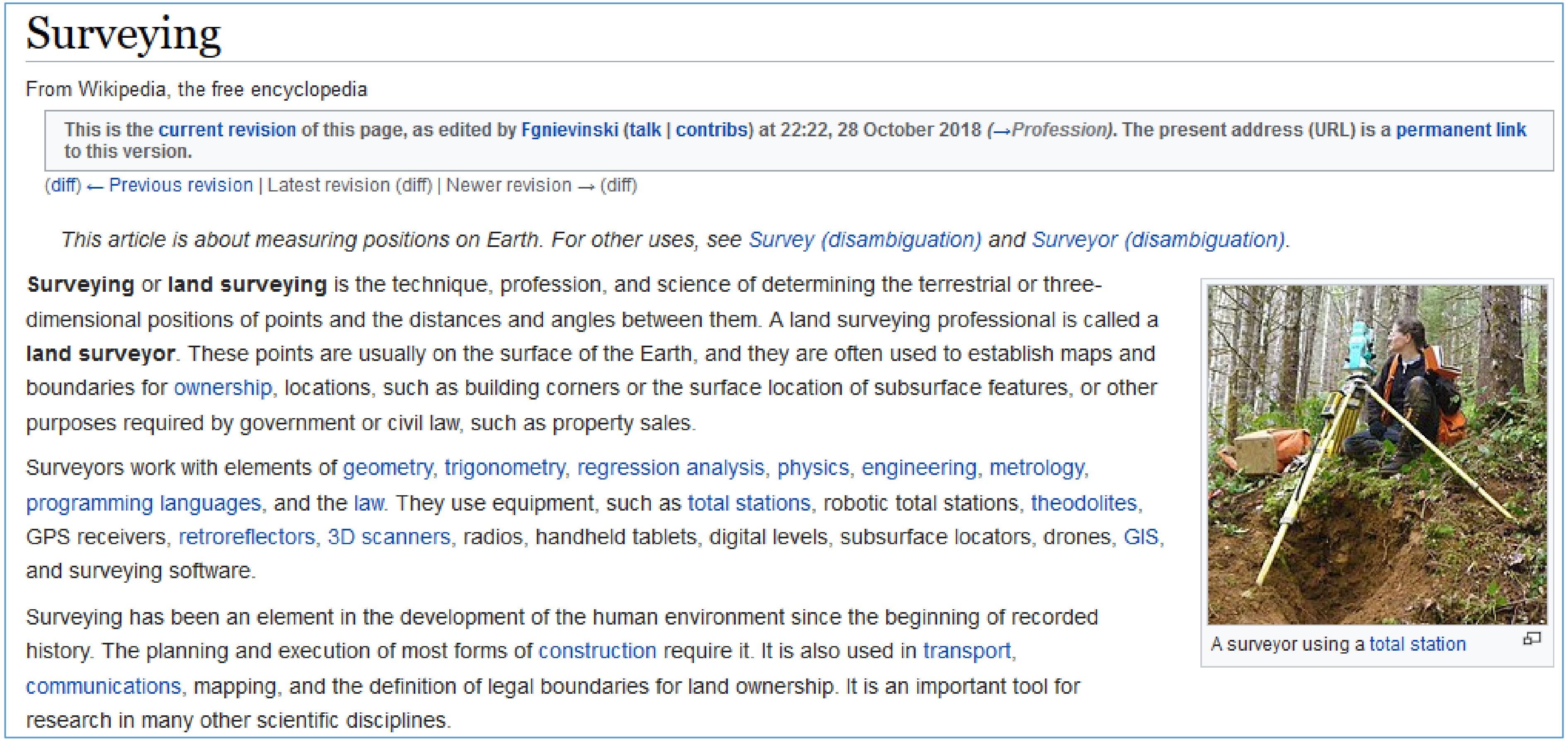
Alignment tolerances [Fisher] [Ruland]

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



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

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.

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.

A surveyor using a total station

Geodetic Metrology

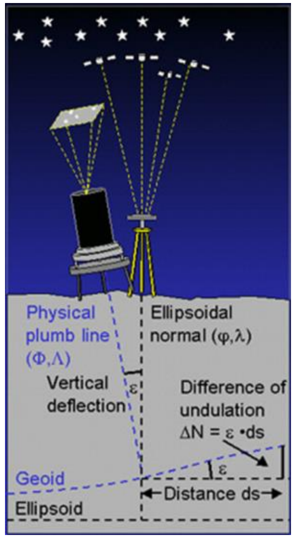
- GM Group provides metrology and alignment for components installed in the accelerators, their beam transfer lines and physics experiments throughout the CERN.

Nearly 60 km of beam lines

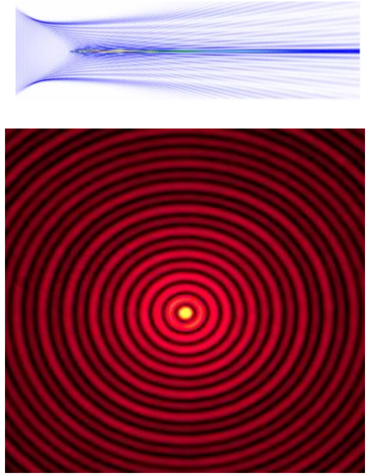
~ 7500 accelerator components

20 experiments made of thousands of detectors

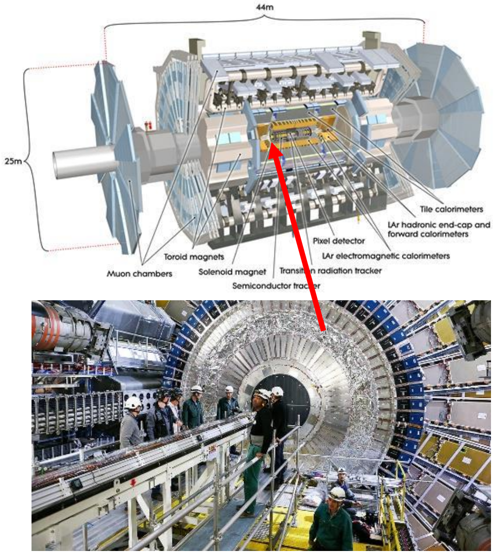
Alignment and Permanent monitoring



Geodetic aspects

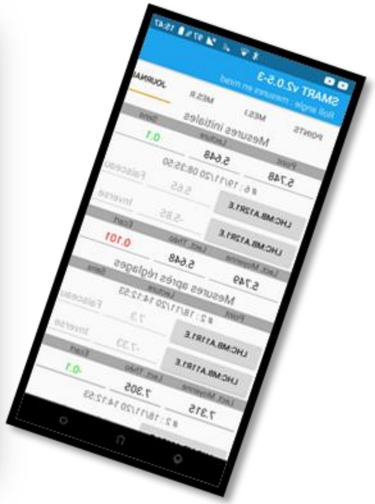


R&D



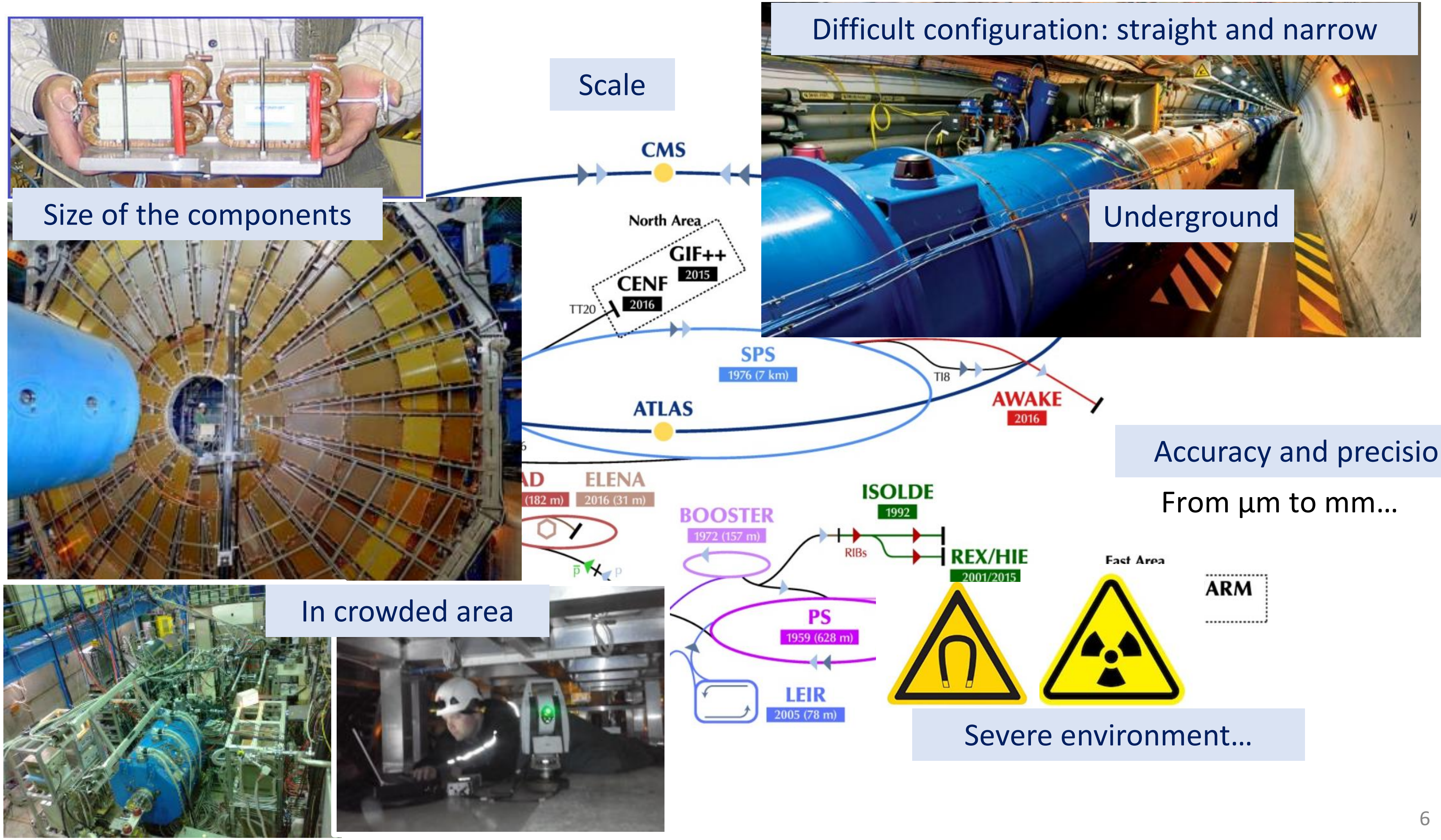
Physics Experiments

Georeferenced 3D Scans



Associated software

GM day to day challenges



Scale

Difficult configuration: straight and narrow

Size of the components

Underground

Accuracy and precision

From µm to mm…

In crowded area

Severe environment…

Outline

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

+ study cases!

Introduction to geodesy

- Definition of geodetic datum and frames
- Geoid
- Deflection of vertical

Geodesy: definition

Geodesy is the science of accurately measuring and understanding 3 fundamental properties of the Earth:

- its geometric shape;
- its orientation in space;
- 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
- Because a large part of instrumentation performs measurements w.r.t to gravity
- To define the relative position of all area on surface and underground: sites, buildings, tunnels, accelerators, experiments

Geodesy: Coordinate system, datum, frame

- Coordinate Reference System (CRS):
  - set of rules for assigning coordinates to points

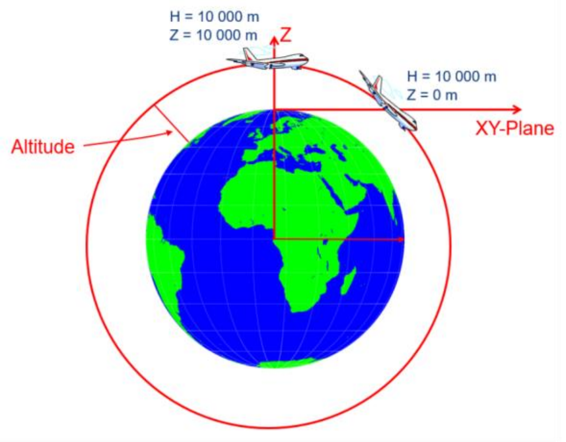
- Geodetic Datum:
  - set of parameters that describe the scale, position and the orientation of the of a 3D coordinate system relative to the Earth

- Coordinate Reference Frame:
  - realization of a CRS by means of a reference frame consisting physical points and associated values of the coordinates

Geodesy: definition of a geodetic datum

A **geodetic datum** (or geodetic reference datum) is:

- A coordinate system
- An ellipsoid
- A point of origin
- Sometime a projection is also given



Z versus H coordinate

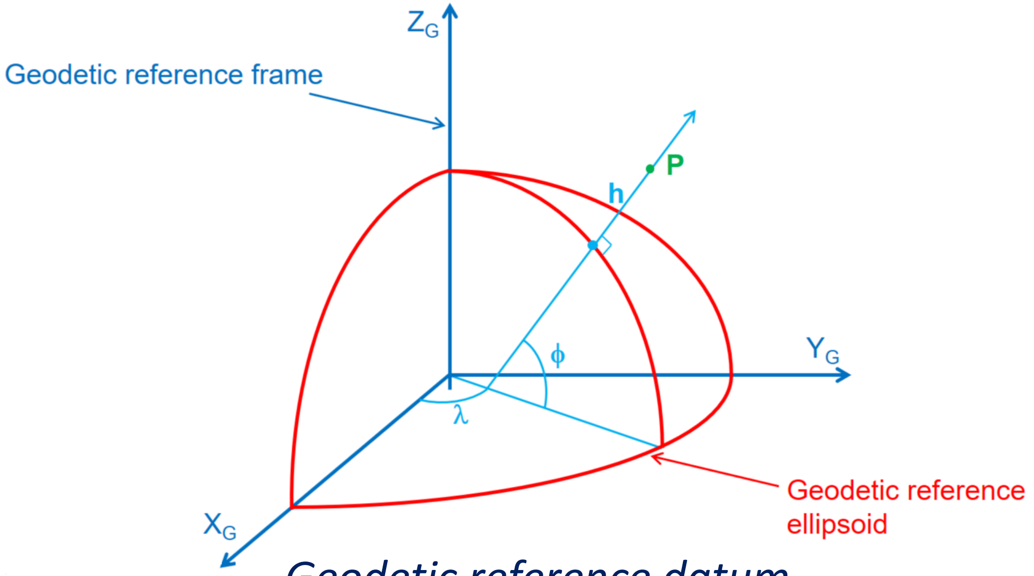
Datum may be:

- global, meaning that it represents the whole Earth;
- or local (it represents an ellipsoid best fit to only a portion of Earth).

… There are hundreds of reference datums.

In this geodetic datum, a point is localized by its Cartesian coordinates (X, Y, Z).

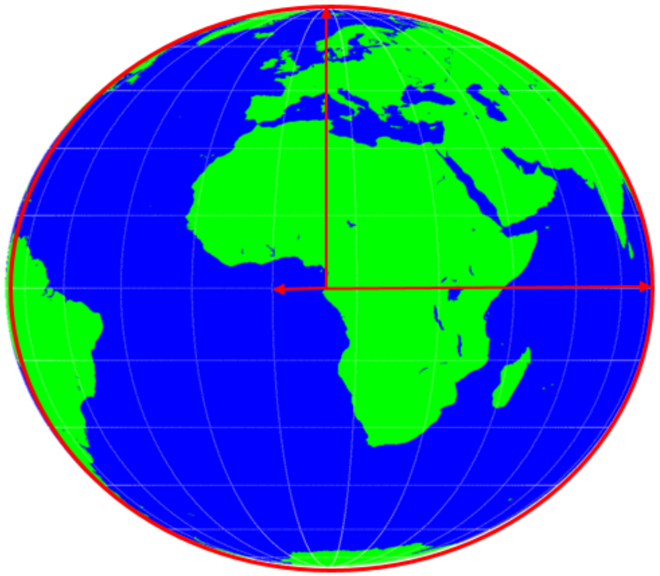
It is based on an ellipsoid and points can also be defined with geodetic coordinates:
- latitude, longitude and ellipsoidal height.



Geodetic reference datum

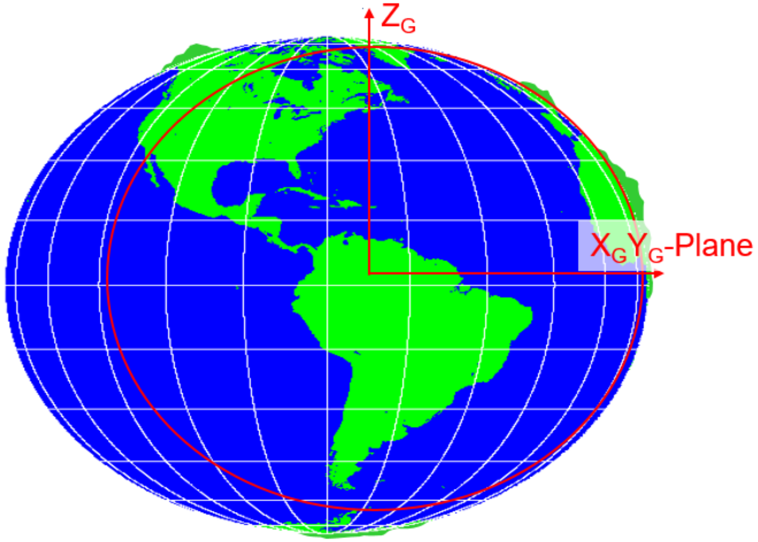
Geodesy: Different systems and datum

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

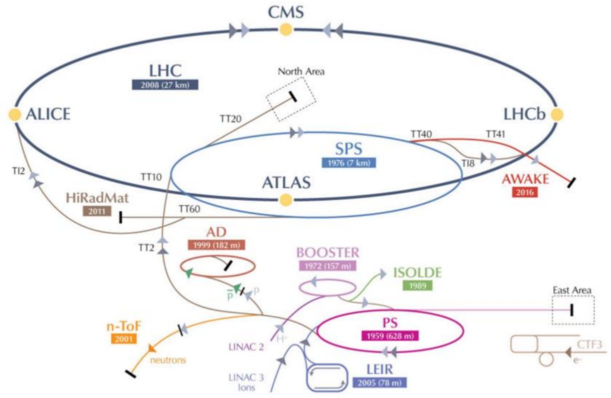


For a particular application, continents, countries: ED50, MN95, etc.

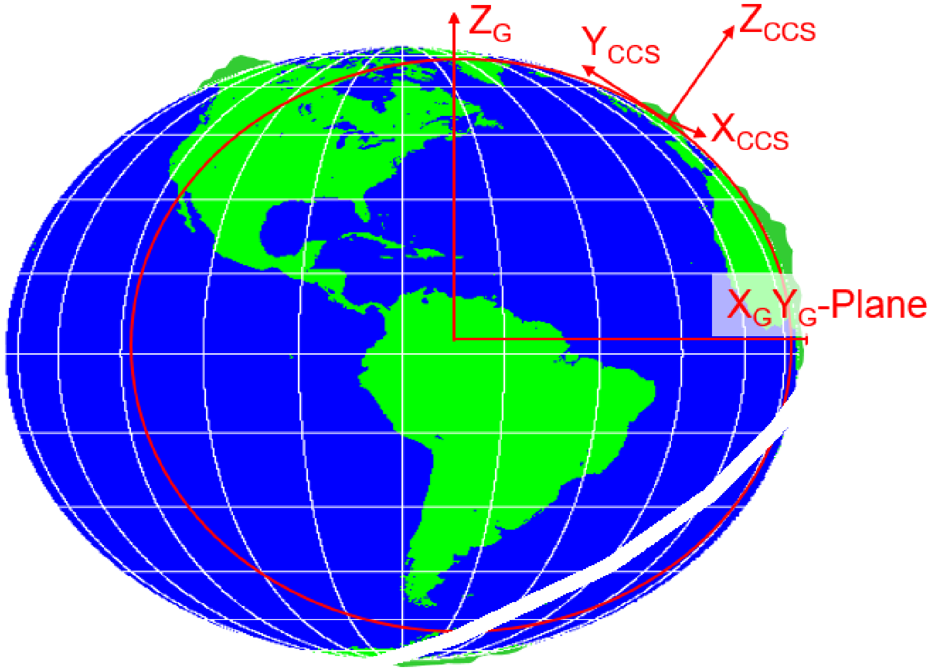
Since reference datum can have different radii and different center points, a specific point on the Earth can have substantially different coordinates depending on the datum used to make the measurement: «datum shift», from zero to hundreds of meters.

Geodesy: CERN Geodetic Reference Frame

- CERN Coordinate System (CCS)
- CERN Geodetic Reference Frame (CGRF),



CERN accelerator complex chain

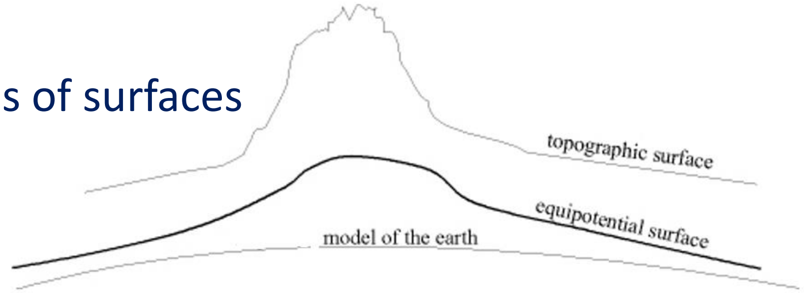


CGRF: reference surface that depends on the accuracy requested and the size of the project.

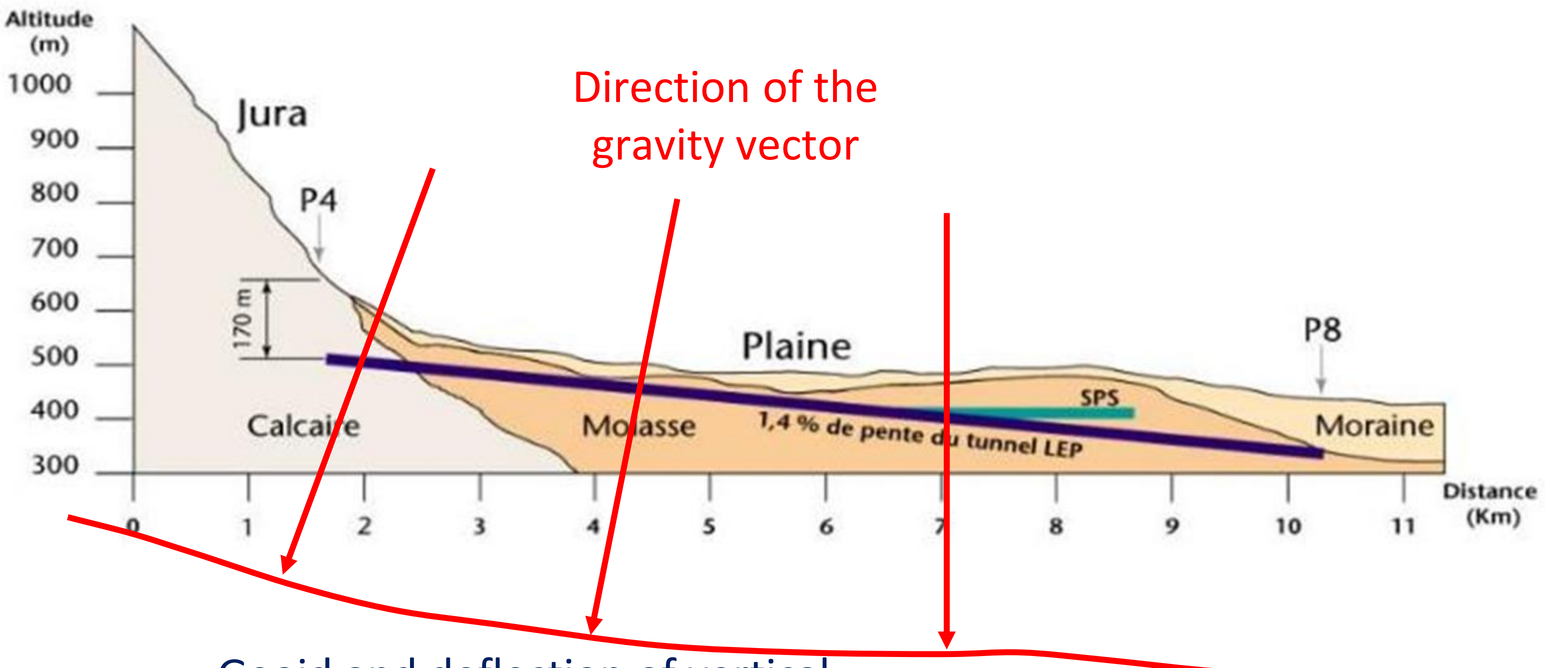
CGRF datum(s):

- 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)

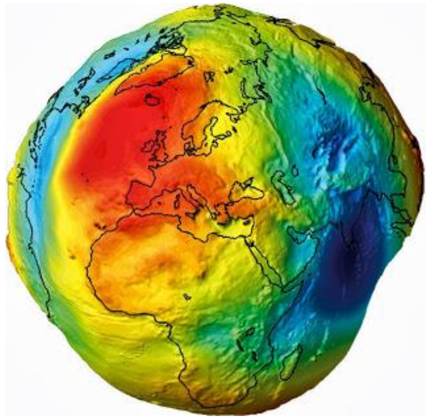
Geodesy: Geoid


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)


Direction of the gravity vector

Geoid and deflection of vertical


3D view of the geoid
(radial variations exagerated)

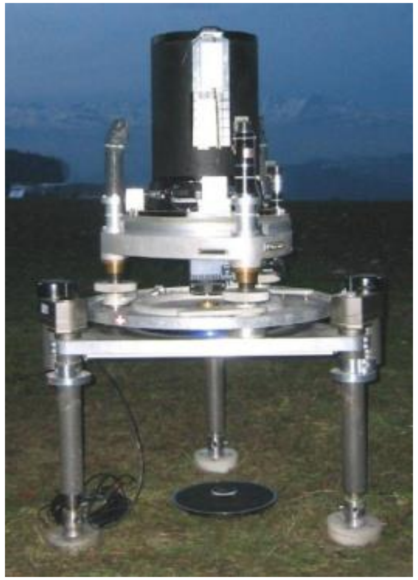
[Jones]

Geodesy: deflection of vertical

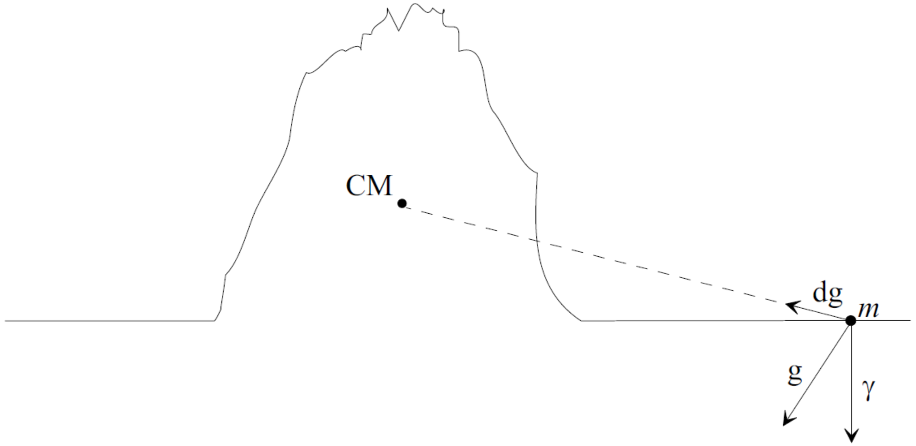
The deflection of vertical is the angle of divergence between the gravity vector (normal to the geoid) and the normal to the ellipsoid

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

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

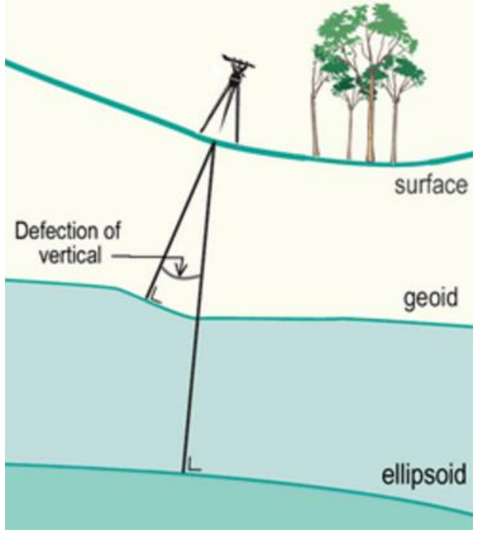


Zenithal camera



Effect of a nearby mass anomaly

[Jones]

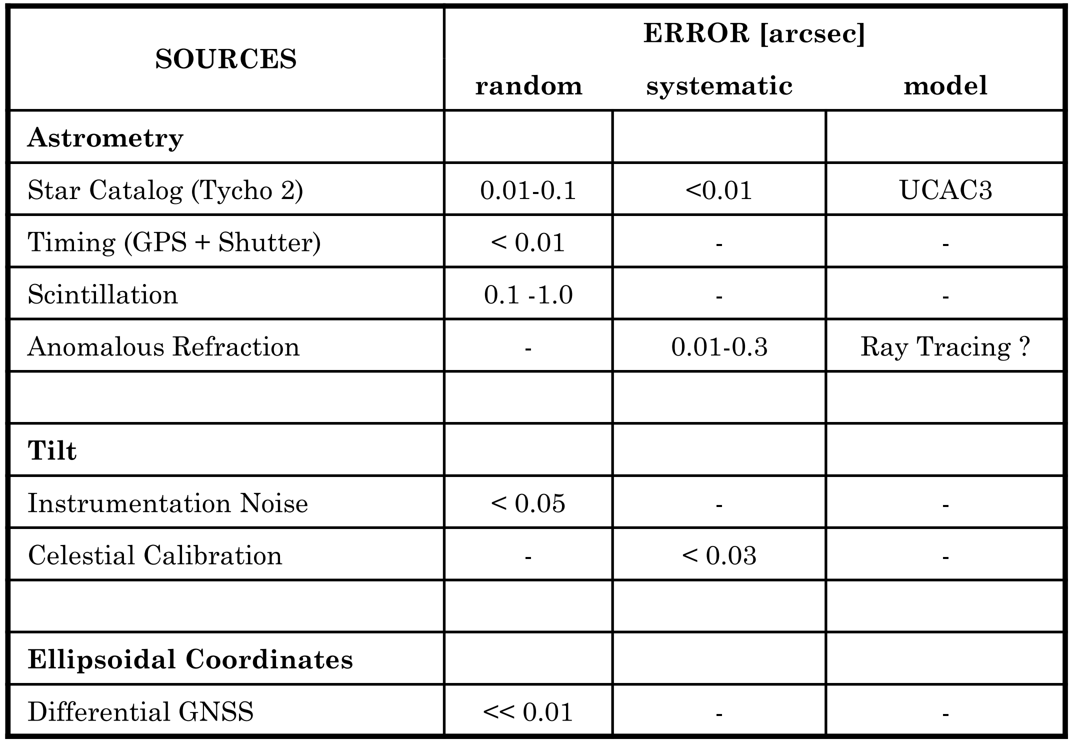


Deflection of vertical

Geodesy: deflection of vertical

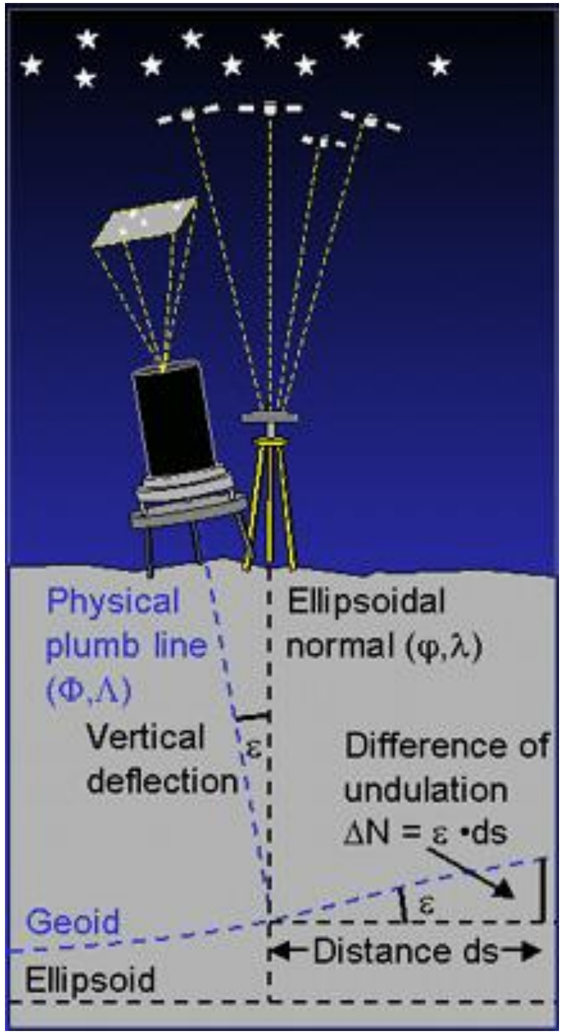
Astro-gravimetric Equipotential Determination

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



Determination of the deflection of the vertical

[Guillaume]

Units

Maximum deviation of vertical = 15’’

- Give it in degrees, radian, gon, cc.

Second of arc (‘’)	Minute of arc (‘)	Degree (°)	Radian (rad)	Gon (gr)	Centi centigrad (cc)
15’’					

Units

Maximum deviation of vertical = 15’’

- Give it in 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

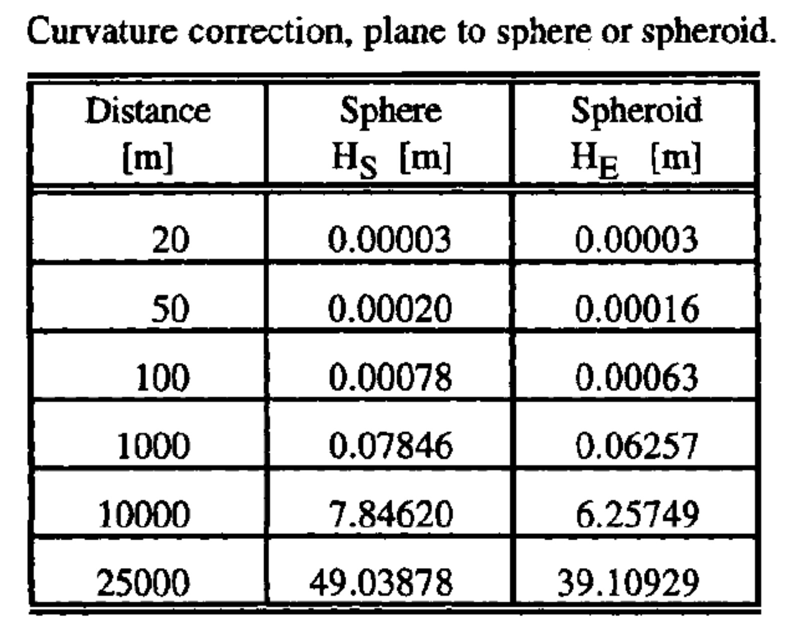
Study case

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)

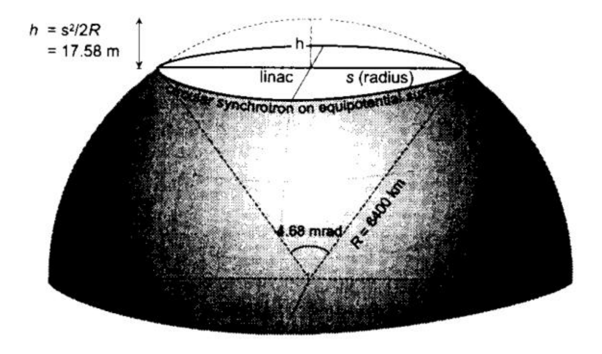
Geodesy: impact

- 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

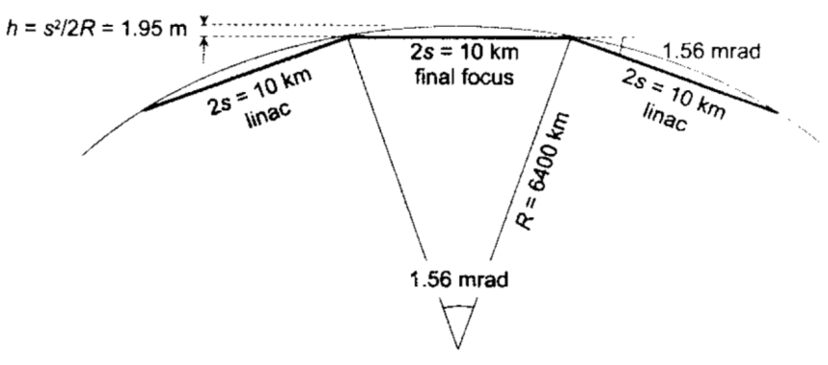


Curvature correction, plane to sphere or spheroid.

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

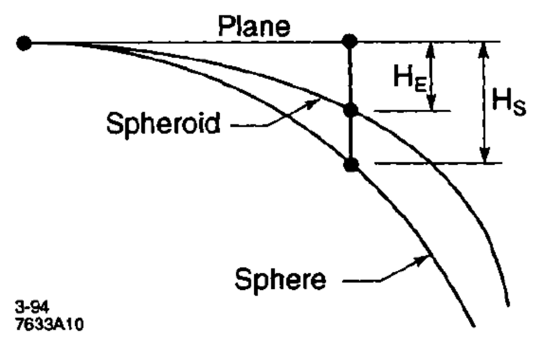


Effect of earth curvature on linear and circular accelerators



Three plane lay-out

[Ruland]



Curvature correction.

[Ruland2]

Steps of alignment

On the surface

Definition of alignment tolerances

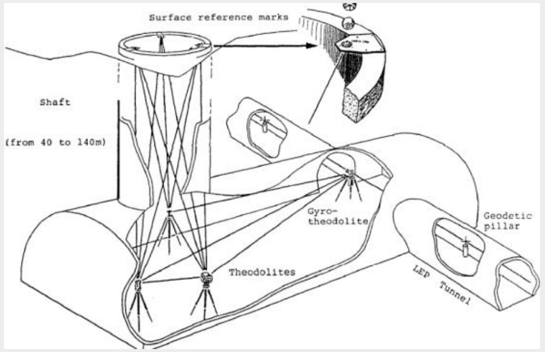
Inside the tunnel

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 the theoretical trajectory

Absolute alignment of the components

Relative alignment of the components

Maintenance of the alignment

Time scale

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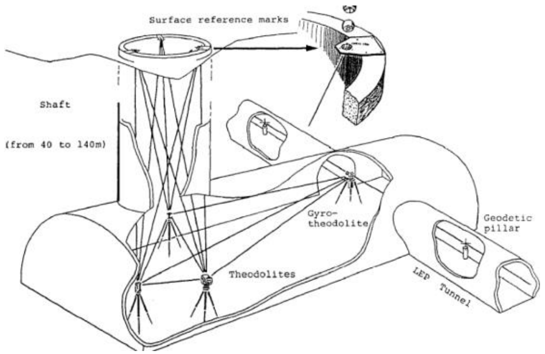


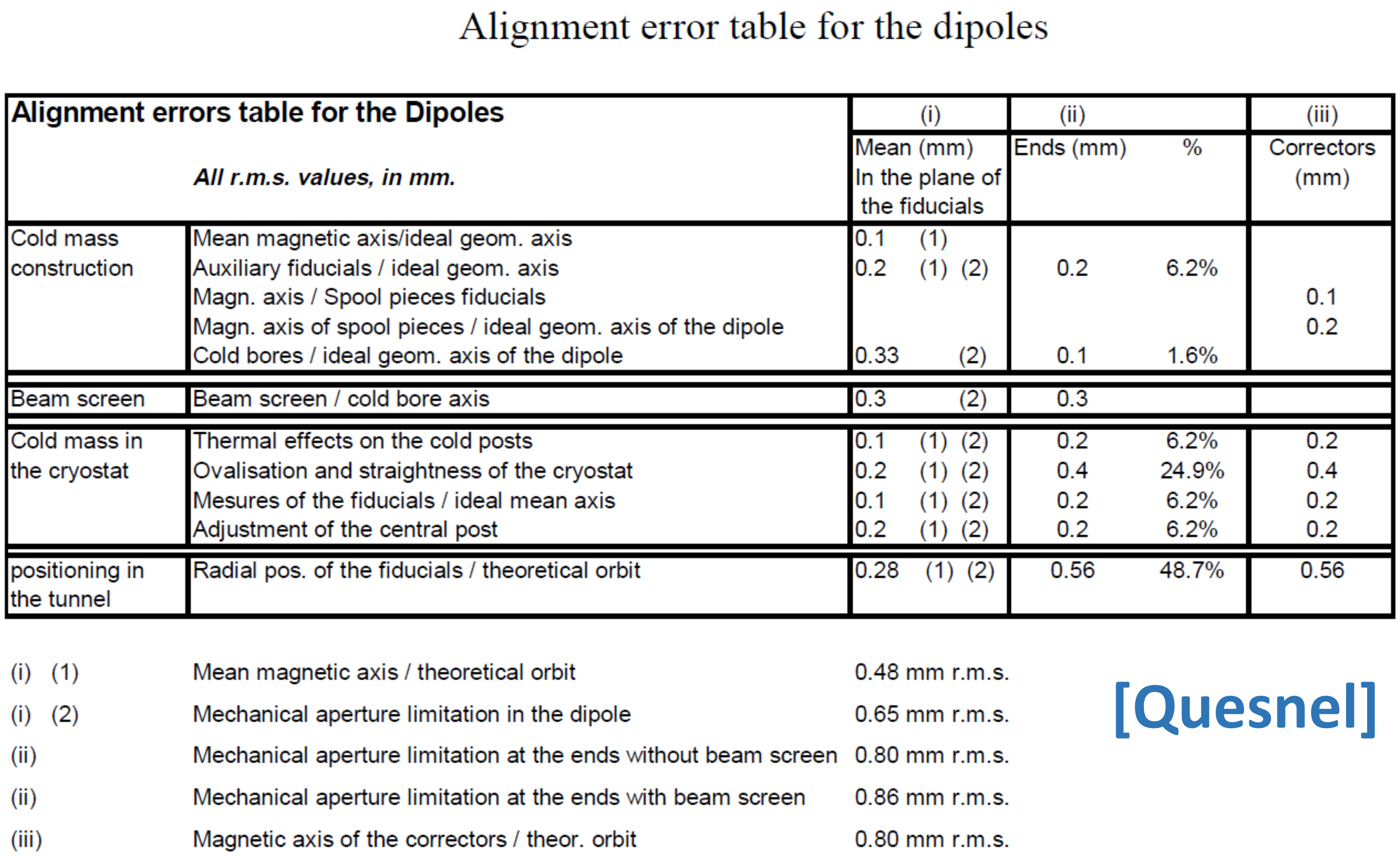
Absolute alignment of the components

Relative alignment of the components

Maintenance of the alignment

Definition of alignment tolerances

Contributions to the error budget, many different services involved (Mechanics, Cryo, Vacuum, Surveying …)

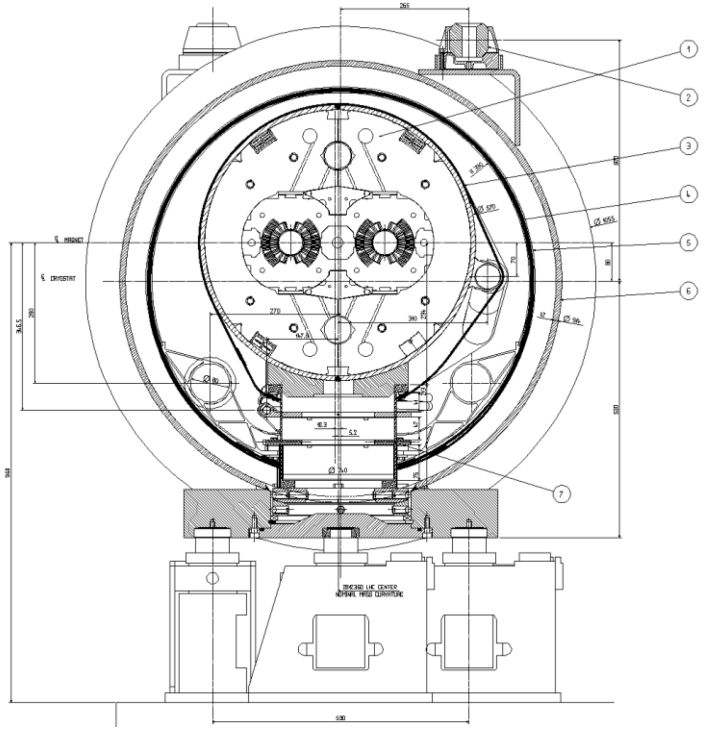


Alignment error table for the dipoles

Alignment errors table for the Dipoles		(i)	(ii)		(iii)
	All r.m.s. values, in mm.	Mean (mm) In the plane of the fiducials	Ends (mm)	%	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]

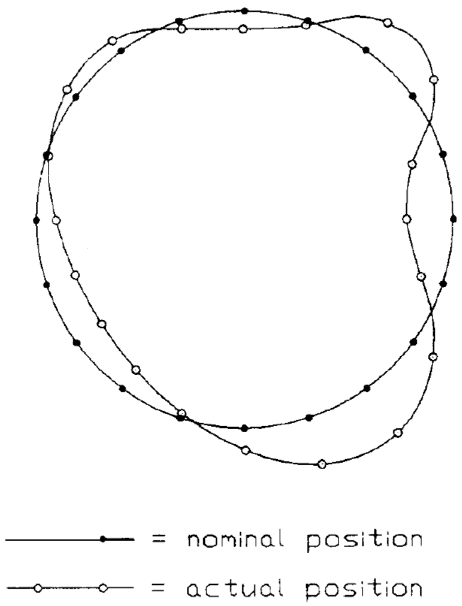


LHC Dipole Cross Section

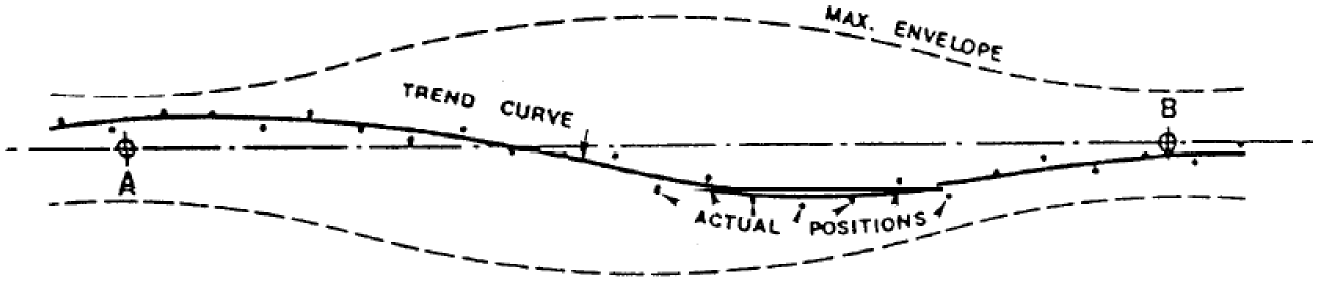
Alignment tolerances

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

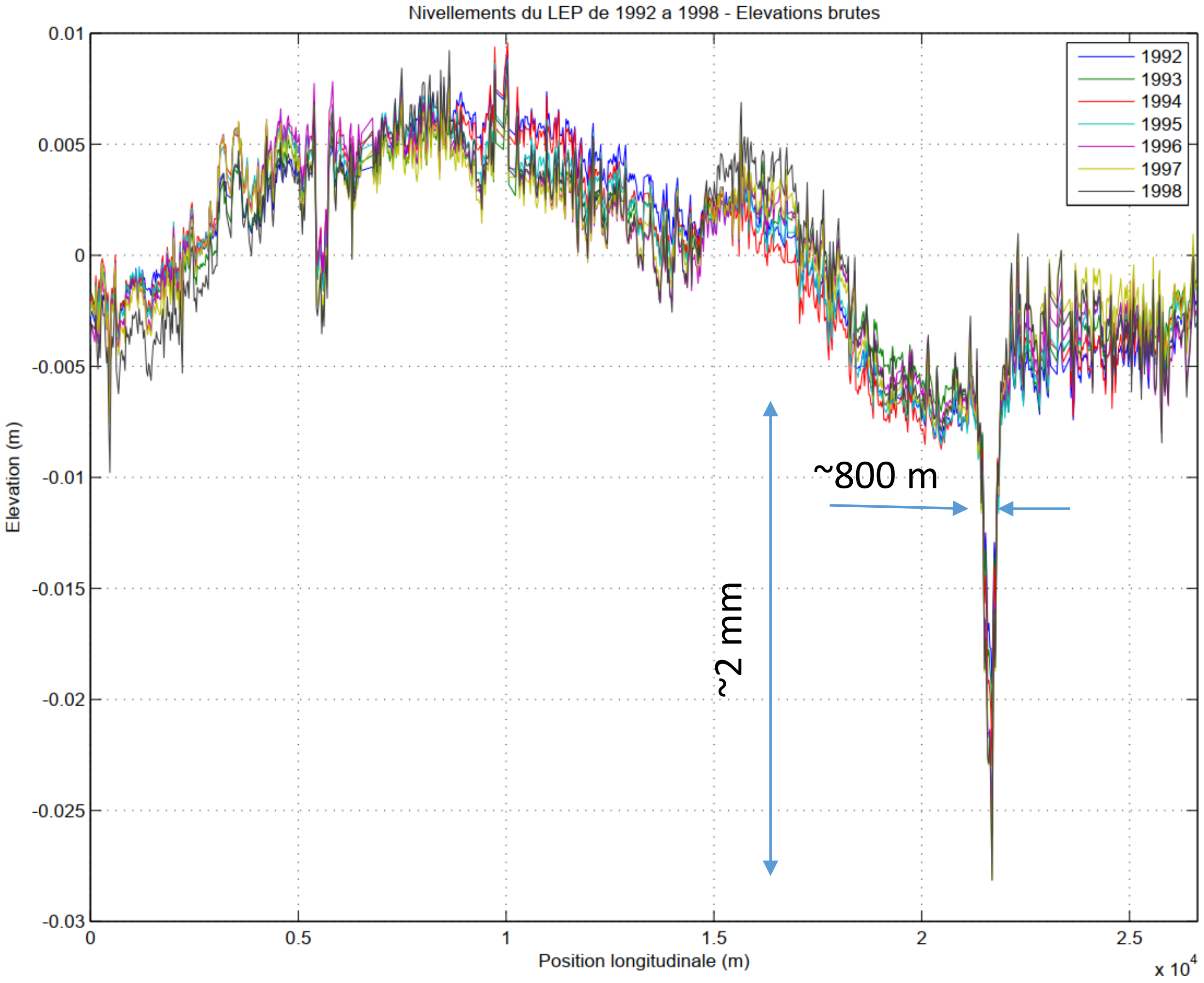
[Mayoud]

Alignment tolerances

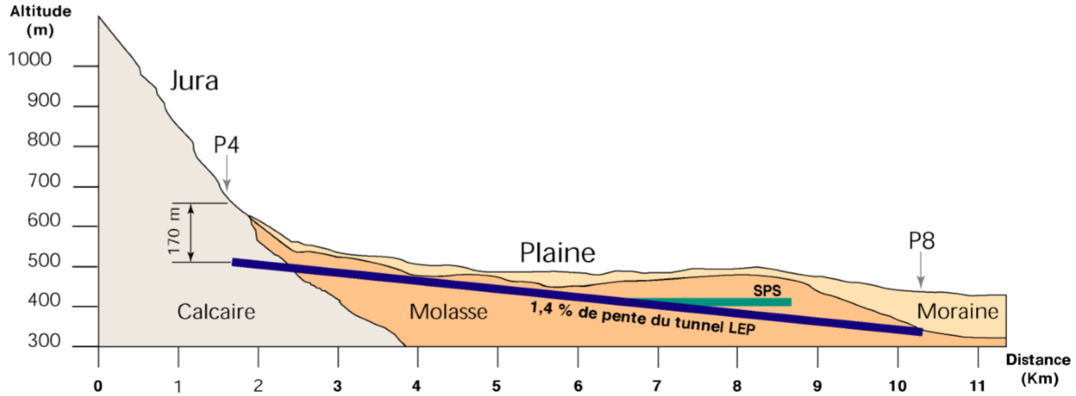
Typical values

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



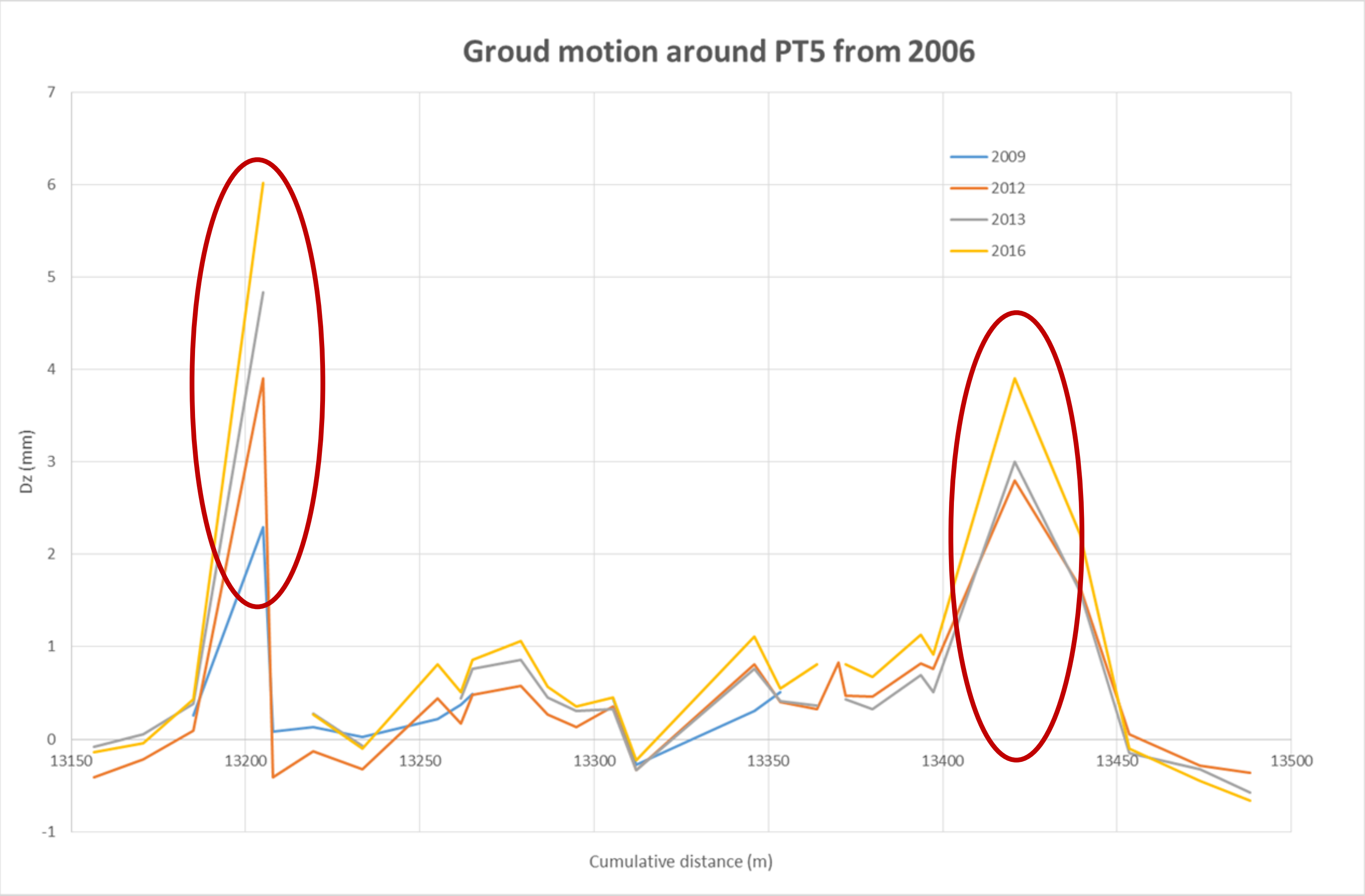
LEP levelling between 1992 and 1998



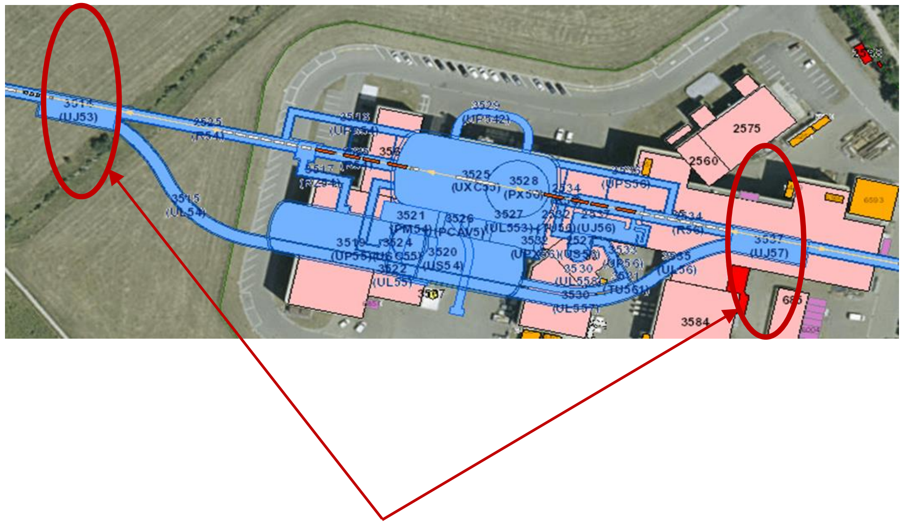
Example 1: vertical displacements along the LEP tunnel

- LEP tunnel is a plane which is not horizontal : 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

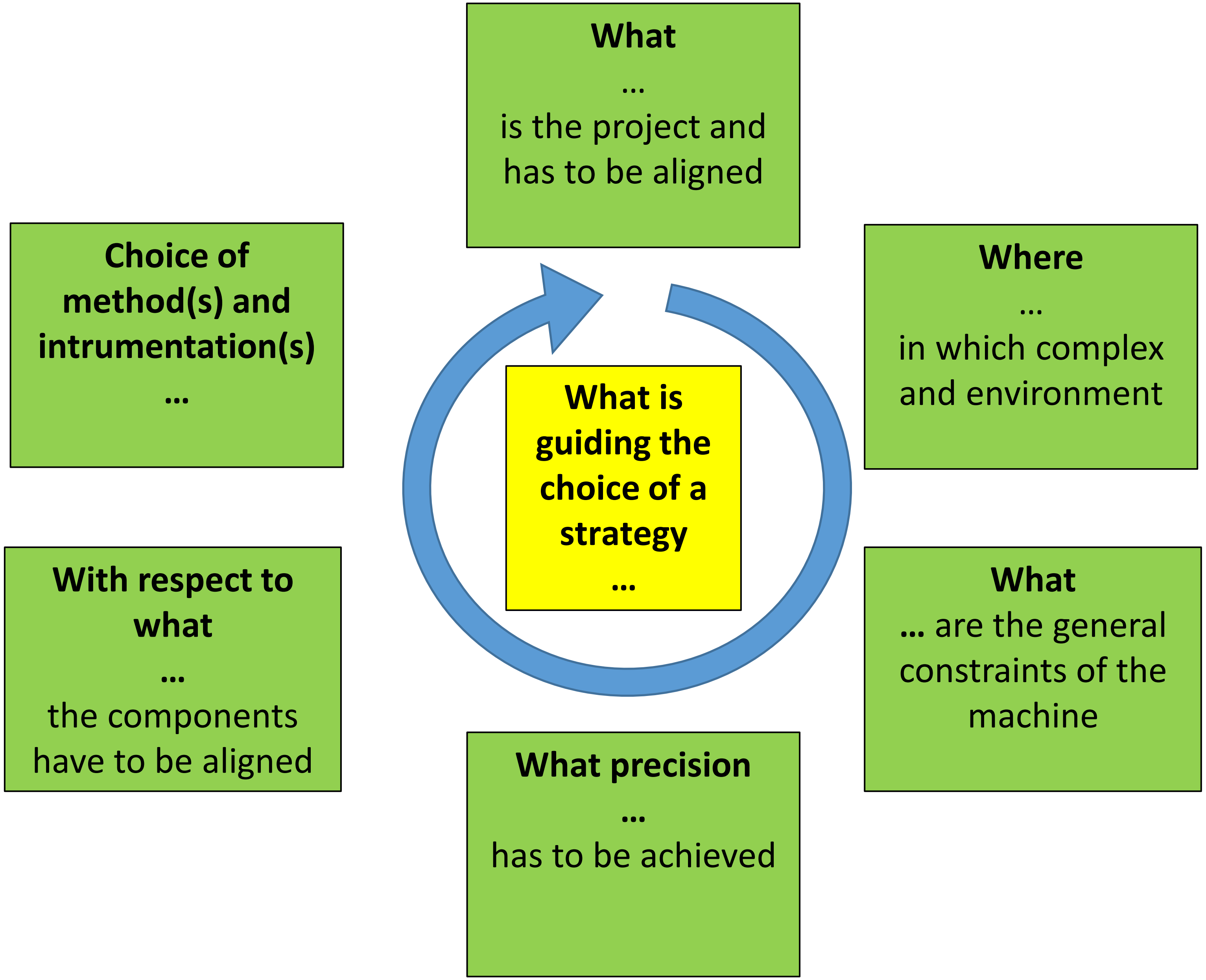


Example 2: zoom of the vertical displacement of the tunnel floor around point 1 and point 5 of the LHC (~ 300m from both sides of IP) between 2006 and 2018



New technical galleries dug during LS1

Definition of an alignment strategy



What is guiding the choice of a strategy …

What
…
is the project and has to be aligned

Where
…
in which complex and environment

What
… are the general constraints of the machine

What precision
…
has to be achieved

With respect to what
…
the components have to be aligned

Choice of method(s) and intrumentation(s)
…

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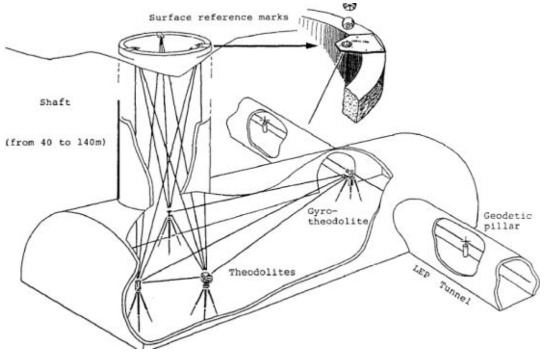

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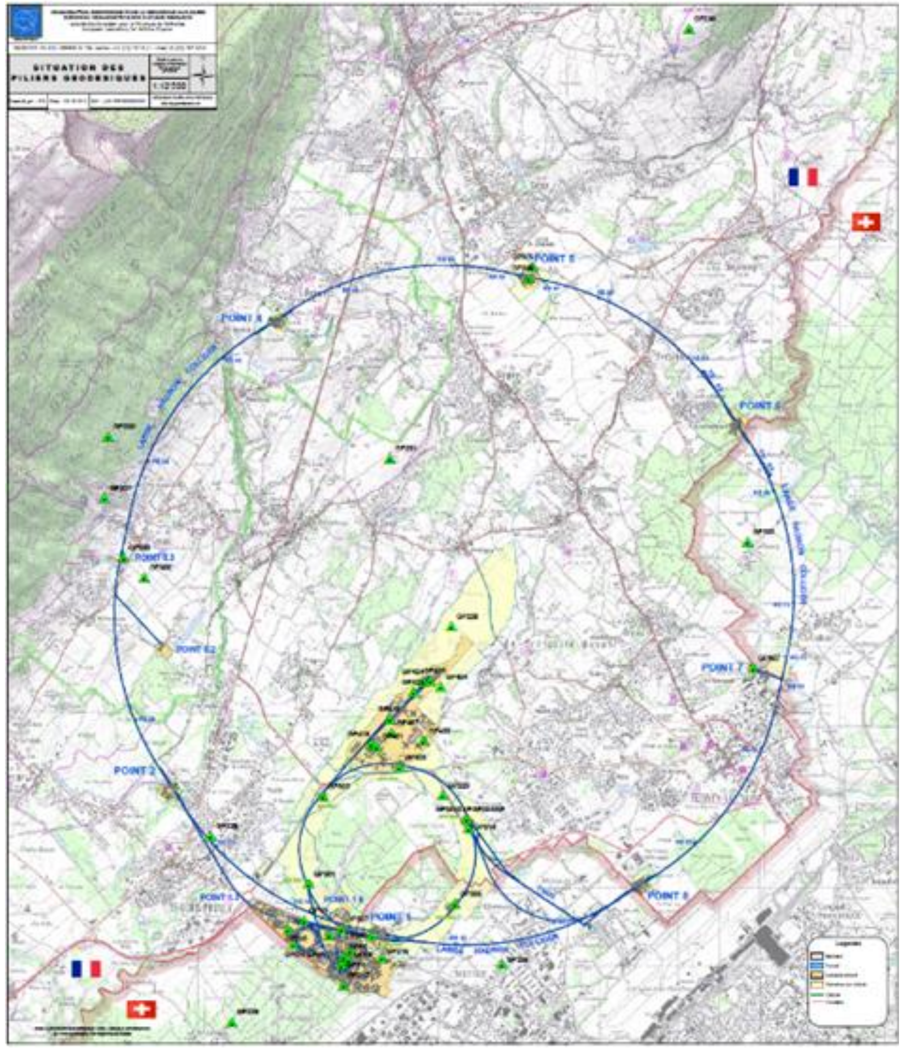
Geodetic surface reference network

- 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

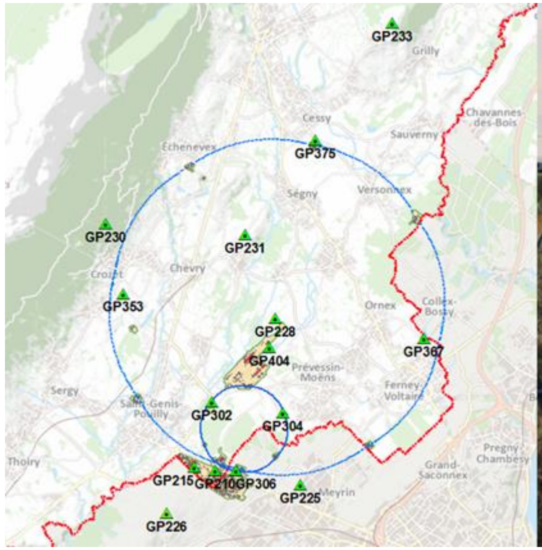

Geodetic pillar

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


Configuration of CERN geodetic surface reference network

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.



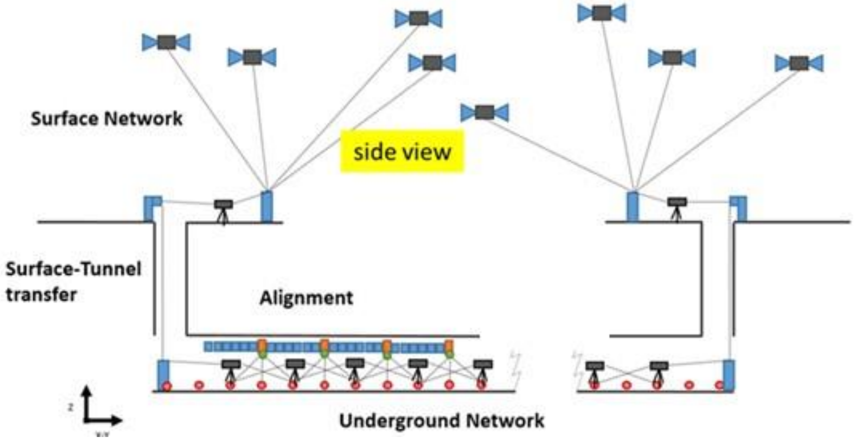
HL-LHC
Geodetic network

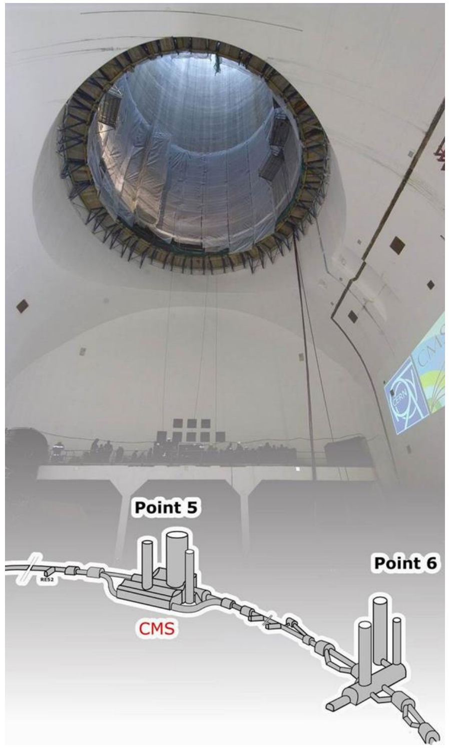
HL-LHC
Geodetic pillar

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

Underground geodetic network


LHC underground geodetic network

The underground networks consist of:
- dense networks of monuments
- preferably in the floor or on the walls

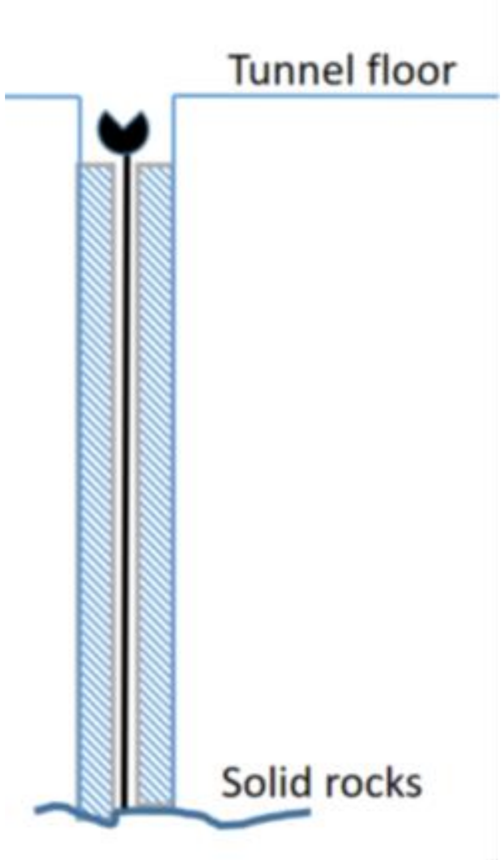
Several means are proposed for their determination:
- total station, direct levelling, gyro-theodolite measurements


LHC underground geodetic network

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
- a relative accuracy in altitude between 3 consecutive monuments of 0.1 mm

Underground geodetic network

- Deep levelling references are distributed in the tunnels
- These vertical references made of invar are 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 are linked to these deep levelling references considered as stable along time



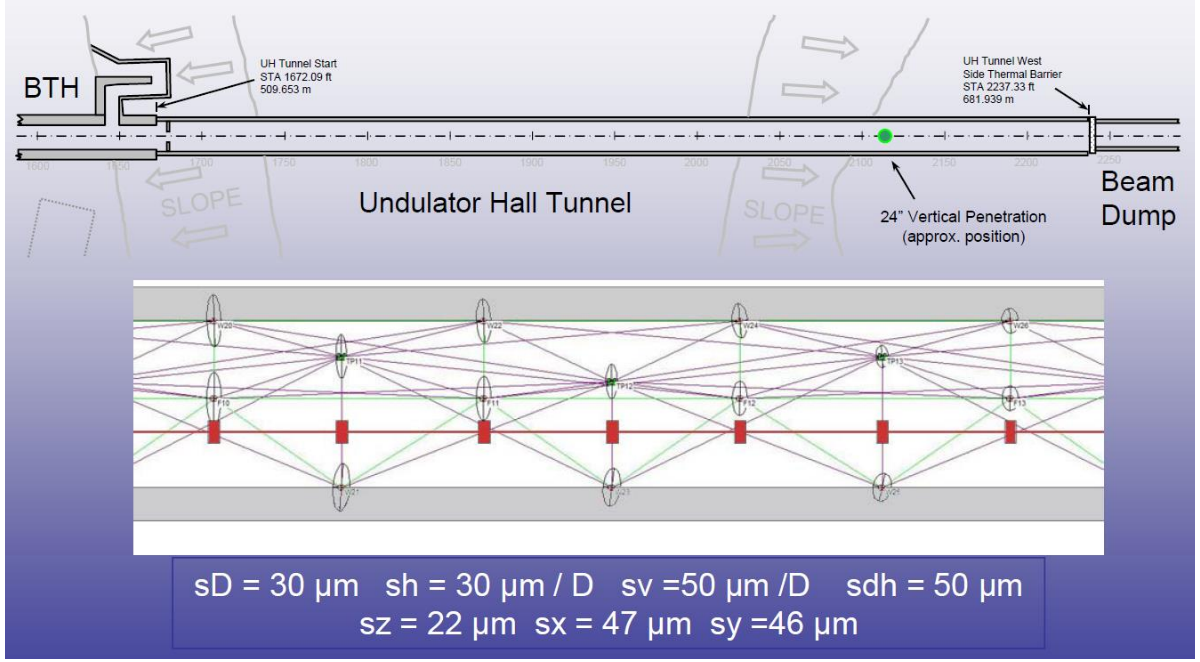
Deep reference concept

Levelling rod on a deep reference

Conical interface of a deep reference

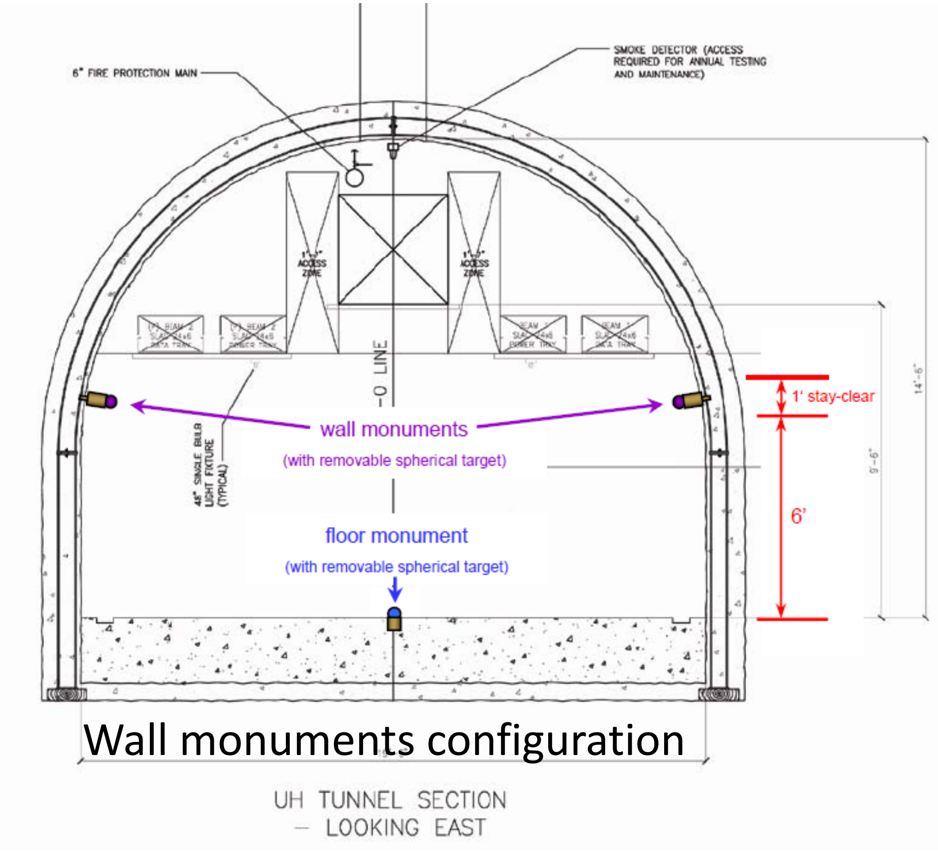
Underground geodetic network

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



sD = 30 µm sh = 30 µm / D sv =50 µm /D sdh = 50 µm
sz = 22 µm sx = 47 µm sy =46 µm

Geodetic network in a narrow tunnel



Wall monuments configuration

Wall monument

[Lecoq]

Steps of alignment

On the surface

Time scale

Definition of alignment tolerances

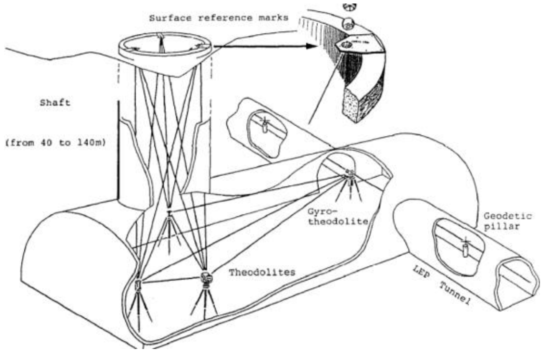
Definition of alignment strategy

Inside the tunnel

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 the theoretical trajectory

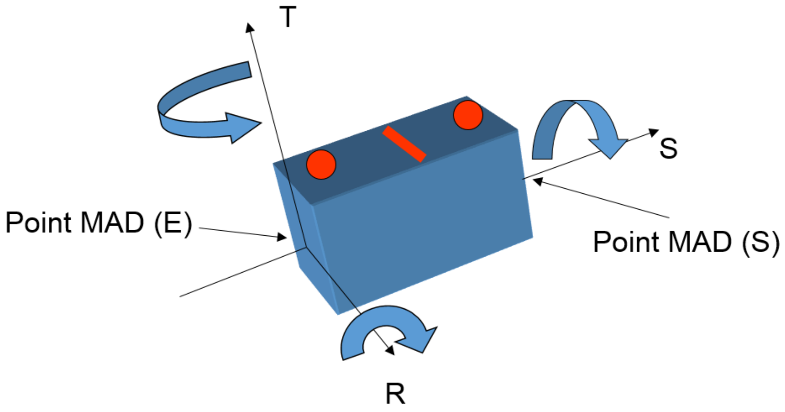
Absolute alignment of the components

Relative alignment of the components

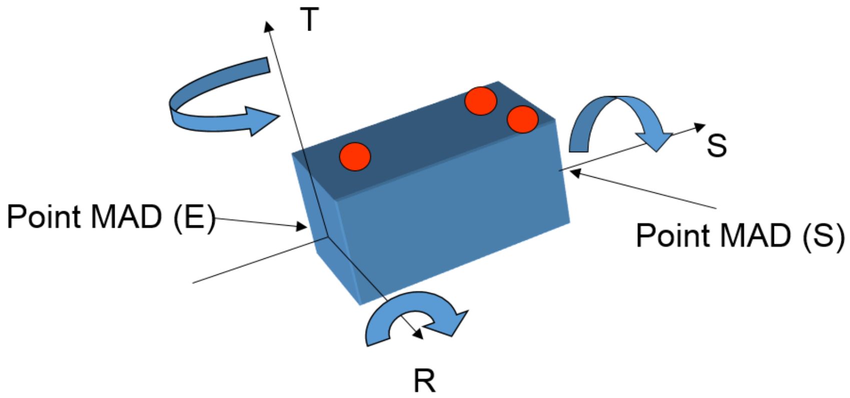
Maintenance of the alignment

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



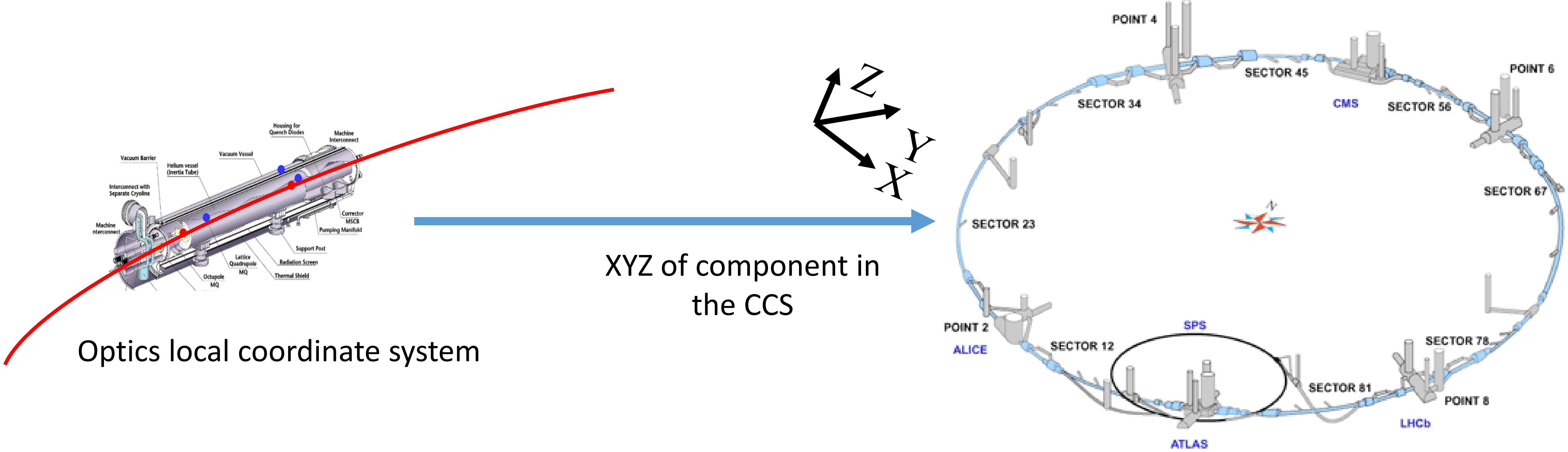
Coordinate system associated with a component: 3 fiducials

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, their position on the theoretical trajectory is needed

- It is defined by physicists, using the MAD-X software [*general-purpose tool for charged particle optics design and studies in accelerators and beam lines*]
- The component positions are given in an optics local coordinates system
- There are then transformed in the CCS coordinates system
  - For this the definition of a start point and orientations known in both systems is needed



XYZ of component in the CCS

Optics local coordinate system

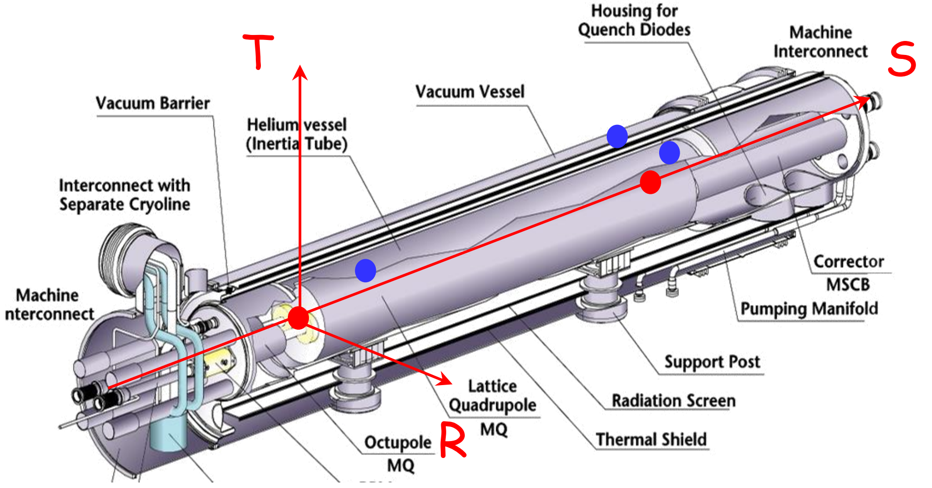
Fiducialisation

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:

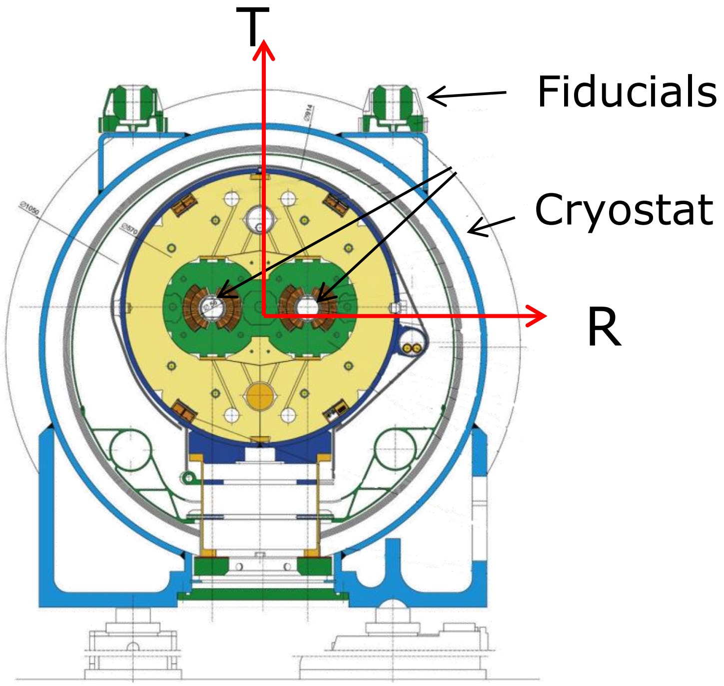
- Mechanical measurements using a gauge (typically for warm magnets)
- Laser tracker measurements when the requirements are of the order of 0.1 mm rms
- CMM measurements, for smaller components and requirements of the order of micrometers.

Coordinate Measuring Machine - CMM



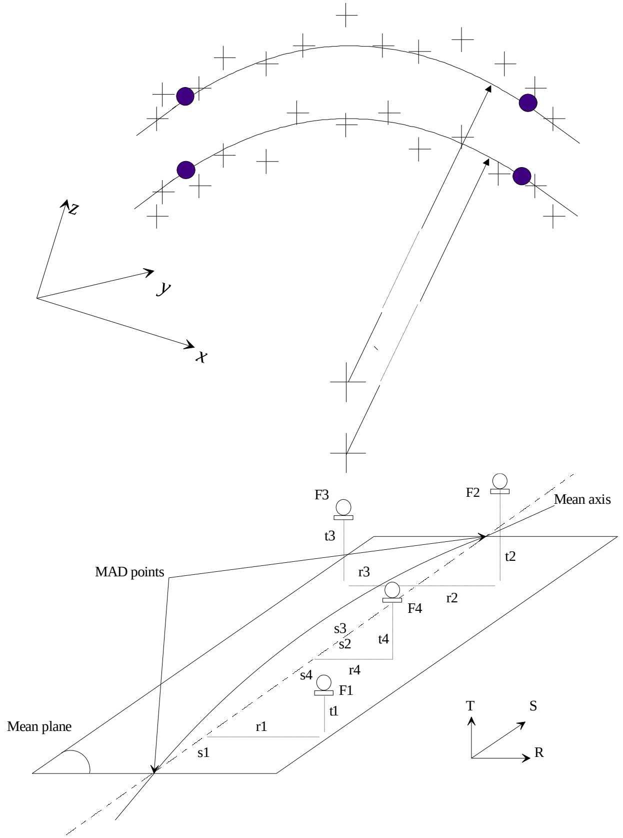
Fiducials in blue defined w.r.to component reference axis in red

Fiducialisation



LHC dipole cross section

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

Steps of alignment

Time scale

On the surface

Definition of alignment tolerances

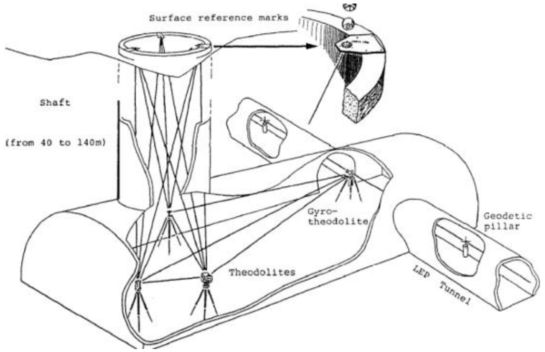
Definition of alignment strategy

Installation and determination of surface geodetic network

Inside the tunnel

Transfer of reference in the tunnel

Installation and determination of an underground geodetic network



Fiducialisation of the components

Definition of the theoretical trajectory

Absolute alignment of the components

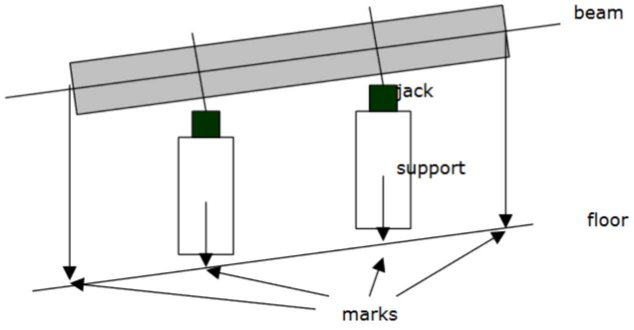
Relative alignment of the components

Maintenance of the alignment

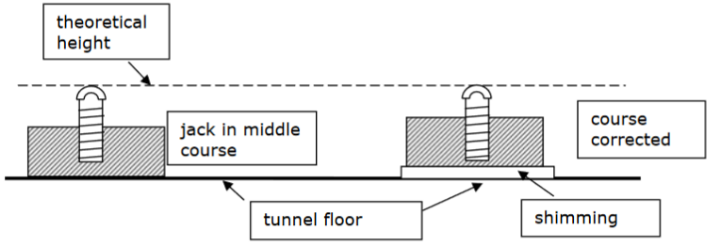
Absolute alignment (1)

Sequence of tasks:

1. **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



2. **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 (2)

Sequence of tasks:

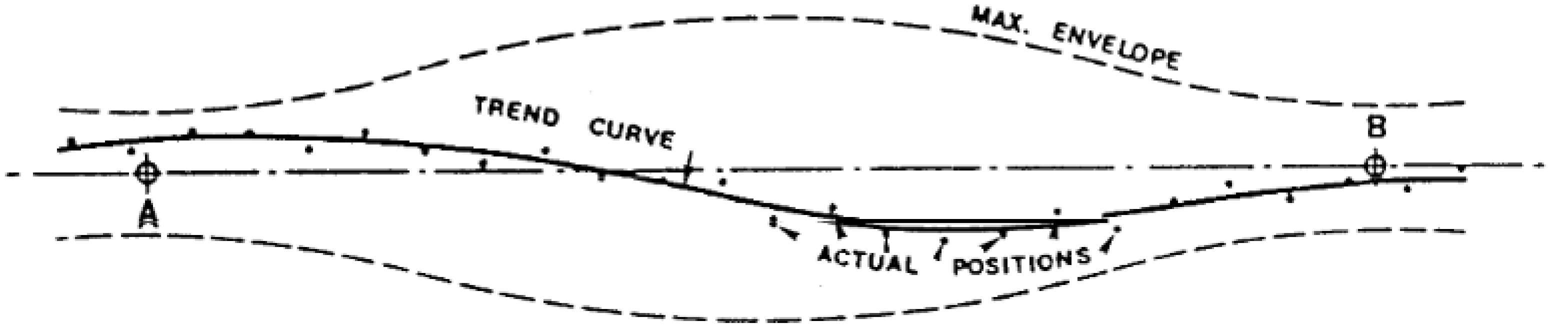
3. **First positioning of components:**
    - takes place once the components are installed on their jacks
    - Each component is aligned independently with respect to the underground geodetic network
    - A component is considered aligned once its fiducials have reached their theoretical position

    - 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 (1)

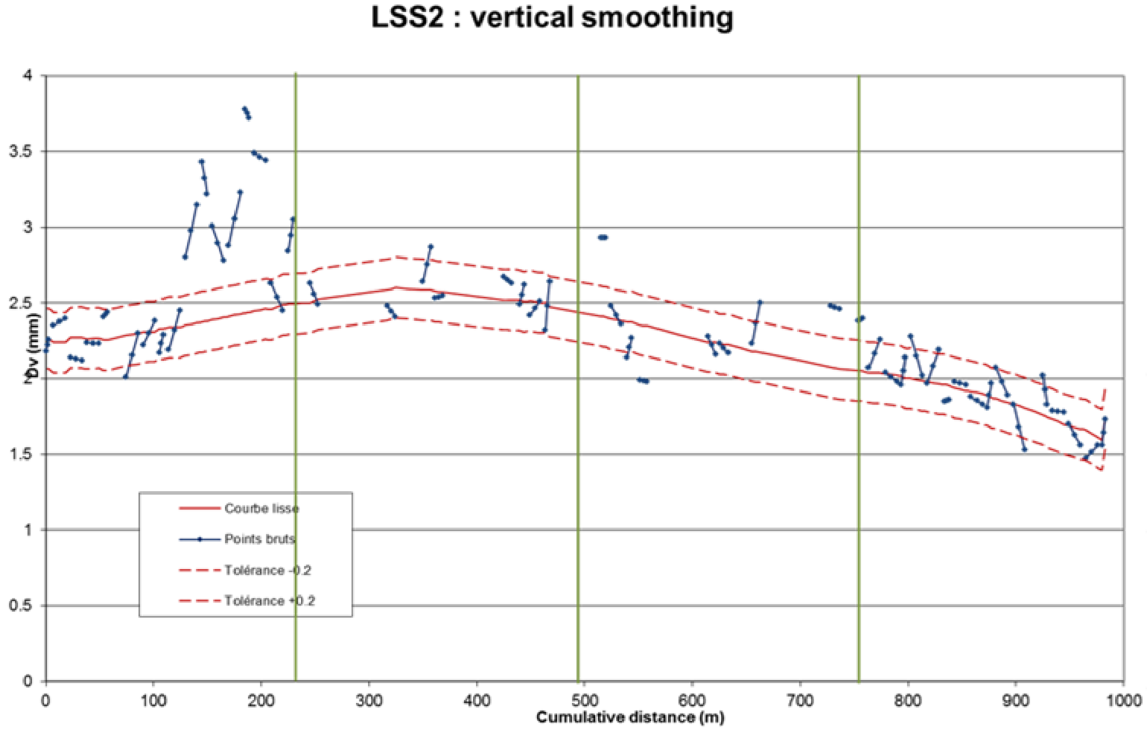
Smoothing:

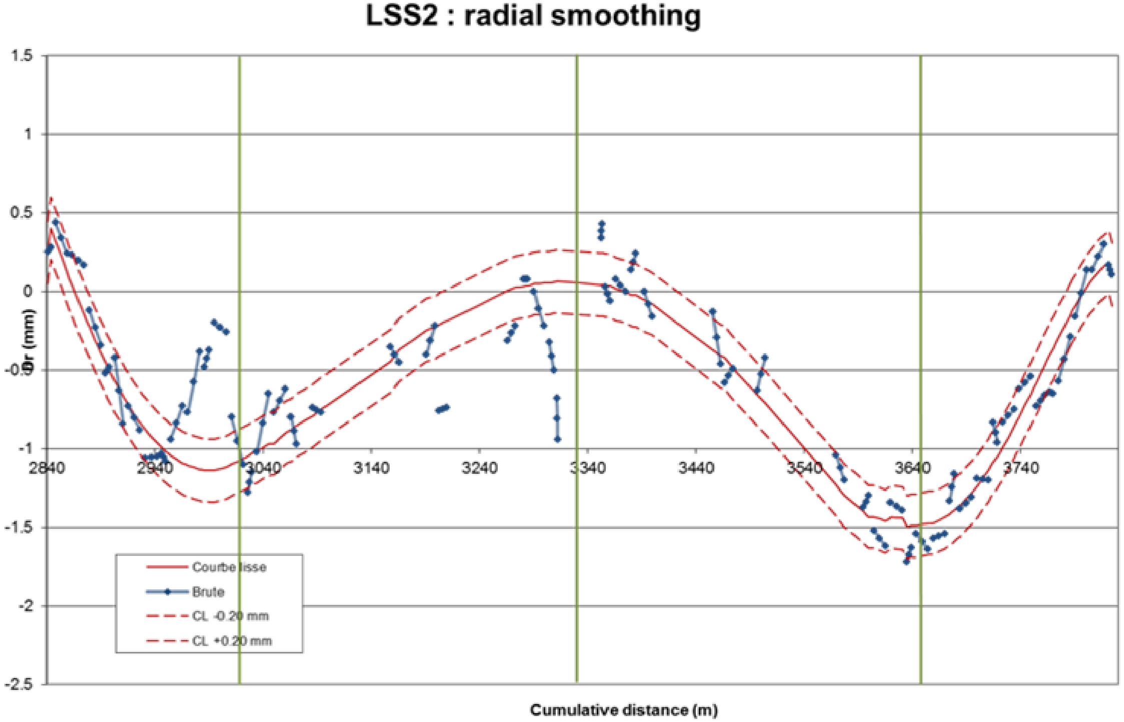
- The objective is to obtain a relative radial and vertical accuracy requested, for example 0.15 mm over a distance of 150 m
- The smoothing initially corrects both residual errors in the first positioning and ground motion.
- The process can only start when the magnets are connected, under vacuum and cooled down, so that all the mechanical forces are taken into account.



Position of magnets with respect to theoretical orbit

Relative alignment: smoothing (2)





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

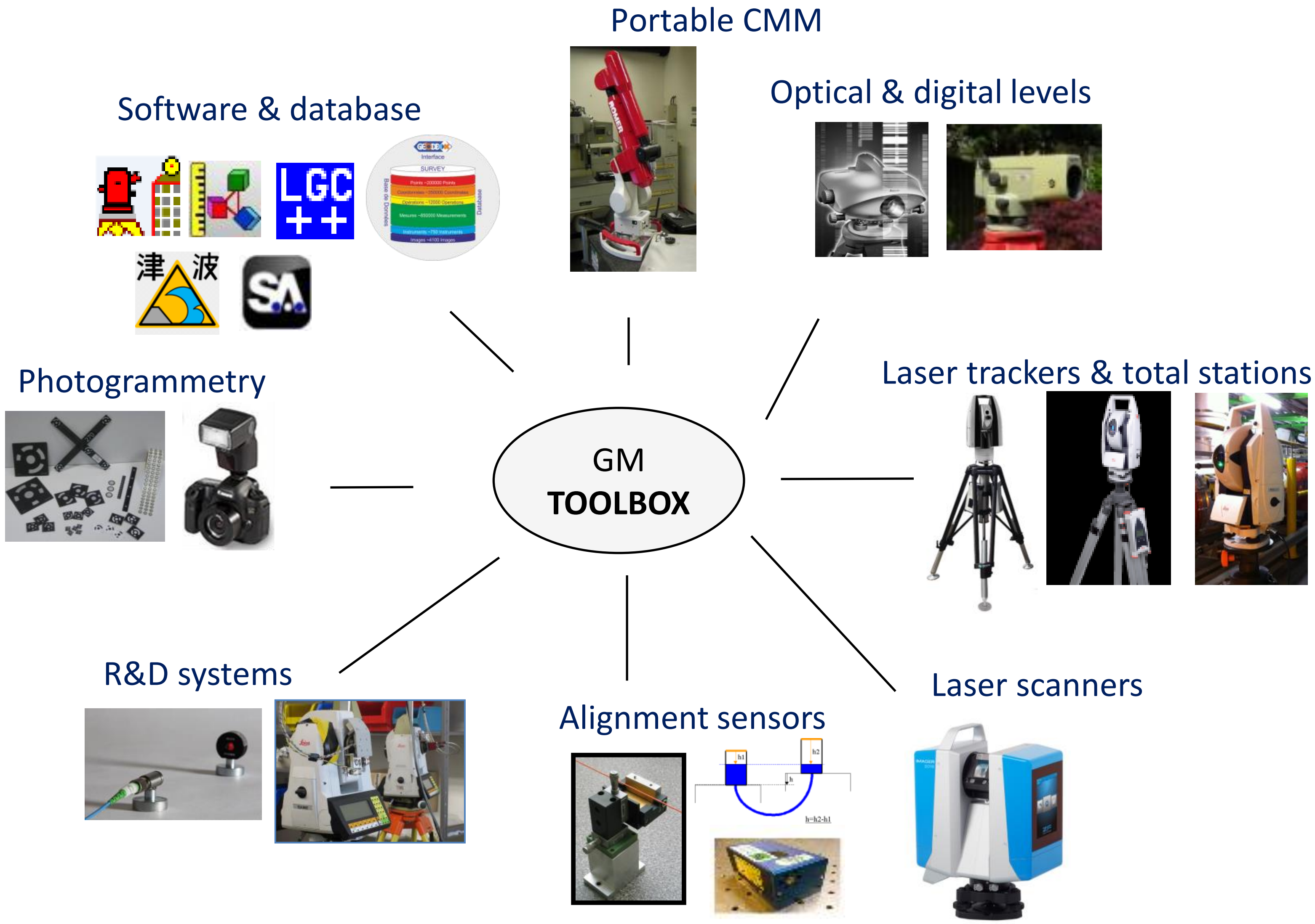
Tooling for alignment

To perform the alignment work, 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…

CERN Geodetic Metrology tool kit



Portable CMM

Software & database

Optical & digital levels

Photogrammetry

GM
TOOLBOX

Laser trackers & total stations

R&D systems

Alignment sensors

Laser scanners

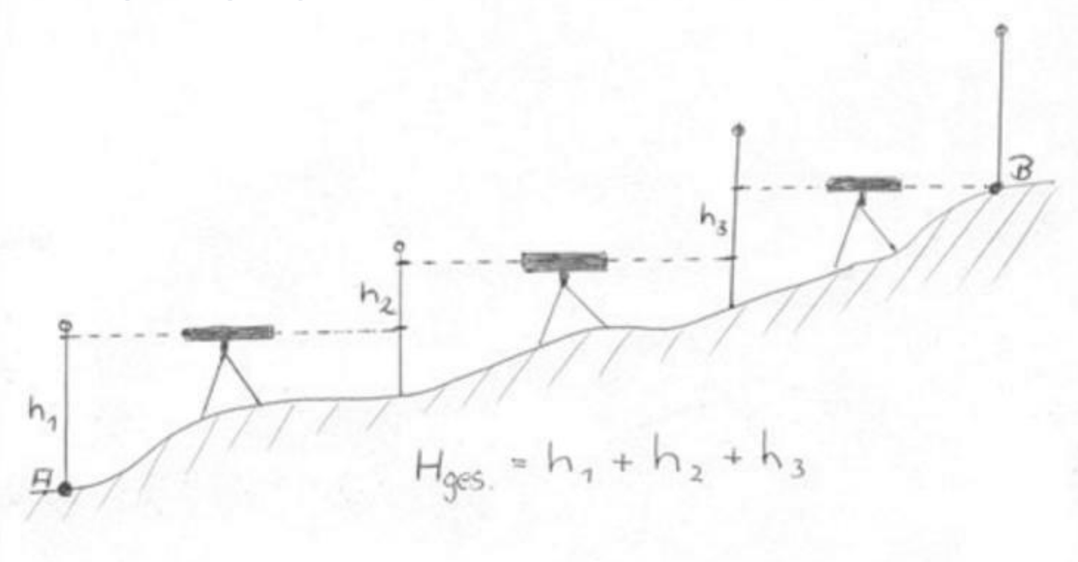
Instrumentation toolkit

- Determination of the position
    - Standard instruments
    - Alignment systems
- Adjustment

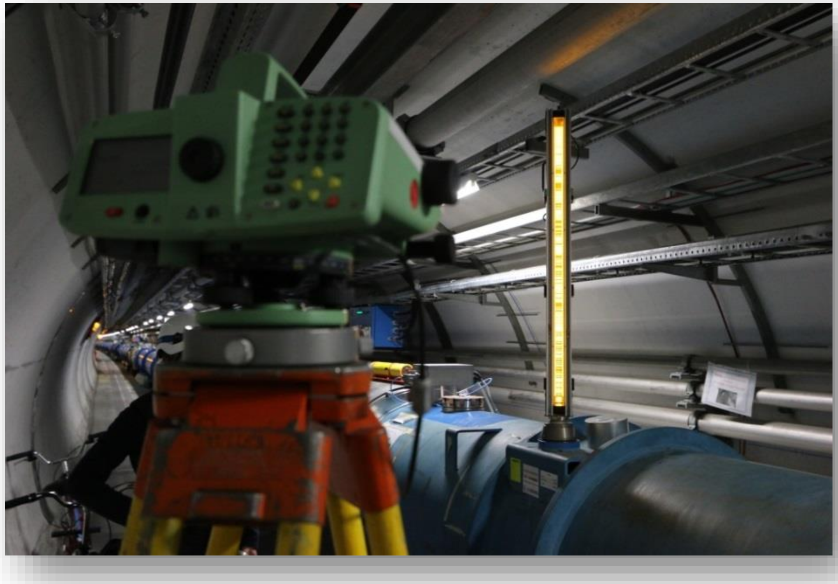
Instrumentation toolkit

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

Levels



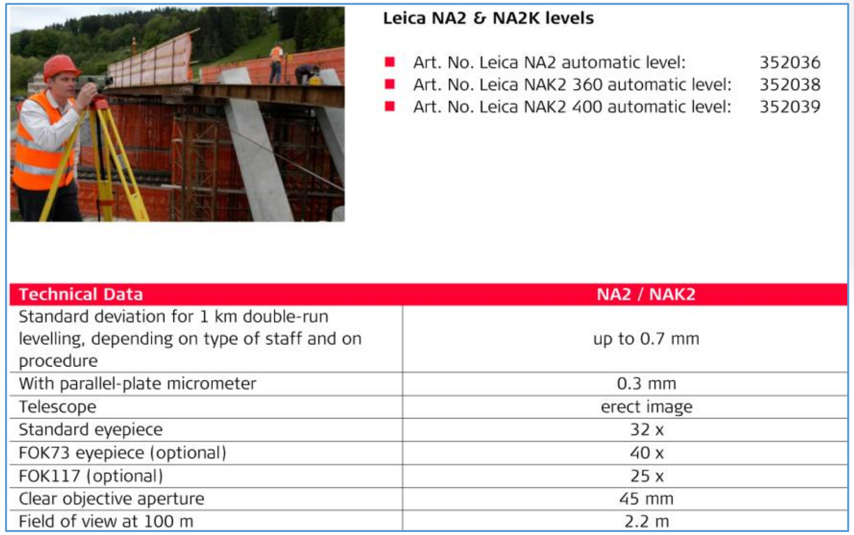
Height measurements between B and A using levels



Digital level and barcode rod

Barcode rod

Digital level

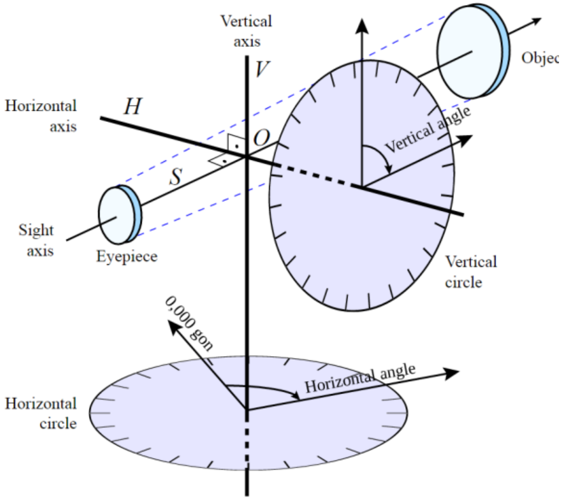


Leica NA2 & NA2K levels

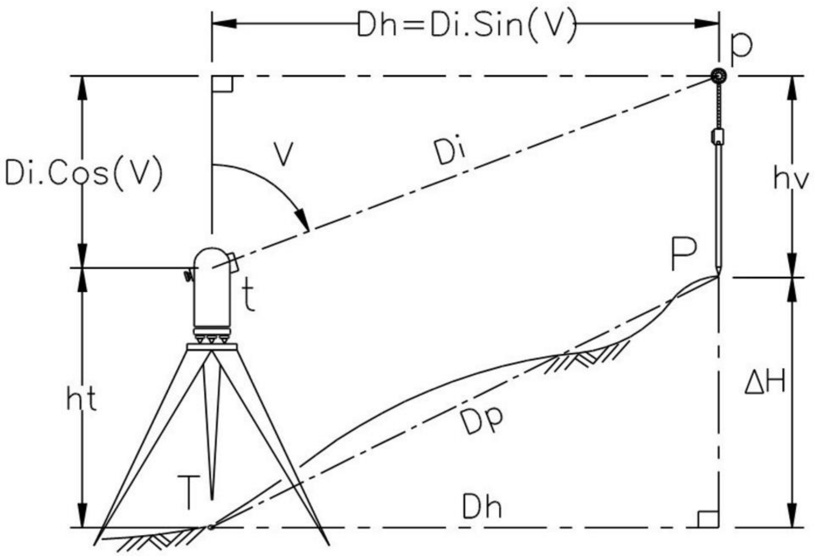
Art. No. Leica NA2 automatic level:	352036
Art. No. Leica NAK2 360 automatic level:	352038
Art. No. Leica NAK2 400 automatic level:	352039

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

Total station

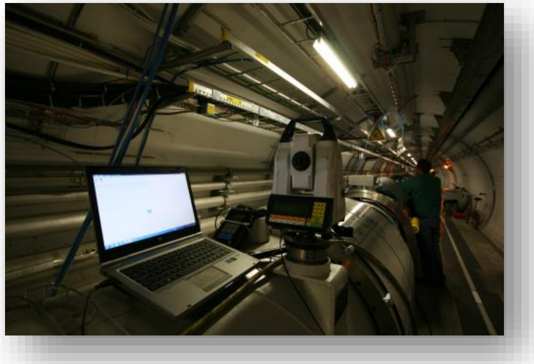


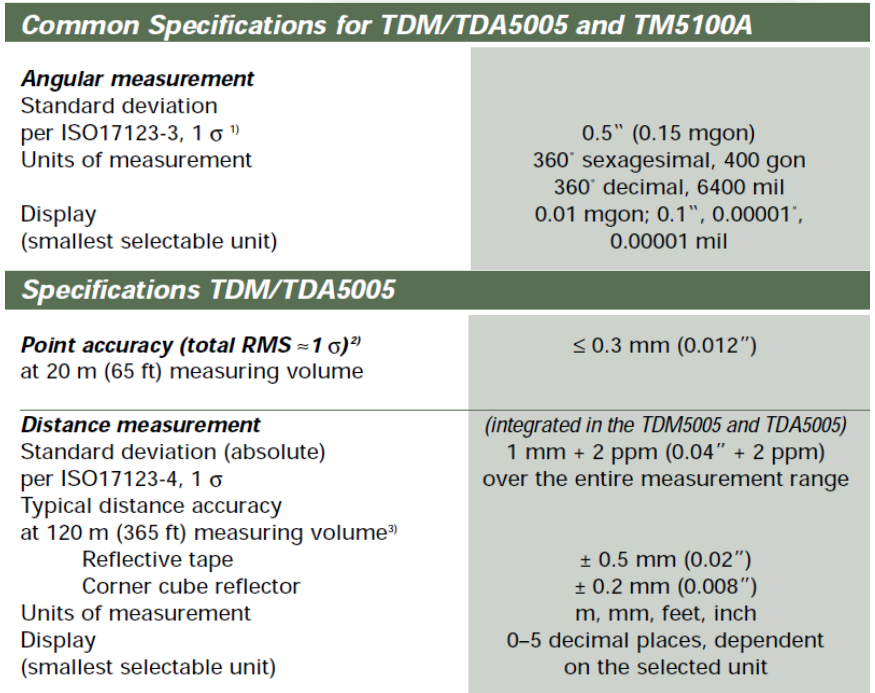
Total station: angle measurements



Total station: point measurement

A total station in the LHC





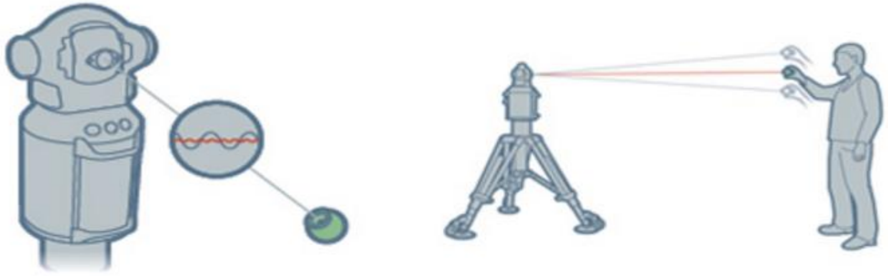
Common Specifications for TDM/TDA5005 and TM5100A	
Angular measurement	
Standard deviation per ISO17123-3, 1 σ $^{1)}$	0.5" (0.15 mgon)
Units of measurement	360° sexagesimal, 400 gon 360° decimal, 6400 mil
Display (smallest selectable unit)	0.01 mgon; 0.1", 0.00001°, 0.00001 mil

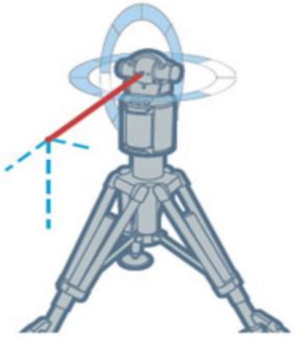
Specifications TDM/TDA5005	
Point accuracy (total RMS ≈ 1 σ)$^{2)}$ at 20 m (65 ft) measuring volume	≤ 0.3 mm (0.012″)
Distance measurement	*(integrated in the TDM5005 and TDA5005)*
Standard deviation (absolute) per ISO17123-4, 1 σ	1 mm + 2 ppm (0.04″ + 2 ppm) over the entire measurement range
Typical 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)

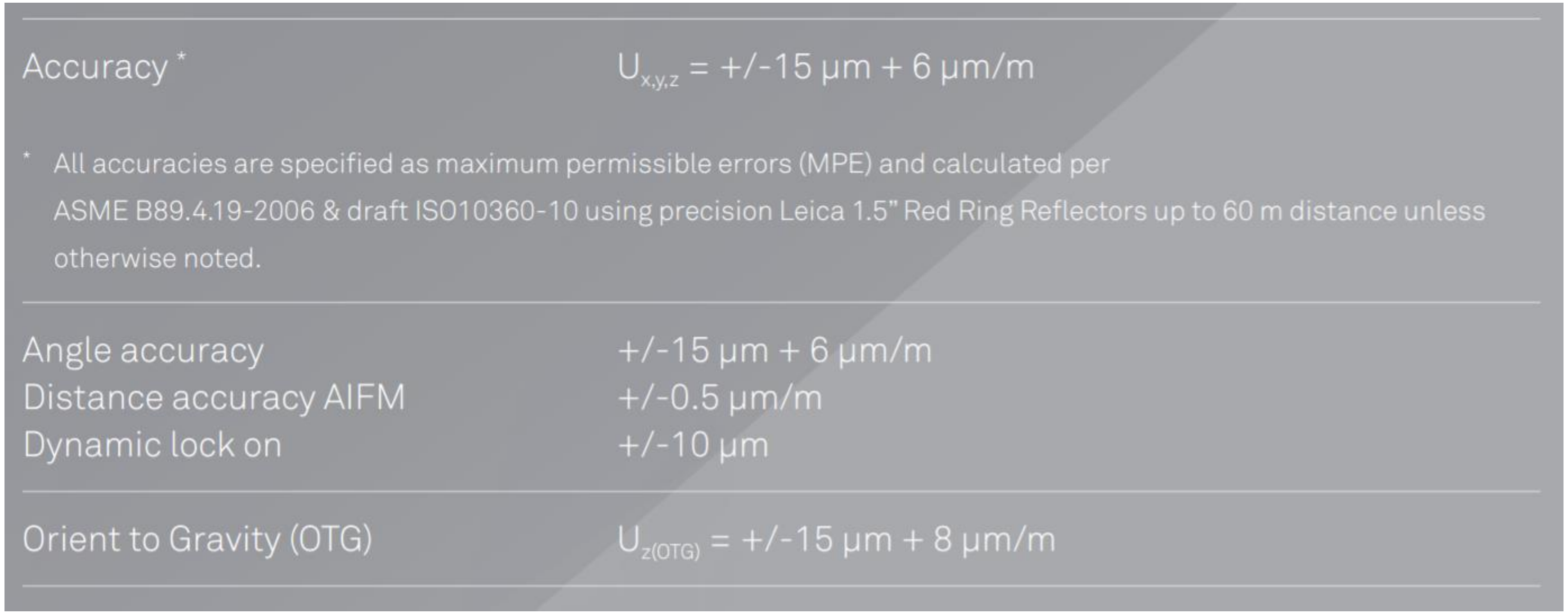
Laser tracker





Laser tracker

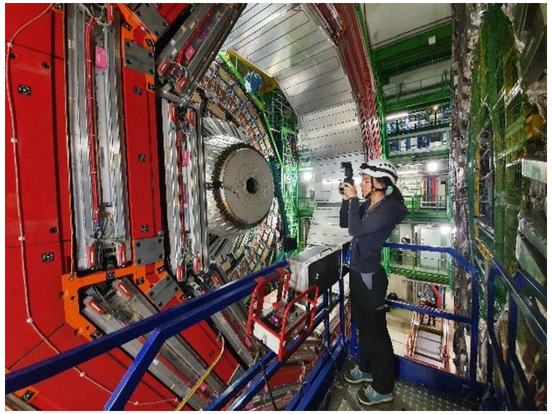
- Measure 3D coordinates by tracking a laser beam to a retro-reflective target
- Combination of two techniques:
  - A distancemeter (Interferometer or Absolute Distance Meter)
  - Angular encoders to measure the laser tracker’s rotations around two mechanical axes

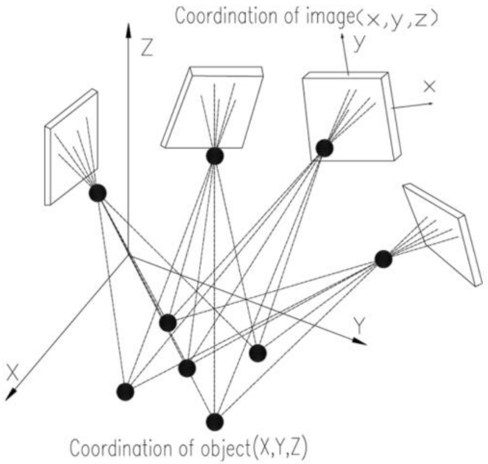


Accuracy *	$U_{x,y,z}$ = +/-15 µm + 6 µm/m
Angle accuracy	+/-15 µm + 6 µm/m
Distance accuracy AIFM	+/-0.5 µm/m
Dynamic lock on	+/-10 µm
Orient to Gravity (OTG)	$U_{z(OTG)}$ = +/-15 µm + 8 µm/m

* 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.

Photogrammetry


Photogrammetry in CMS



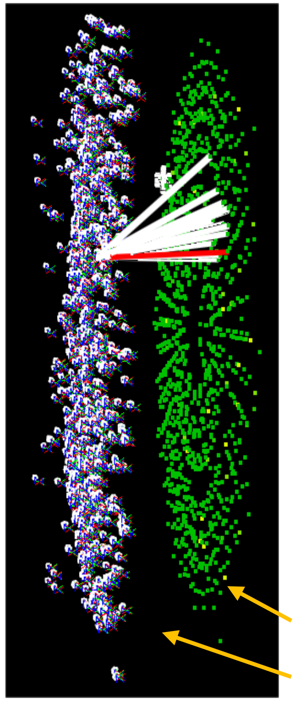
Concept of photogrammetry

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

- No needs of stable station for image acquisition
- Flexible use following object size
  - Components < 1 m (1 sigma < 10 µm)
  - Components up to 15-25 m (1 sigma < 0.3 to 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 time interruption for installation, production process

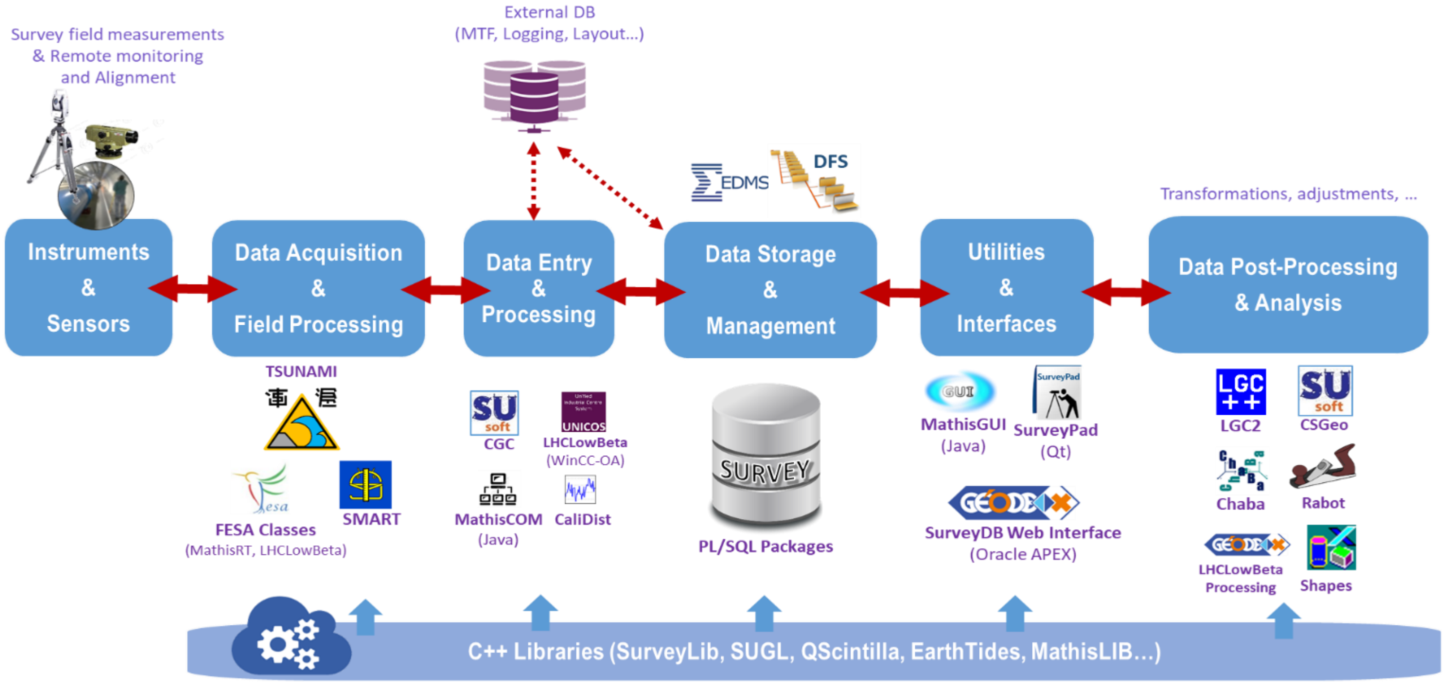

ATLAS TGC3-C Big Wheel measurement

Object diameter: ~25 m
Distance to object: 5-6 m
Number of photos: ~960
Number of observations: ~ 90000
Number of unknowns: ~9400
Number of points: ~1200
Precision: ~0.5 mm

TGC3-C measured points
Camera positions

Software and Database Applications

- Data acquisition
- Processing & analysis



Survey field measurements
& Remote monitoring
and Alignment

External DB
(MTF, Logging, Layout...)

EDMS

DFS

Transformations, adjustments, ...

Instruments & Sensors

Data Acquisition & Field Processing

Data Entry & Processing

Data Storage & Management

Utilities & Interfaces

Data Post-Processing & Analysis

TSUNAMI

FESA Classes
(MathisRT, LHCLowBeta)

SMART

CGC

LHCLowBeta
(WinCC-OA)

MathisCOM
(Java)

CaliDist

SURVEY

PL/SQL Packages

MathisGUI
(Java)

SurveyPad
(Qt)

SurveyDB Web Interface
(Oracle APEX)

LGC2

CSGeo

Chaba

Rabot

LHCLowBeta
Processing

Shapes

C++ Libraries (SurveyLib, SUGL, QScintilla, EarthTides, MathisLIB...)

- DAQ for all type of survey instrumentation
- Generalized least squares processing of all available data types
- Statistical analysis of results
- Monte Carlo simulations, generation of random and/or systematic perturbations for the simulations
- Transformation of local geoid heights to ellipsoidal heights
- Transformation of angular measurements observed in a gravity related system, to a CCS system
- Weighted Helmert transformation tools
- …

Survey database

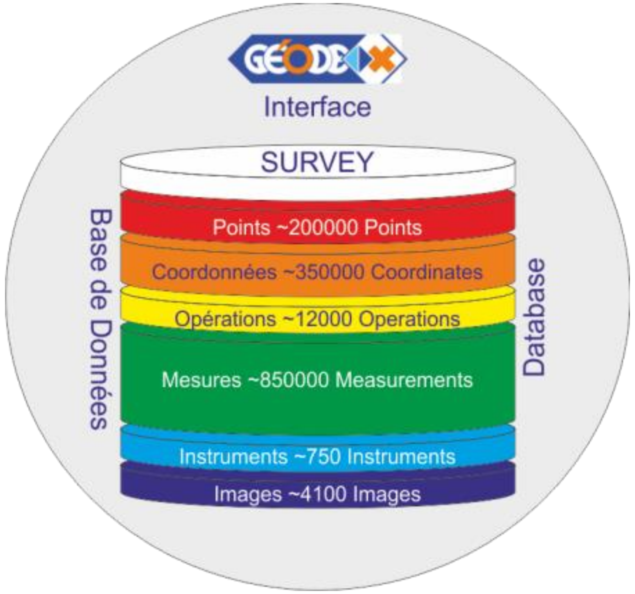
Survey Data Base is a crucial part of the workflow of the survey activities

It contains

- Theoretical positions of all beams at CERN in CCS (CERN Coordinate System);
- Real positions of the networks geodetic points in CCS;
- Deviations of all aligned components from their theoretical position;
- Measurements related to the installation and alignment of accelerators components;
- Instruments data necessary for those measurements.

Multiple users:

- Geodetic Metrology
- And also: Operators, Layout, Integration, GIS



Instrumentation toolkit

- Determination of the position
  - Standard instruments
  - Specific alignment systems
    - Wire offsets
    - Hydrostatic Levelling System (HLS) & applications
    - Wire Positioning System (WPS) & applications
    - Gravity effects on WPS & HLS
    - Laser based alignment systems and R&D
- Adjustment

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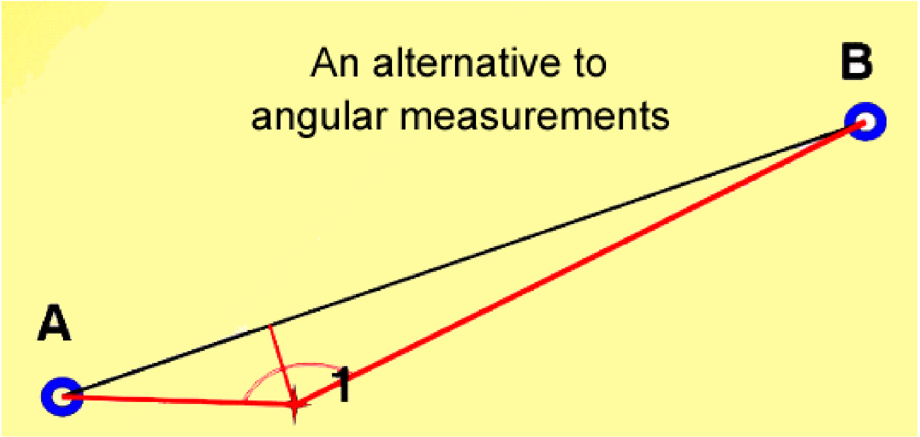
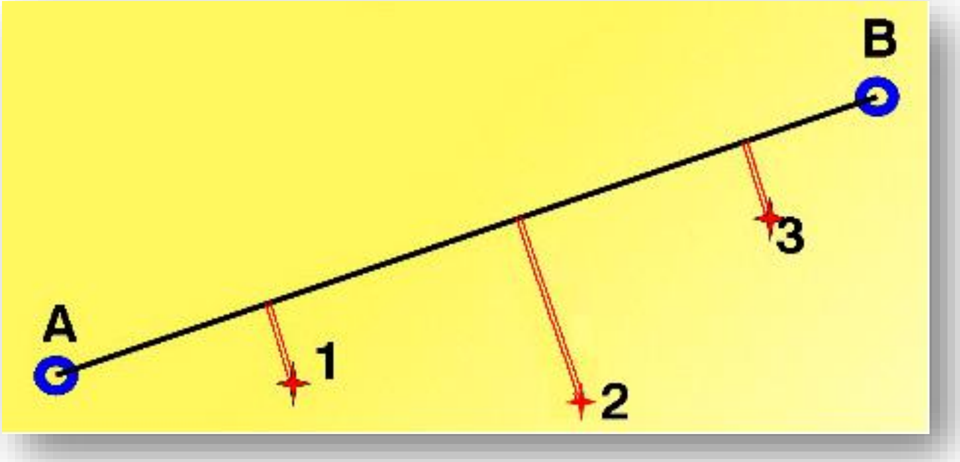
Wire offset measurements

Principle





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

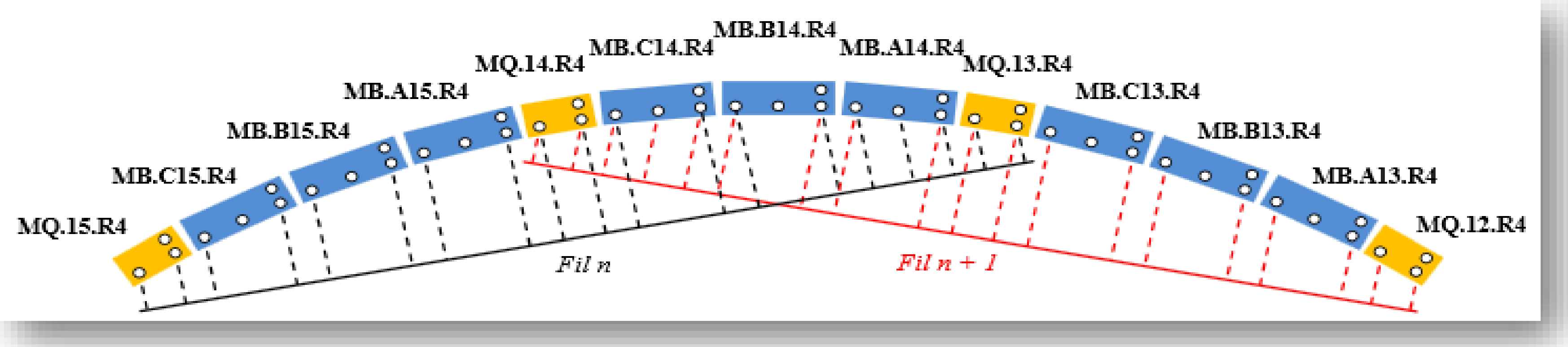
Manual device
Accuracy 0.07mm

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

Instrumentation toolkit

- Determination of the position
  - Standard instruments
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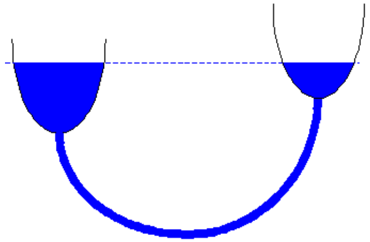
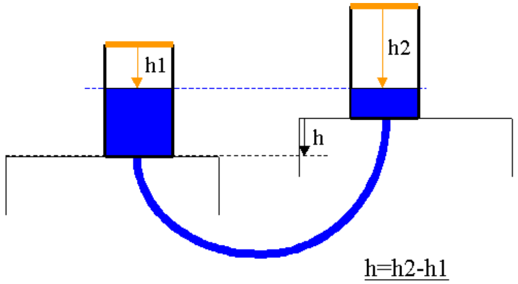
- Adjustment

Hydrostatic Levelling System (HLS)



Communicating vessels



Difference of height measurement

Resolution: 0.2 µm

Measurement range: 5mm

Repeatability: 1 µm

Bandwidth: 10 Hz

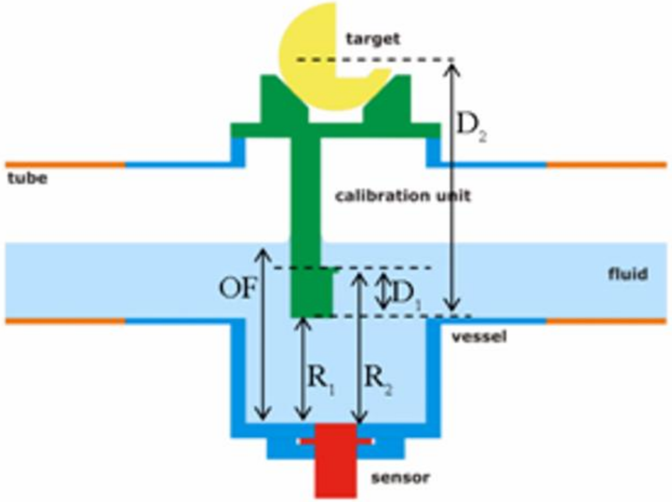
Based on communicating vessels

Water network = reference surface

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

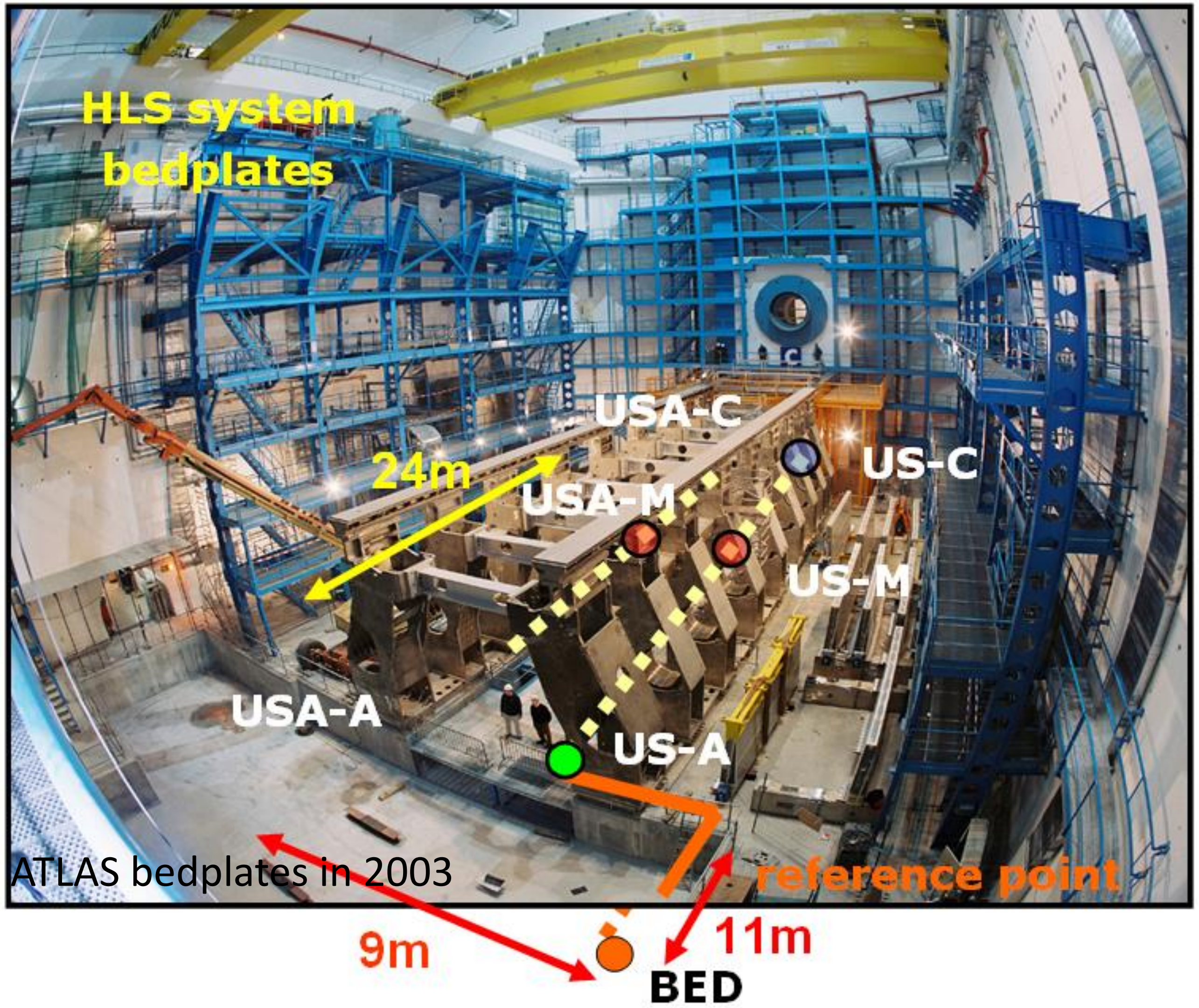
Hydrostatic Levelling Sensor (capacitive-based)

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

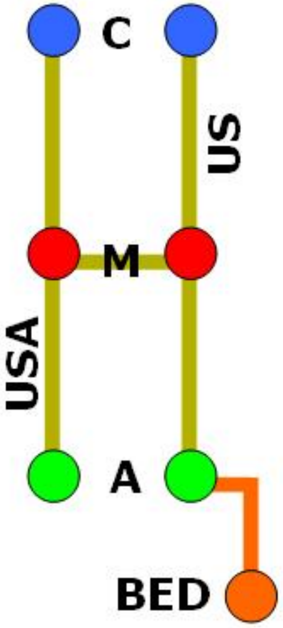


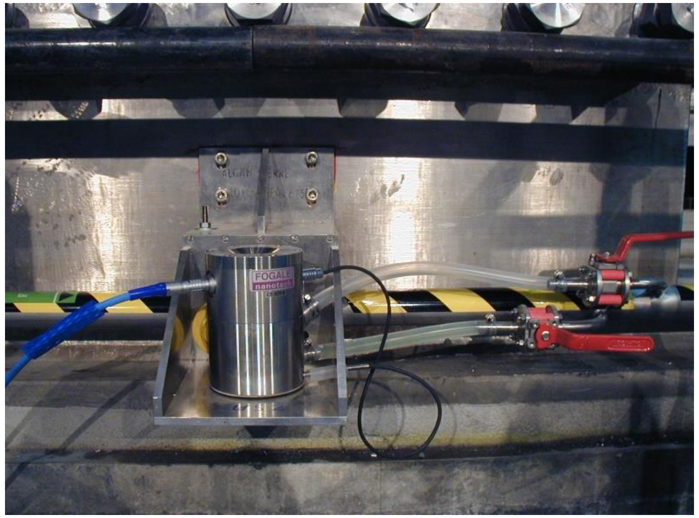
Another type of Hydrostatic Levelling Sensor based on ultra sound

HLS applications: ATLAS bedplates



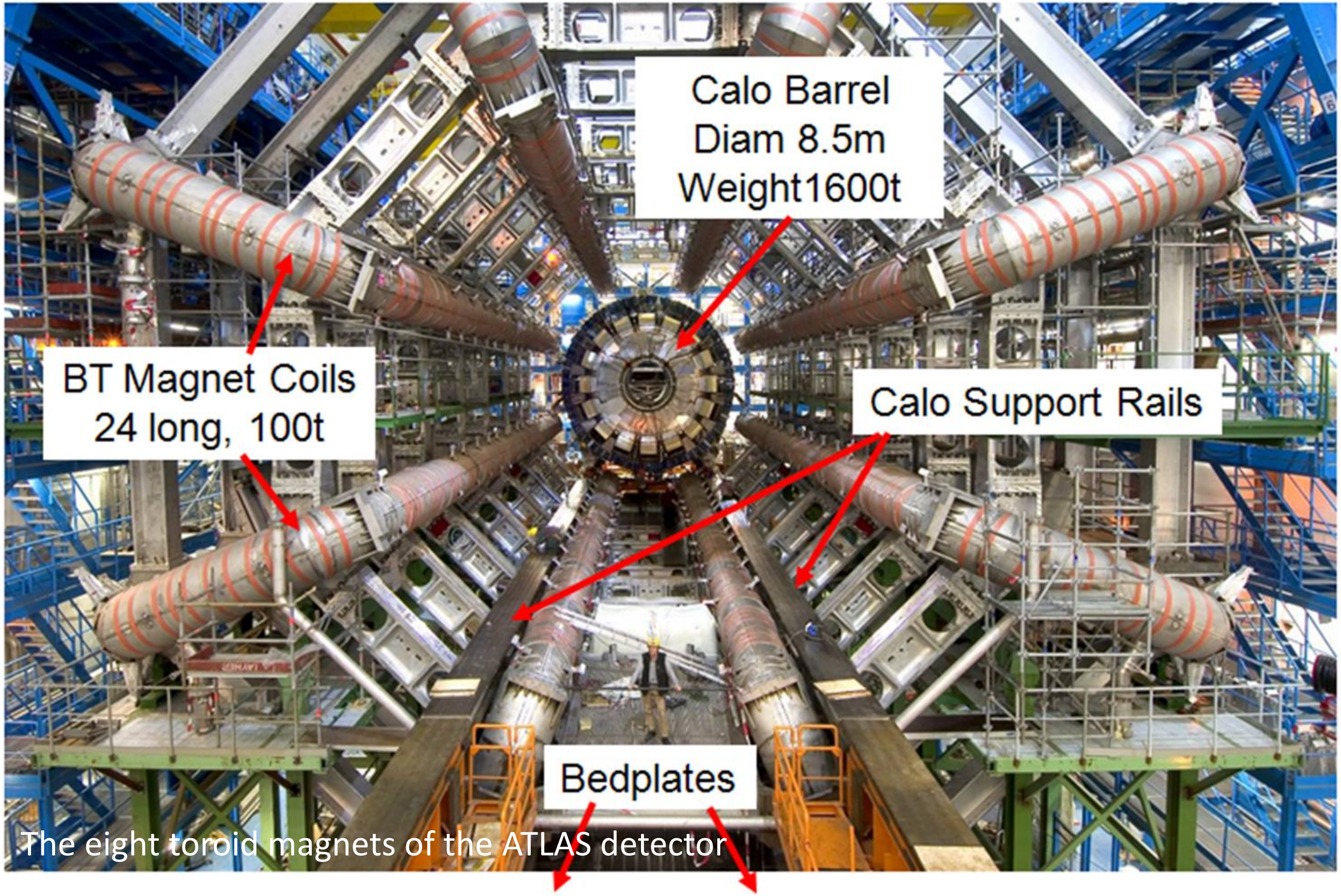
ATLAS bedplates in 2003





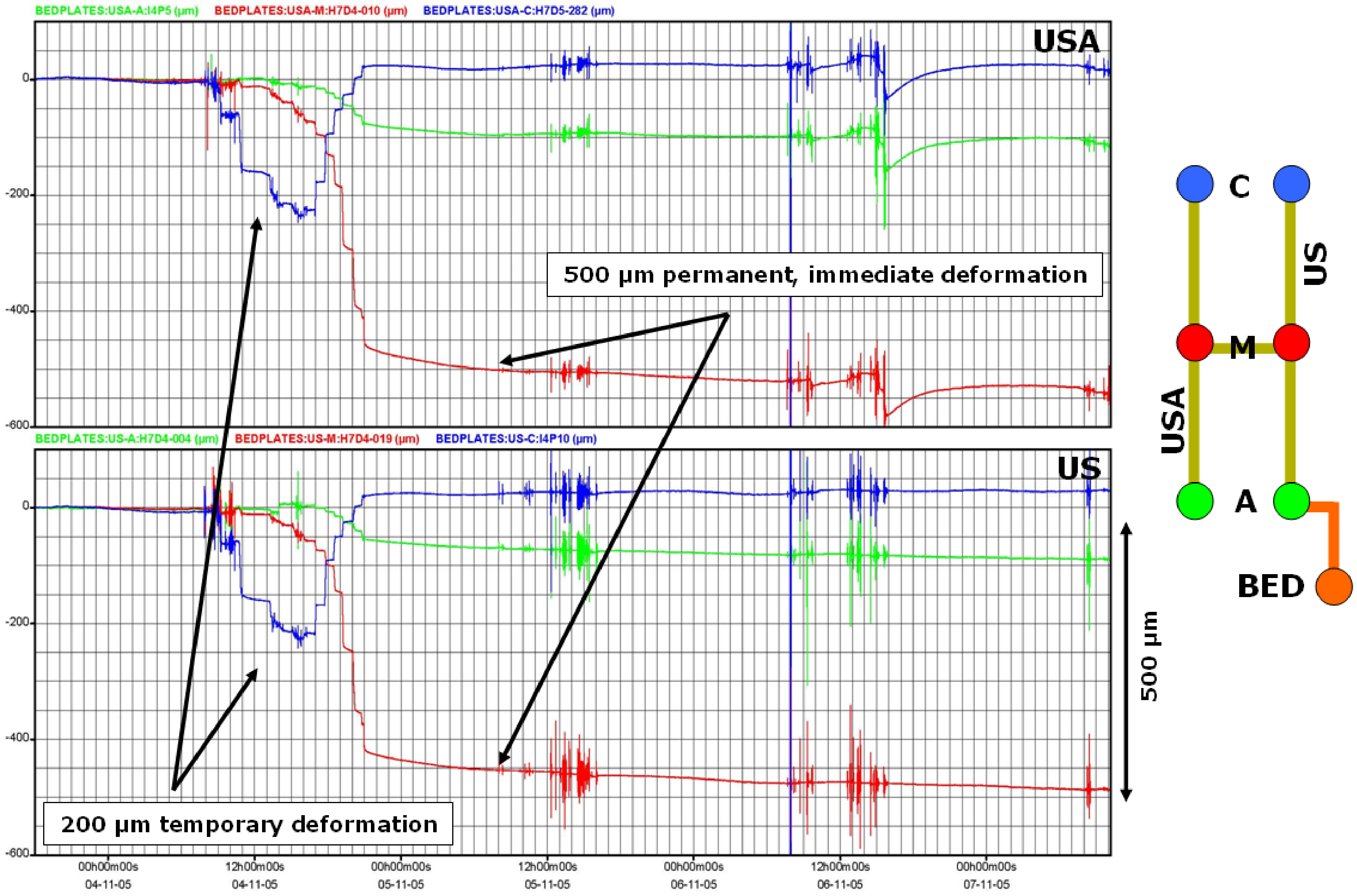
HLS in ATLAS bedplates

HLS applications: ATLAS bedplates



The eight toroid magnets of the ATLAS detector

HLS applications: ATLAS bedplates

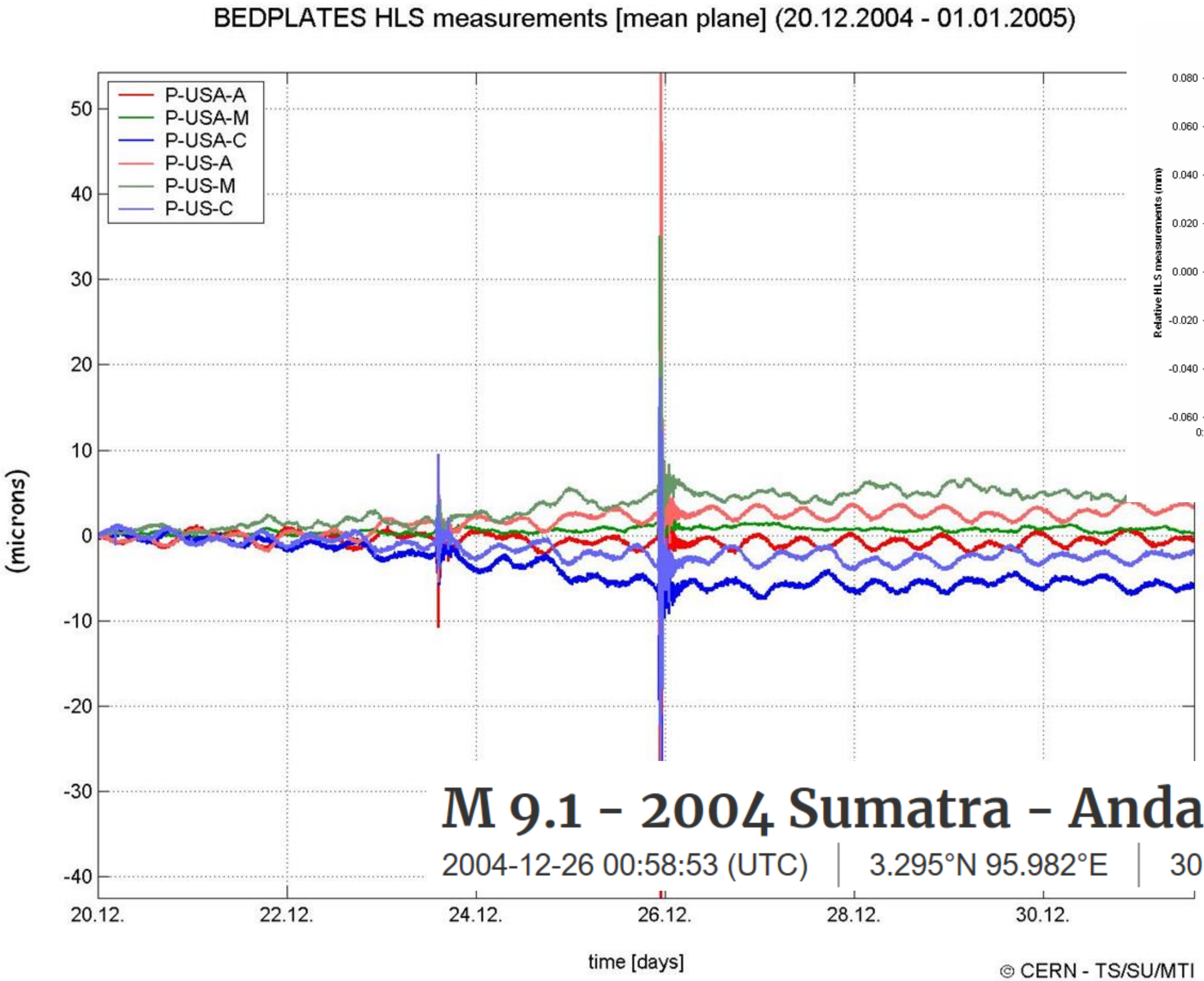


500 µm permanent, immediate deformation

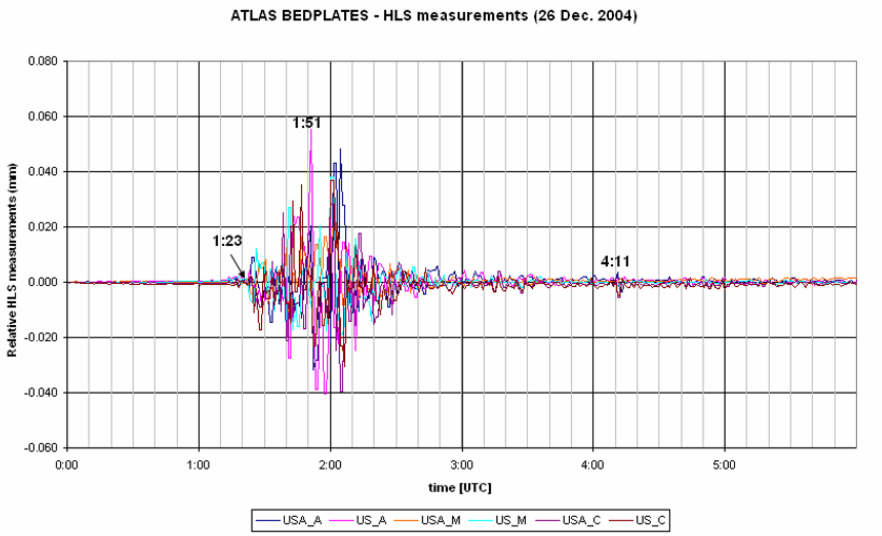
200 µm temporary deformation

HLS measurements during the installation of the ATLAS Tile Barrel calorimeter from C to M (IP) position

HLS applications: ATLAS bedplates



© CERN - TS/SU/MTI
03-Jan-2005



M 9.1 - 2004 Sumatra - Andaman Islands Earthquake

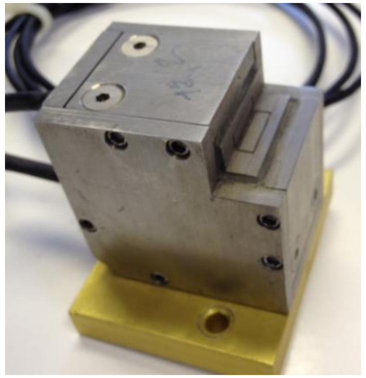
2004-12-26 00:58:53 (UTC) | 3.295°N 95.982°E | 30.0 km depth

Instrumentation toolkit

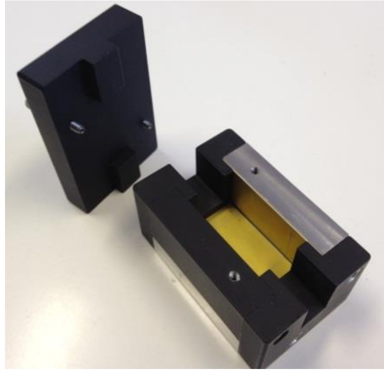
- Determination of the position
  - Standard instruments
  - Specific alignment systems
    - Wire offsets
    - Hydrostatic Levelling System (HLS) & applications
    - Wire Positioning System (WPS) & applications
    - Gravity effects on WPS & HLS
    - Laser based alignment systems and R&D
- Adjustment

Wire positioning System (WPS)

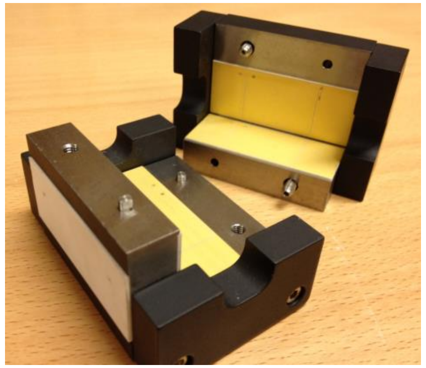
Prototype (1990)



Version 1 in 1994

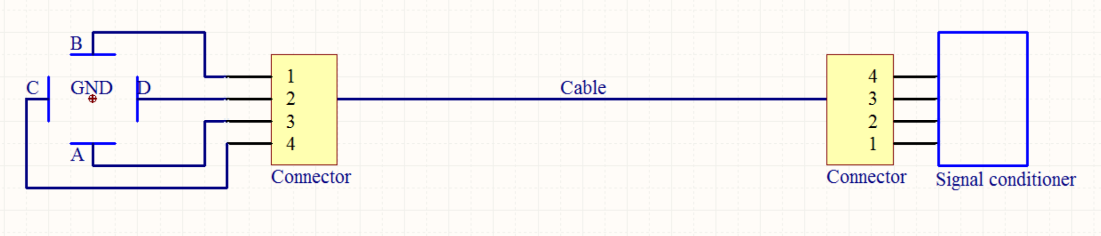


Version 2 in 2000



Version 2 CERN

Differential capacitive sensors

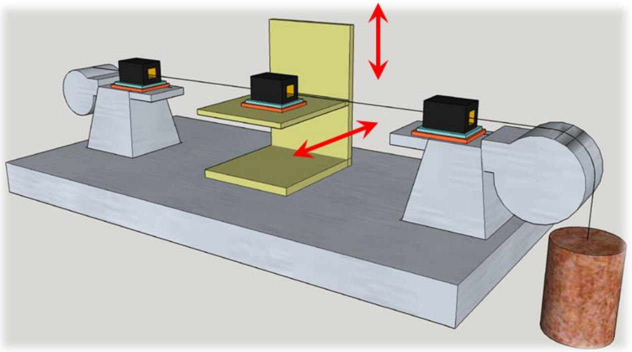


$V, I, digital:$ $\overrightarrow{pos.}\,value$

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

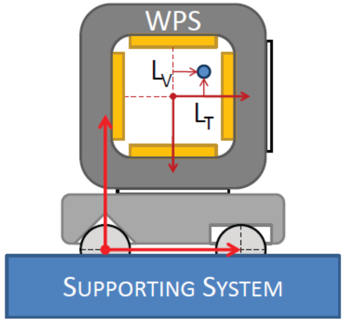
WPS performances



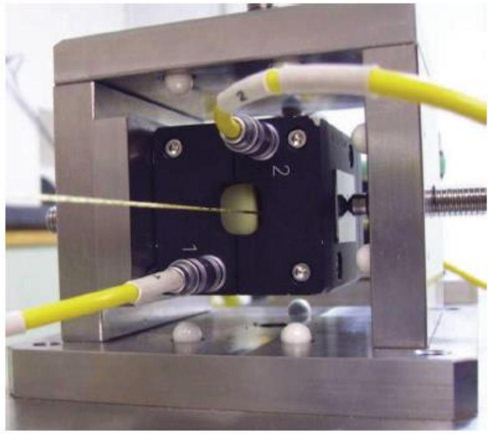
«Absolute» calibration bench

Voltage: 0-10 V

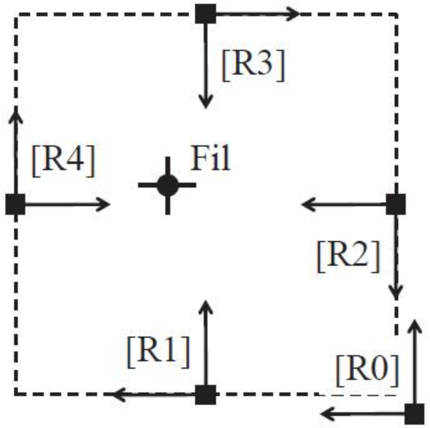
Full Range : +/- 5 mm



WPS kinematic supporting system



Zoom on «Absolute» calibration bench



CERN

Repeatibility : +/- 1 μm (1σ)

Linearity : 2 μm / mm (1σ)

Accuracy : 5 μm (1σ)

WPS: associated wire


Carbon Kevlar

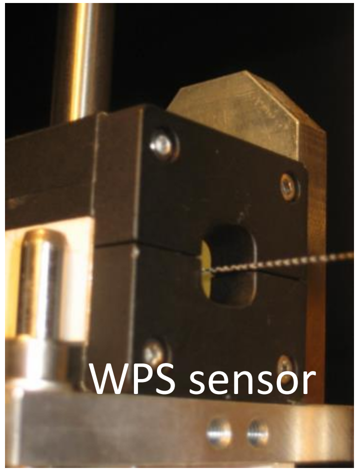

Carbon PEEK/PES


Zoom on carbon Kevlar wire

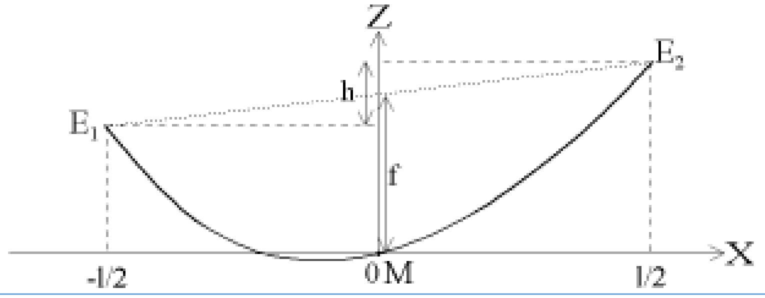

Wire reel

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

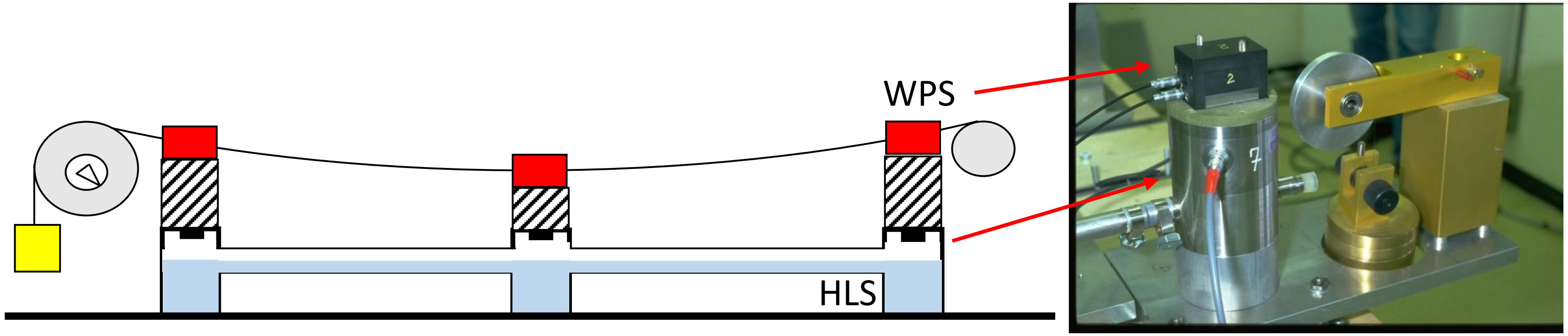

WPS sensor

WPS: impact of sag



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

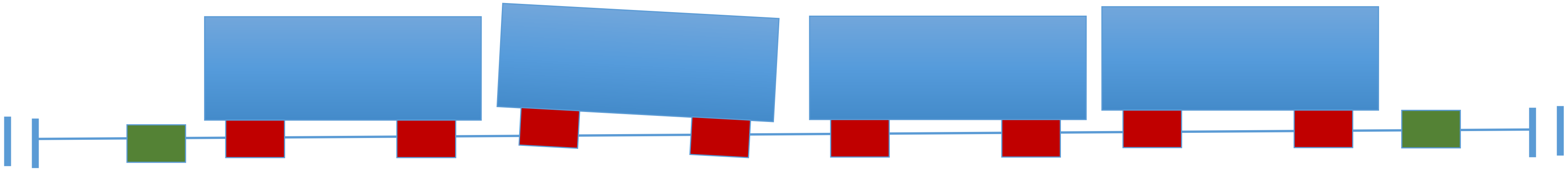
Catenary of a wire



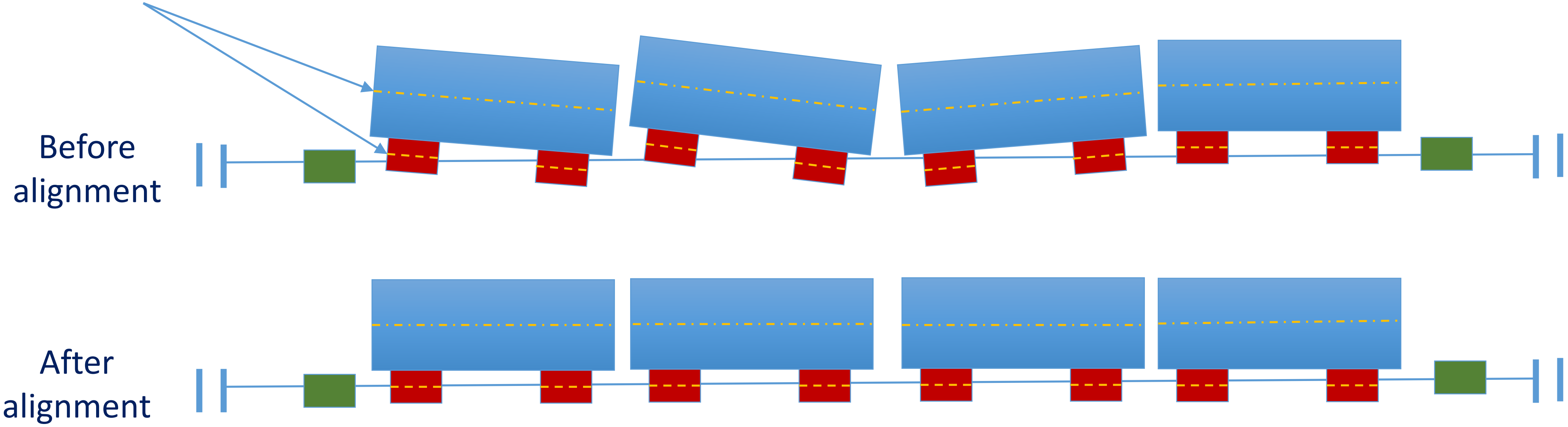
Determination of the wire sag using a superposition of HLS and WPS sensors

WPS: two types of possible use

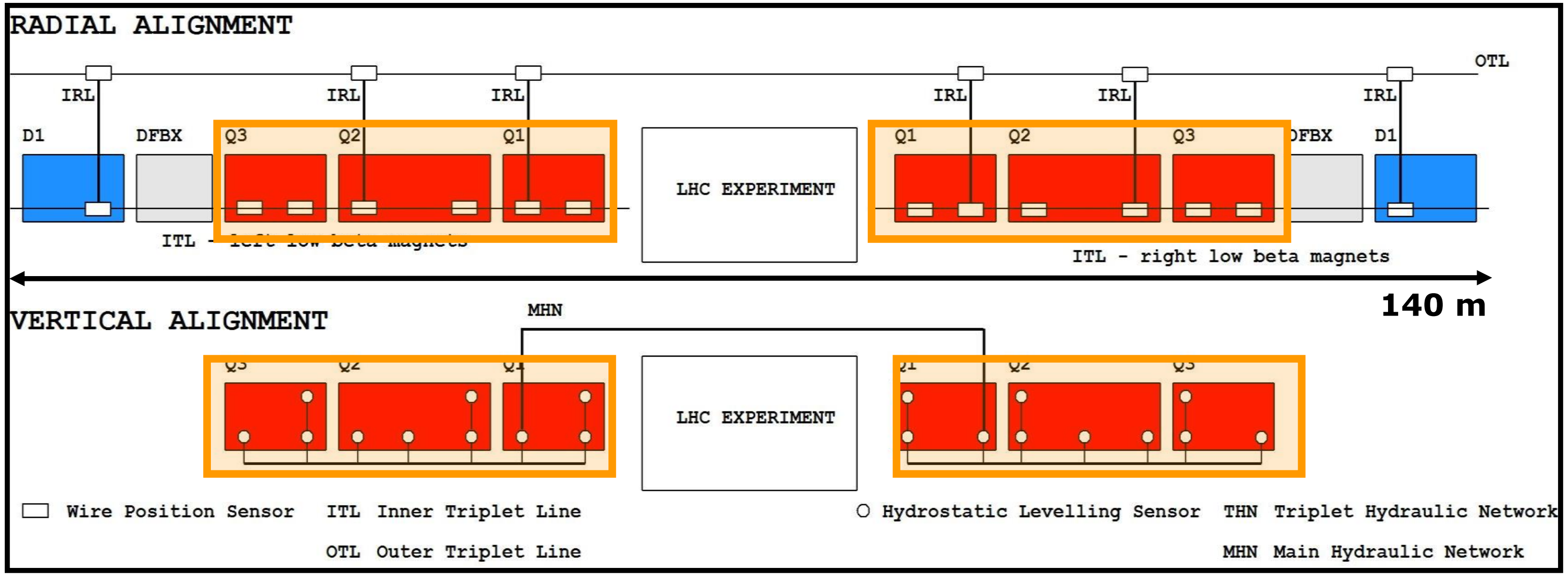
- Movement monitoring or “relative” alignment monitoring



- “Absolute” alignment
    - Link between sensor axis and component axis need to be known (Fiducialisation)

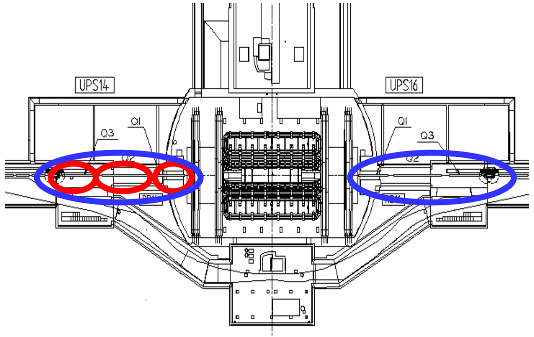


WPS & HLS: alignment of LHC inner triplets

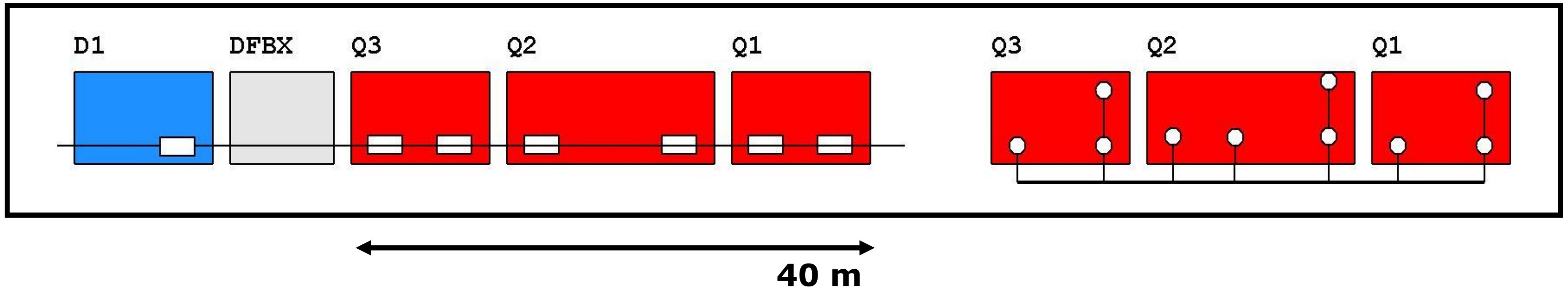


Sensors configuration on inner triplets

🟧 low beta triplet



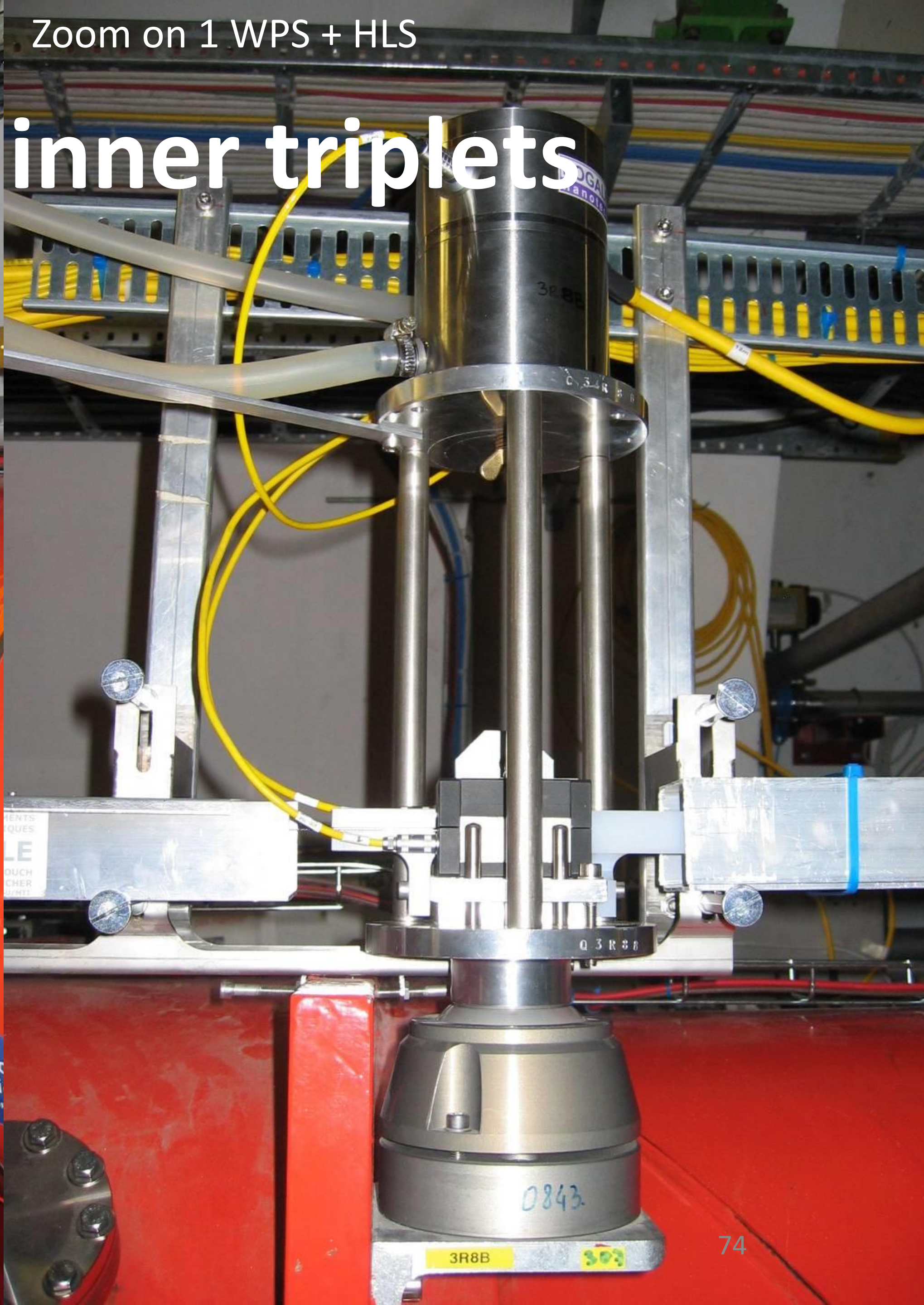
Location of inner triplets



Courtesy of A. Herty

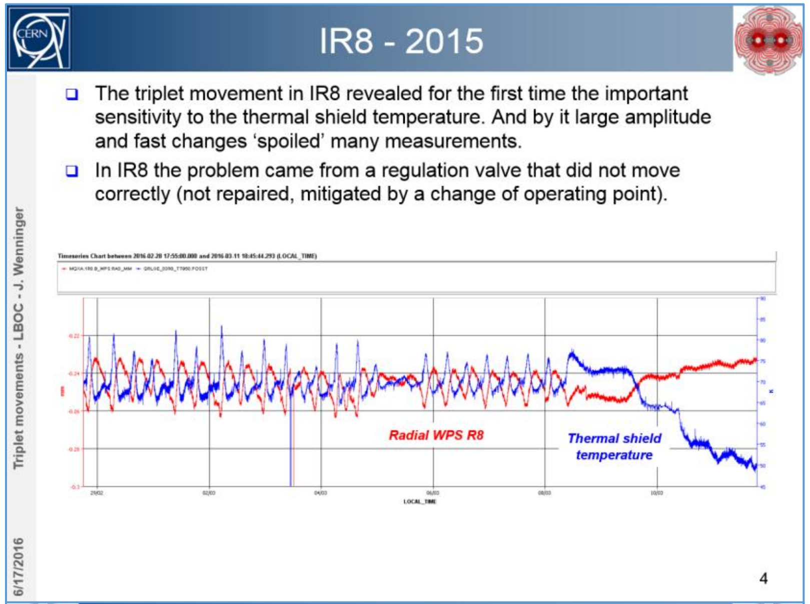
WPS & HLS: alignment of LHC inner triplets

LHC inner triplet with alignment sensors and motorized jacks



Zoom on 1 WPS + HLS

WPS & HLS: Alignment of LHC inner triplets



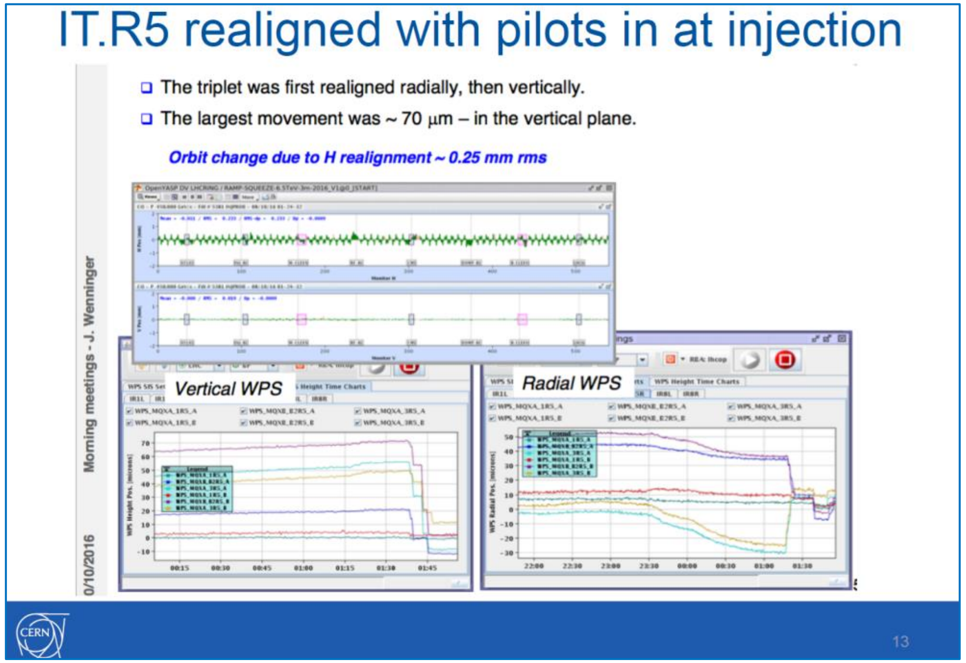
IR8 - 2015

- The triplet movement in IR8 revealed for the first time the important sensitivity to the thermal shield temperature. And by it large amplitude and fast changes 'spoiled' many measurements.
- In IR8 the problem came from a regulation valve that did not move correctly (not repaired, mitigated by a change of operating point).

Triplet movements - LBOC - J. Wenninger

6/17/2016

4



IT.R5 realigned with pilots in at injection

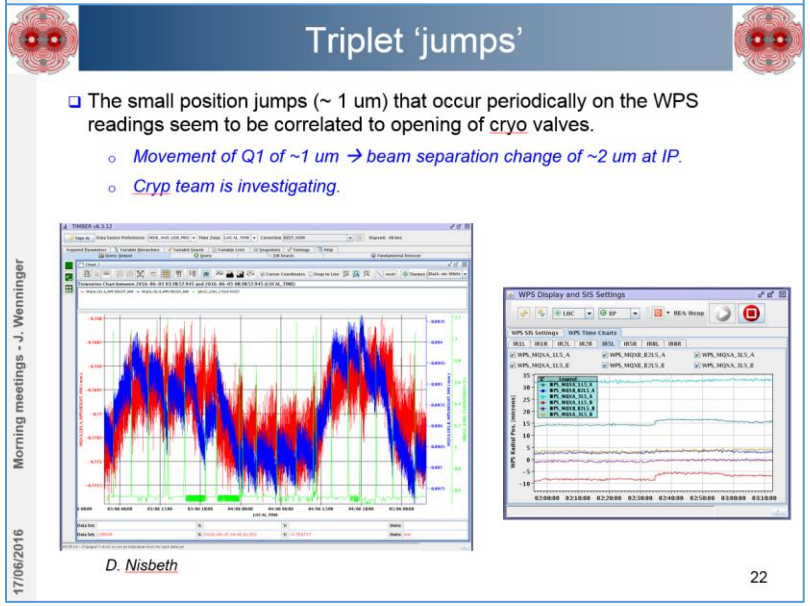
- The triplet was first realigned radially, then vertically.
- The largest movement was ~ 70 µm – in the vertical plane.

Orbit change due to H realignment ~ 0.25 mm rms

Morning meetings - J. Wenninger

0/10/2016

13



Triplet 'jumps'

- The small position jumps (~ 1 um) that occur periodically on the WPS readings seem to be correlated to opening of cryo valves.
  - *Movement of Q1 of ~1 um → beam separation change of ~2 um at IP.*
  - *Cryp team is investigating.*

D. Nisbeth

Morning meetings - J. Wenninger

17/06/2016

22

- 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 !!!

Instrumentation toolkit

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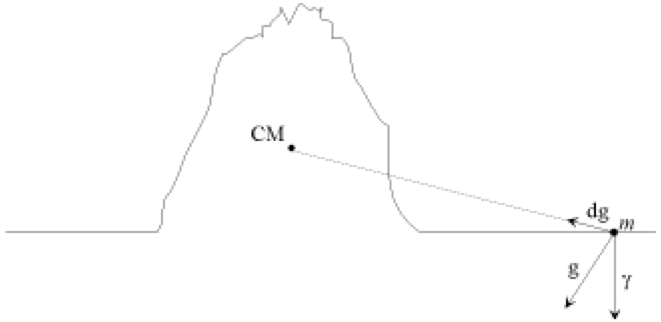
- Adjustment

Alignment systems and gravity

Metrology networks must provide a straight alignment of accelerator linacs

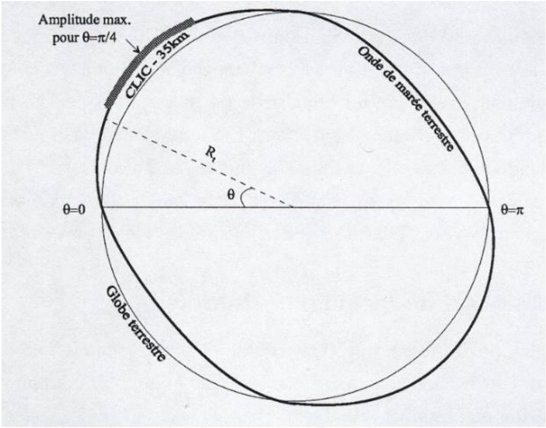
Reference frames (wire and water surface) are influenced by gravity:

- ✓ 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]

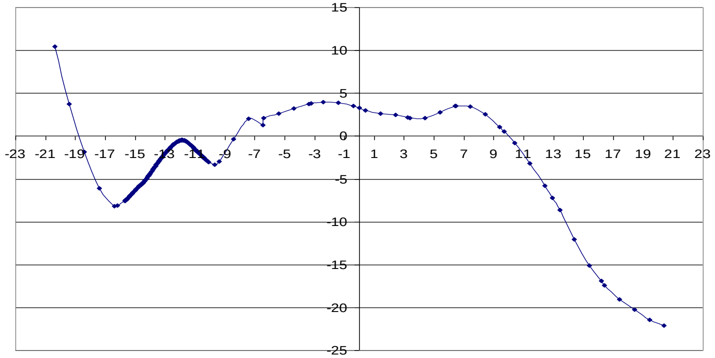
Alignment systems and gravity

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]

Instrumentation toolkit

- Determination of the position
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Laser based alignment systems

Frequency Scanning Interferometry (FSI)

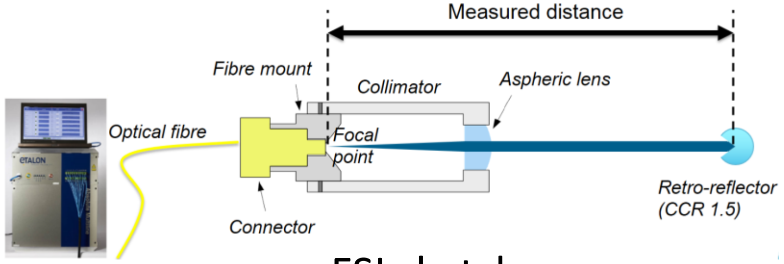
- Validation of the commercial solution based on Frequency Scanning Interferometry (FSI);

- Providing **absolute distance** measurements

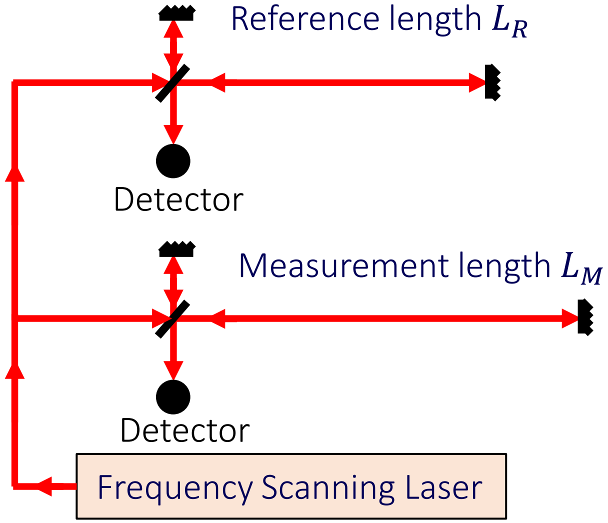
- $\Delta Phase\ (meas.) = \frac{2\pi}{c} * L_M * \Delta\nu$
- $\Delta Phase\ (\ ref.\ ) = \frac{2\pi}{c} * L_R * \Delta\nu$

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

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



FSI sketch



Reference length L_R

Detector

Measurement length L_M

Detector

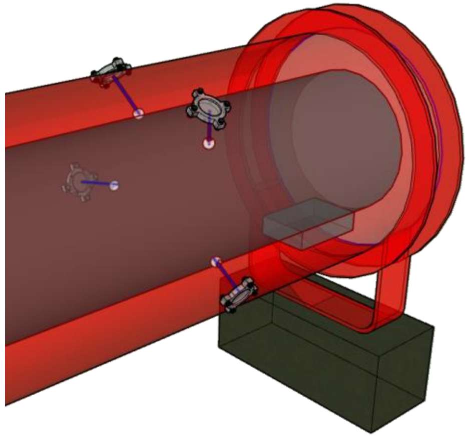
Frequency Scanning Laser

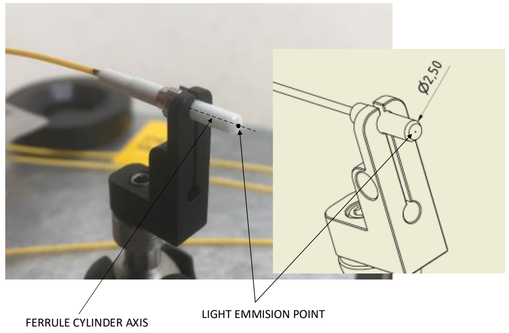
FSI measurement

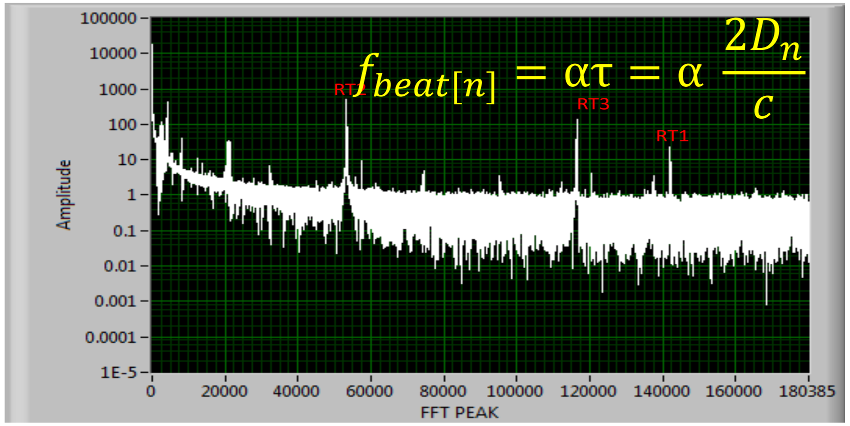
Laser based alignment systems – R&D

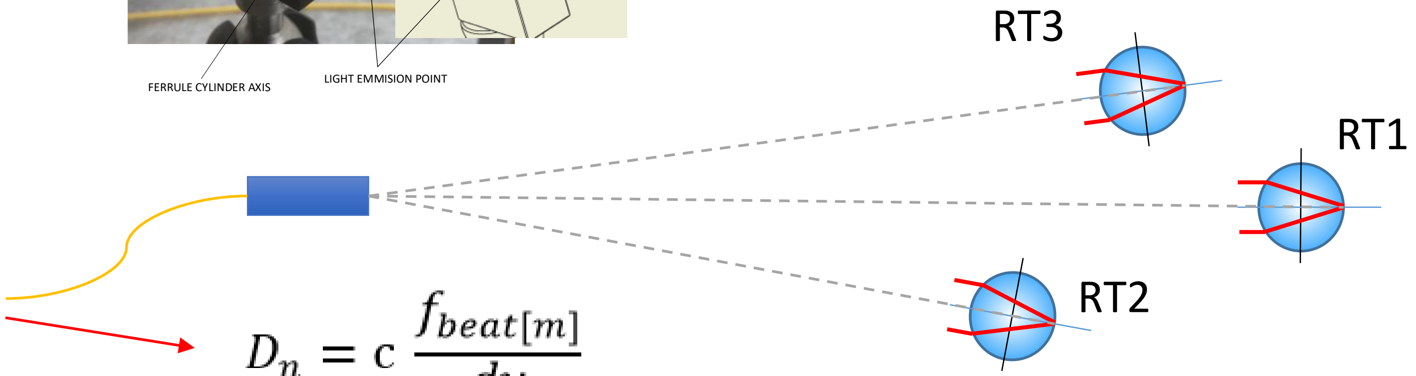
Multi Target Frequency Scanning Interferometry (FSI)

- Providing absolute distance measurements on multiple points from one fiber






$$f_{beat[n]} = \alpha\tau = \alpha\frac{2D_n}{c}$$



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

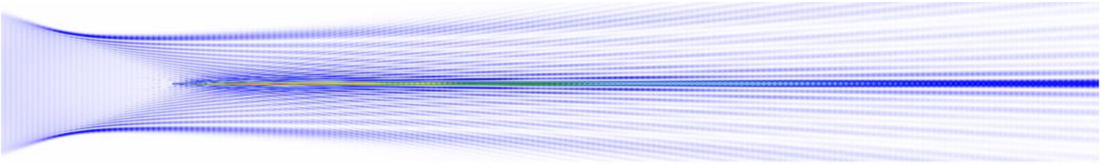
α – is a sweep rate of the laser ($\alpha = \frac{dv}{dt}$ - laser frequency change in time);
c – speed of light;
n – refractive index of light transmission medium;
τ – time of flight of laser to the target

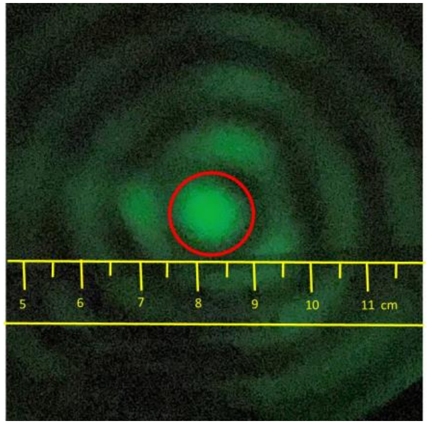
Courtesy Mateusz Sosin / Vivien Rude

Laser based alignment systems – R&D

The Structured Laser Beam (SLB)

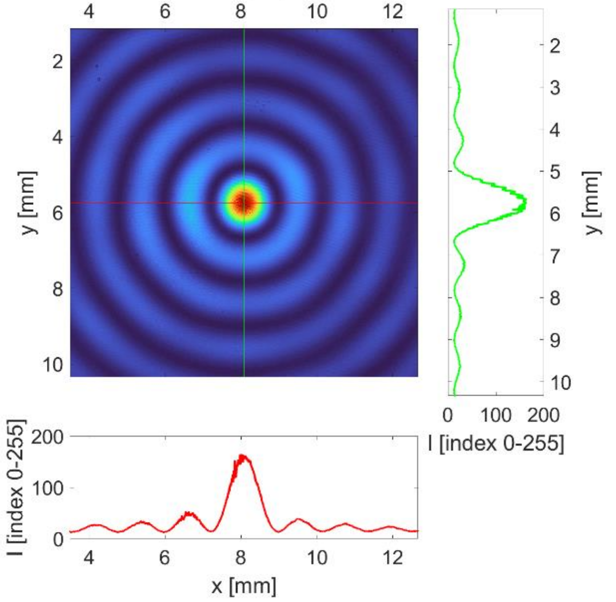
SLB Longitudinal profile





SLB at 900m

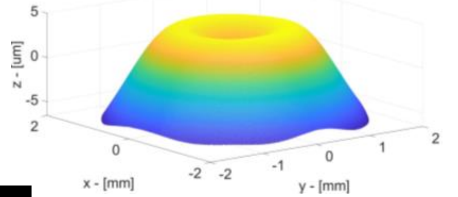
SLB example at 50m



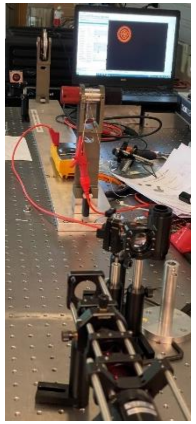
SLB: Pseudo non-diffractive beam

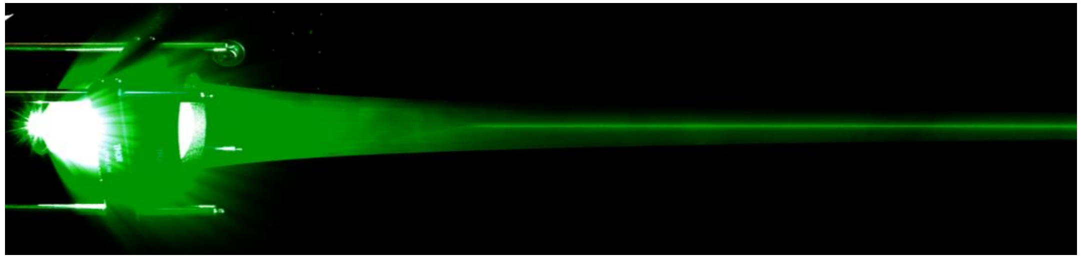
R&D collaboration CERN and IPP (CZ)

https://kt.cern/technologies/structured-laser-beam



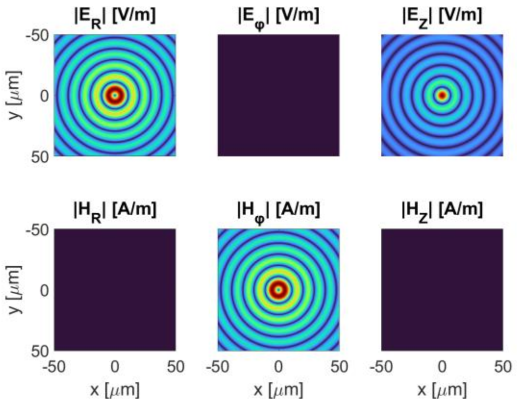
A measured SLB wavefront





Very bright central core, sharp boundarie, small divergence, theoretically infinite range (tested on 900 m)

[Gayde3]



E / H fields in cylindrical coordinates

Among the properties under study:

- Symmetry breaks / Straightness / Wavefront shape / Intensity distribution
- SLB from non-classical polarisation

SLB … an optical alternative to WPS ?

Study case

How to monitor the **vertical deformation** of a tunnel floor during civil engineering works?

How to monitor the **deformation of a tunnel cross section** during civil engineering works?

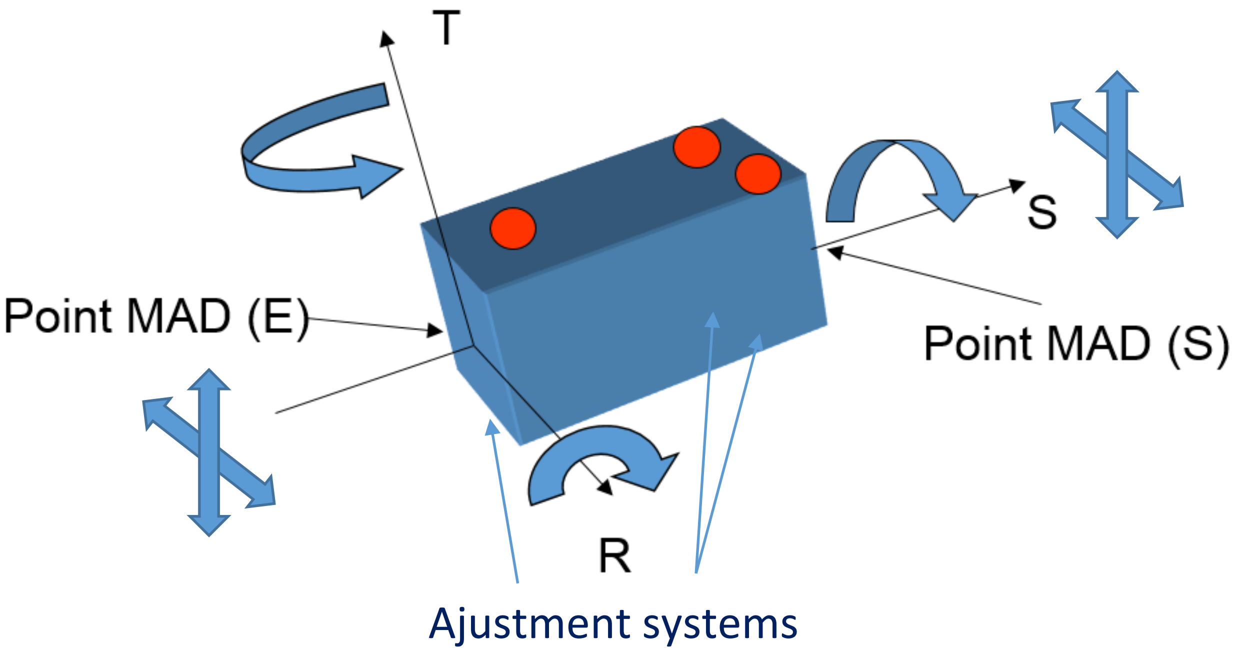
Instrumentation toolkit

- Determination of the position
    - Standard instruments
    - Specific alignment systems
- Adjustment

Adjustment systems

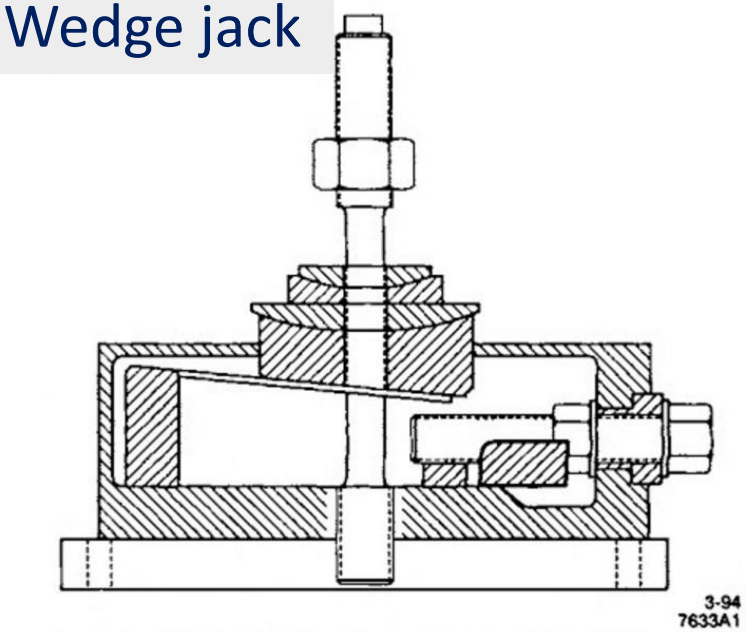
In order to set the components at their nominal position they must be equipped with appropriate adjustment systems allowing:

- To adjust the roll
- To adjust the vertical position
- To adjust the radial and longitudinal position



Standard means of adjustment

Wedge jack

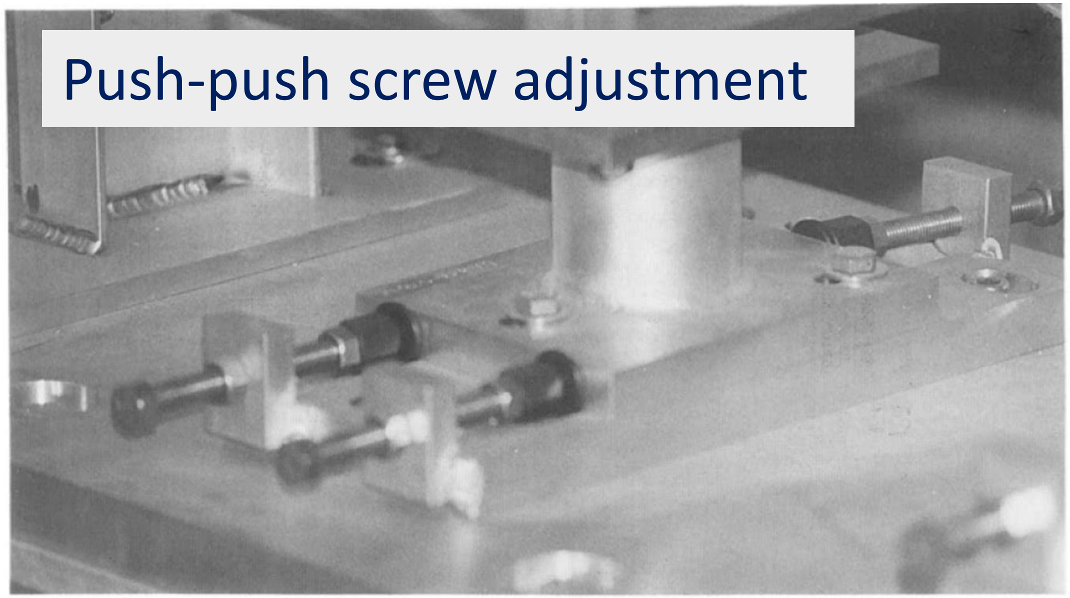


Wedge jack adjuster as used in APS.

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

[Ruland2]

Push-push screw adjustment

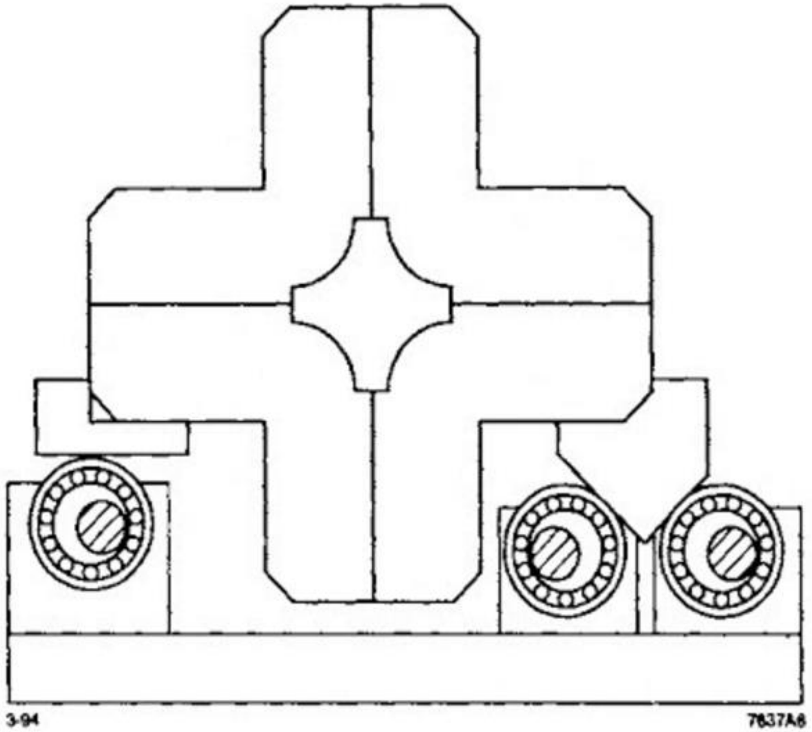


Push-push screw arrangement.

- 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.

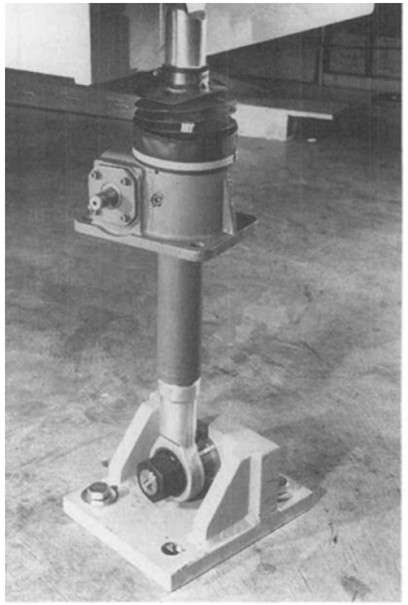
Standard means of adjustment

Roller cams

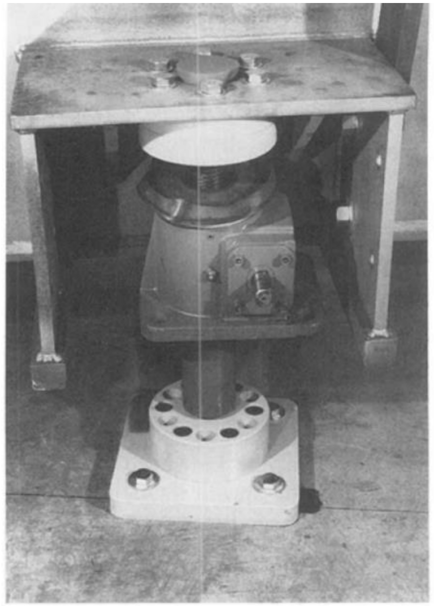


Magnet positioning mount with roller cams.

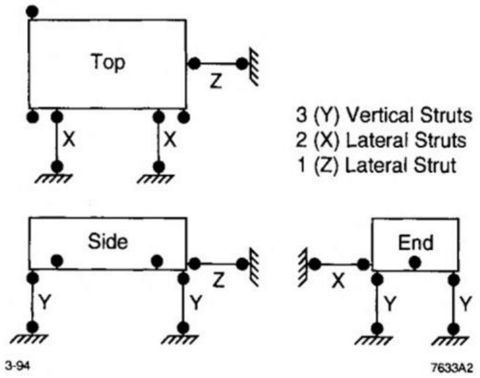
Struts



ALS 5-ton machine screw jack strut.



ALS 20-ton machine screw jack strut.



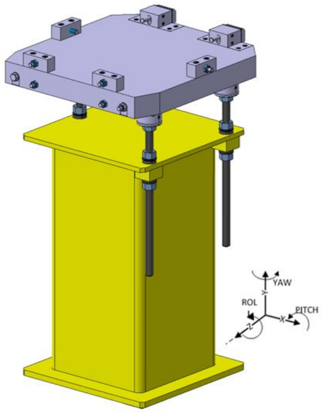
Kinematic suspension.

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

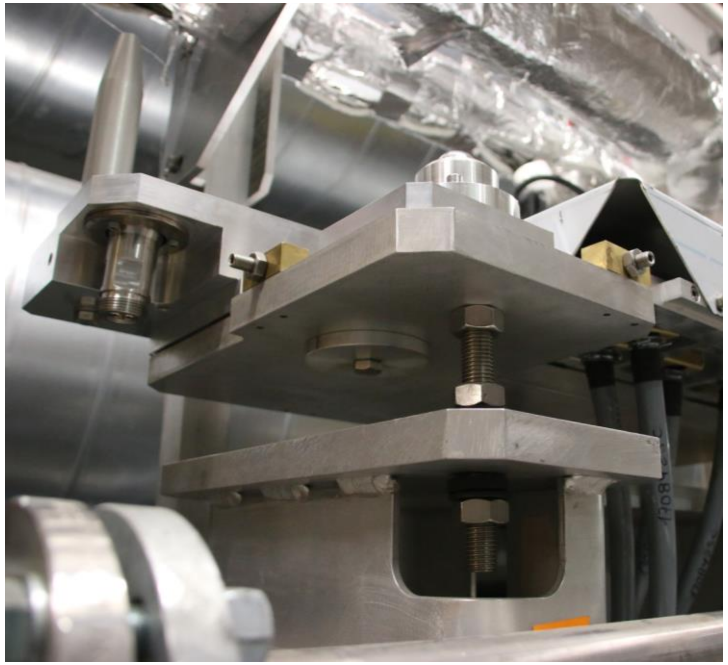
[Ruland2]

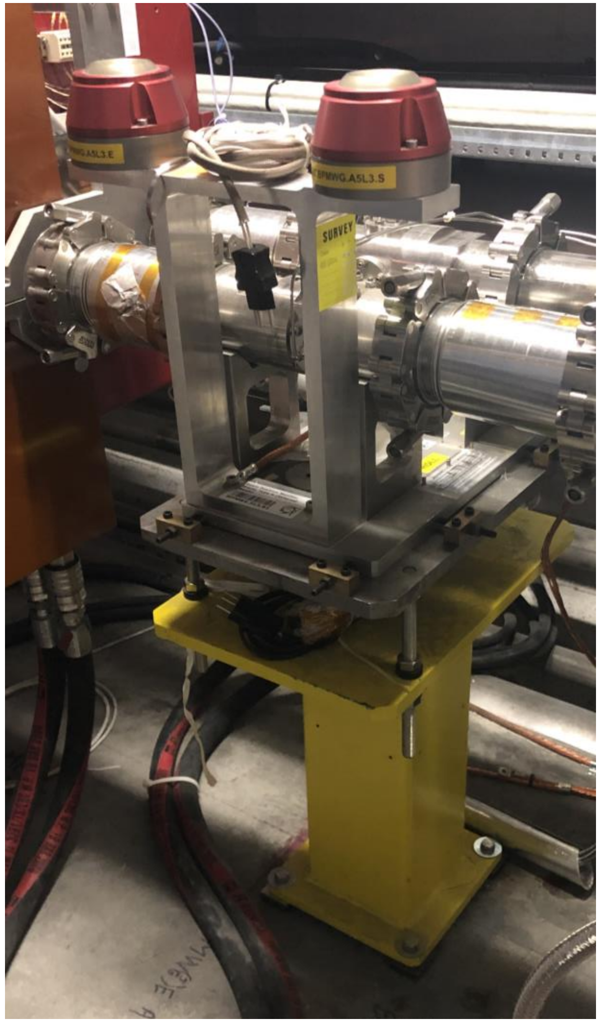
Adjustment systems

- 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



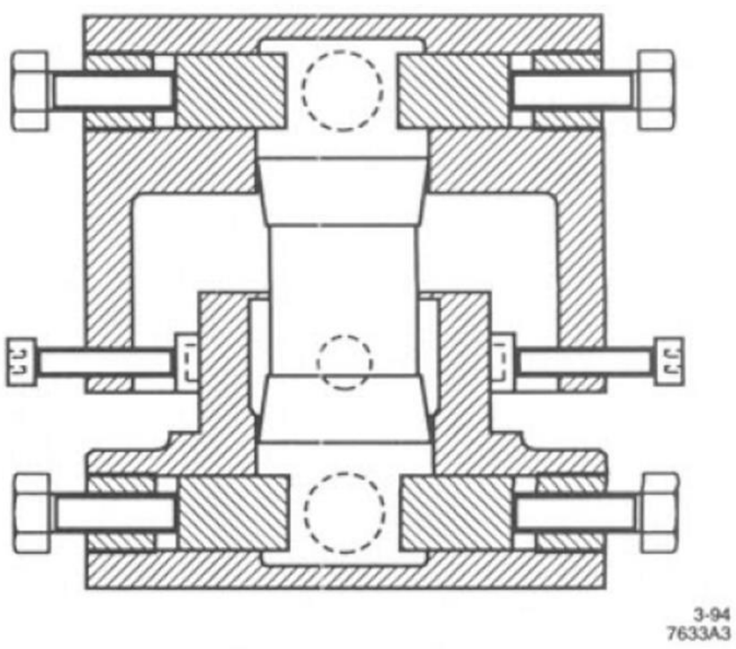
Alignment plate + support





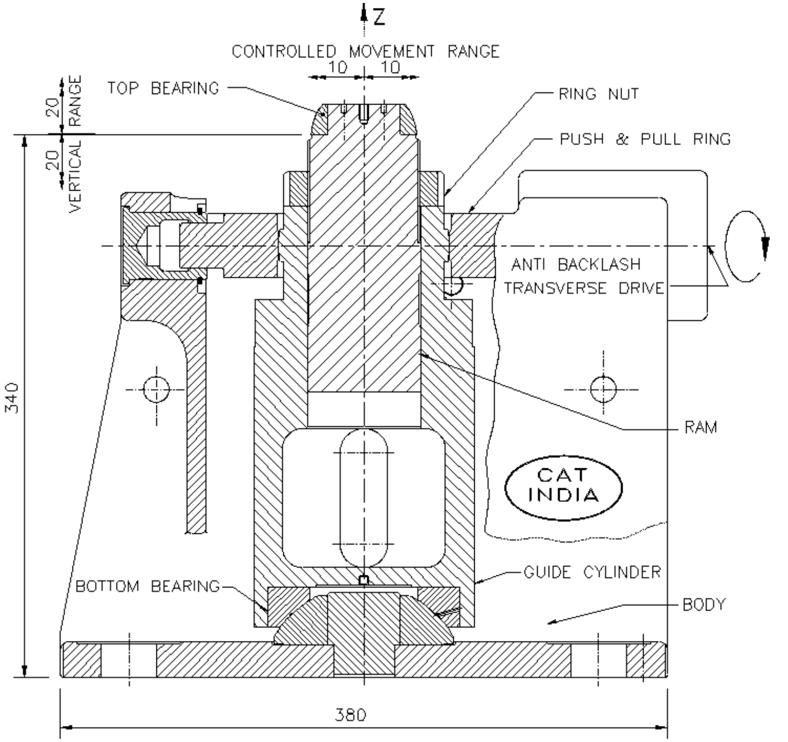
Standard means of adjustment

Polyurethane jack

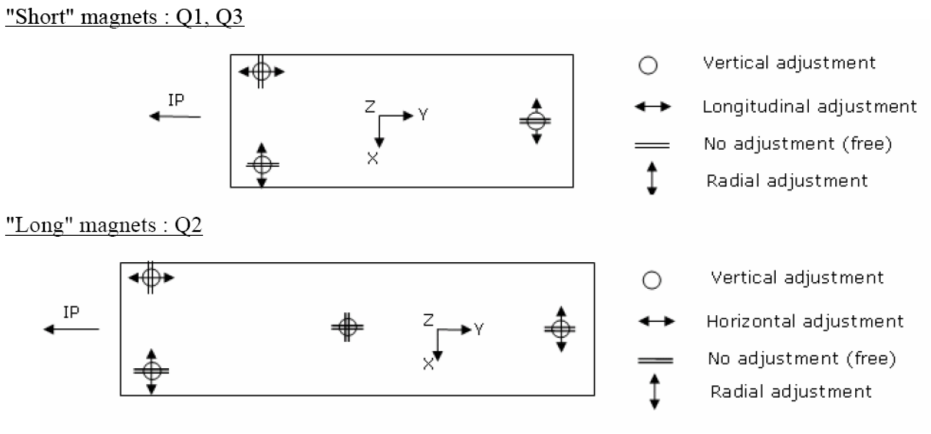


Polurethane pastille

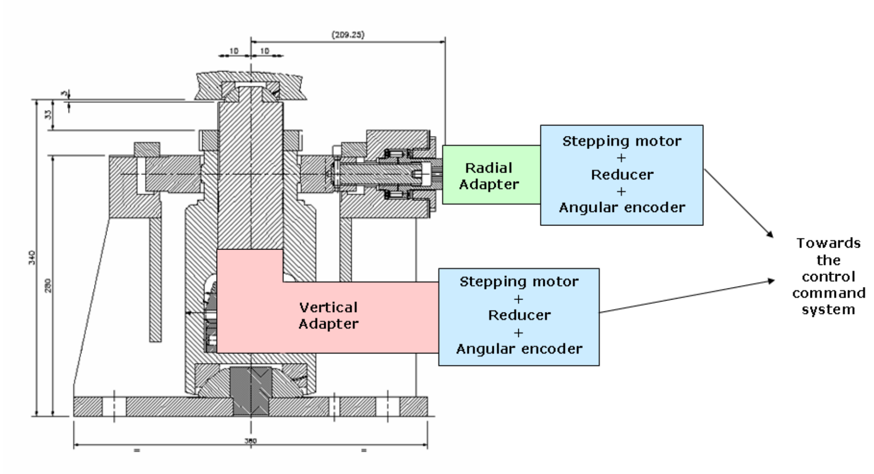
«Indian» LHC jack



Jacks and LHC motorized jacks

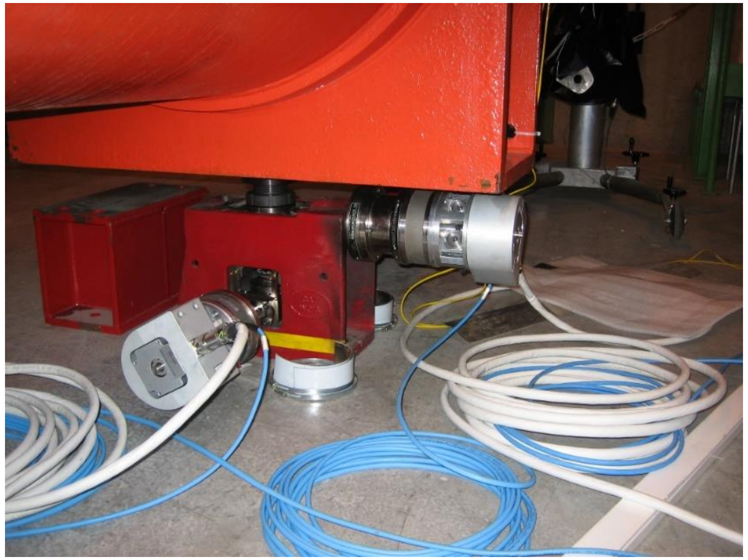


Jack configuration in the LHC



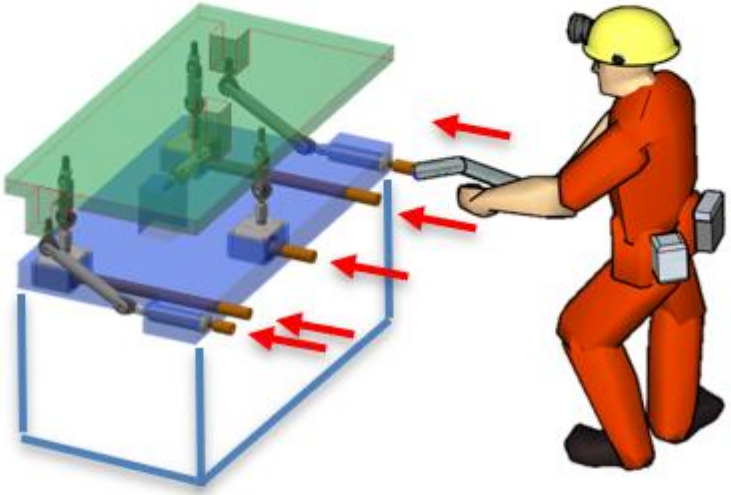
Motorization concept of the LHC jack

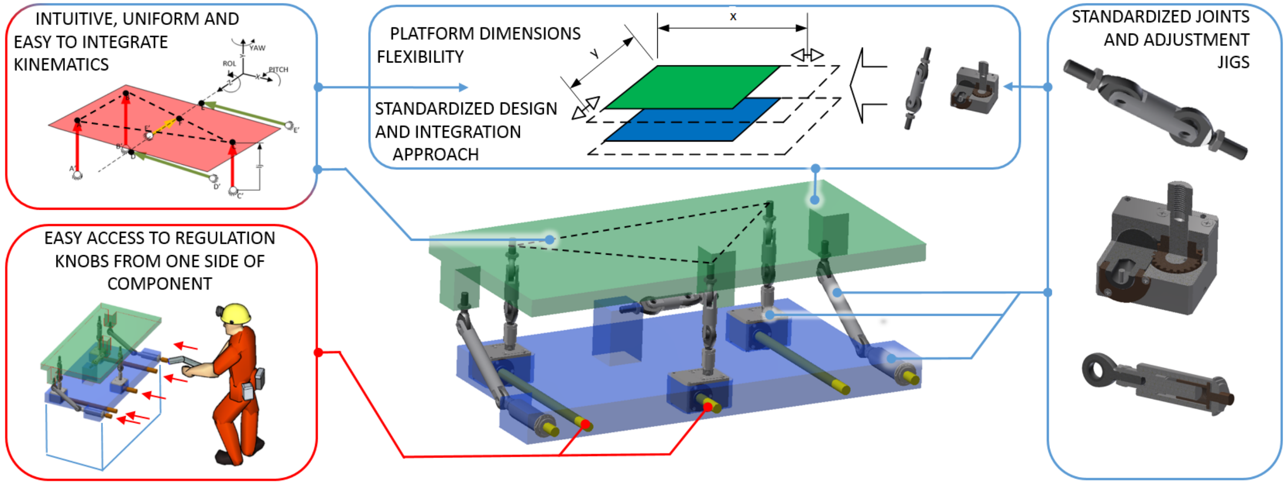
Non-motorized jack



LHC motorized jack

Universal Alignment Platform





INTUITIVE, UNIFORM AND EASY TO INTEGRATE KINEMATICS

PLATFORM DIMENSIONS FLEXIBILITY

STANDARDIZED DESIGN AND INTEGRATION APPROACH

STANDARDIZED JOINTS AND ADJUSTMENT JIGS

EASY ACCESS TO REGULATION KNOBS FROM ONE SIDE OF COMPONENT

PERSONNEL SAFETY
(LIMITED INTERVENTION TIME IN RADIOACIVE ZONES)

STANDARIZATION AND COST OPTIMIZATION

Study case

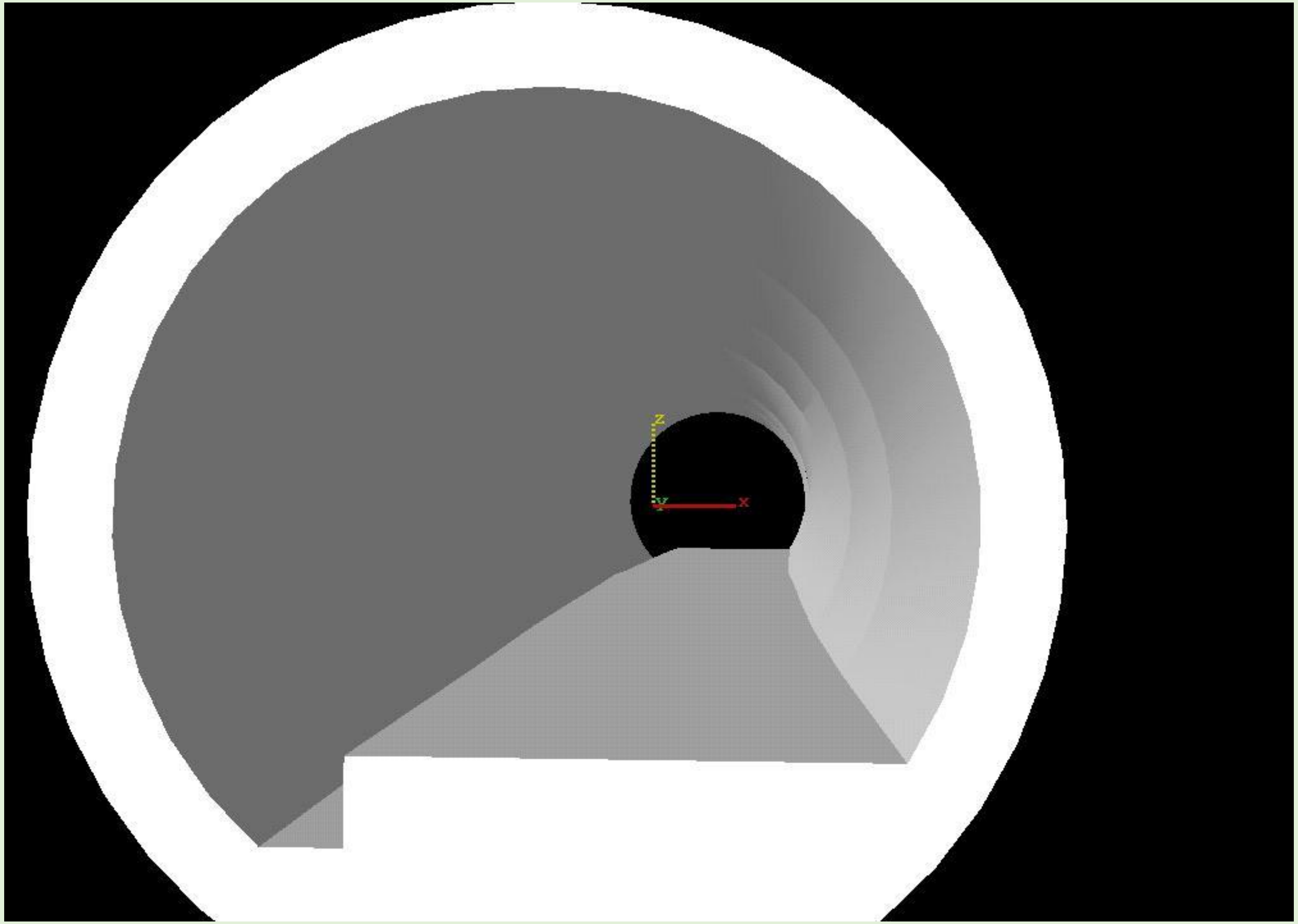
What would you suggest as an alignment strategy for :

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

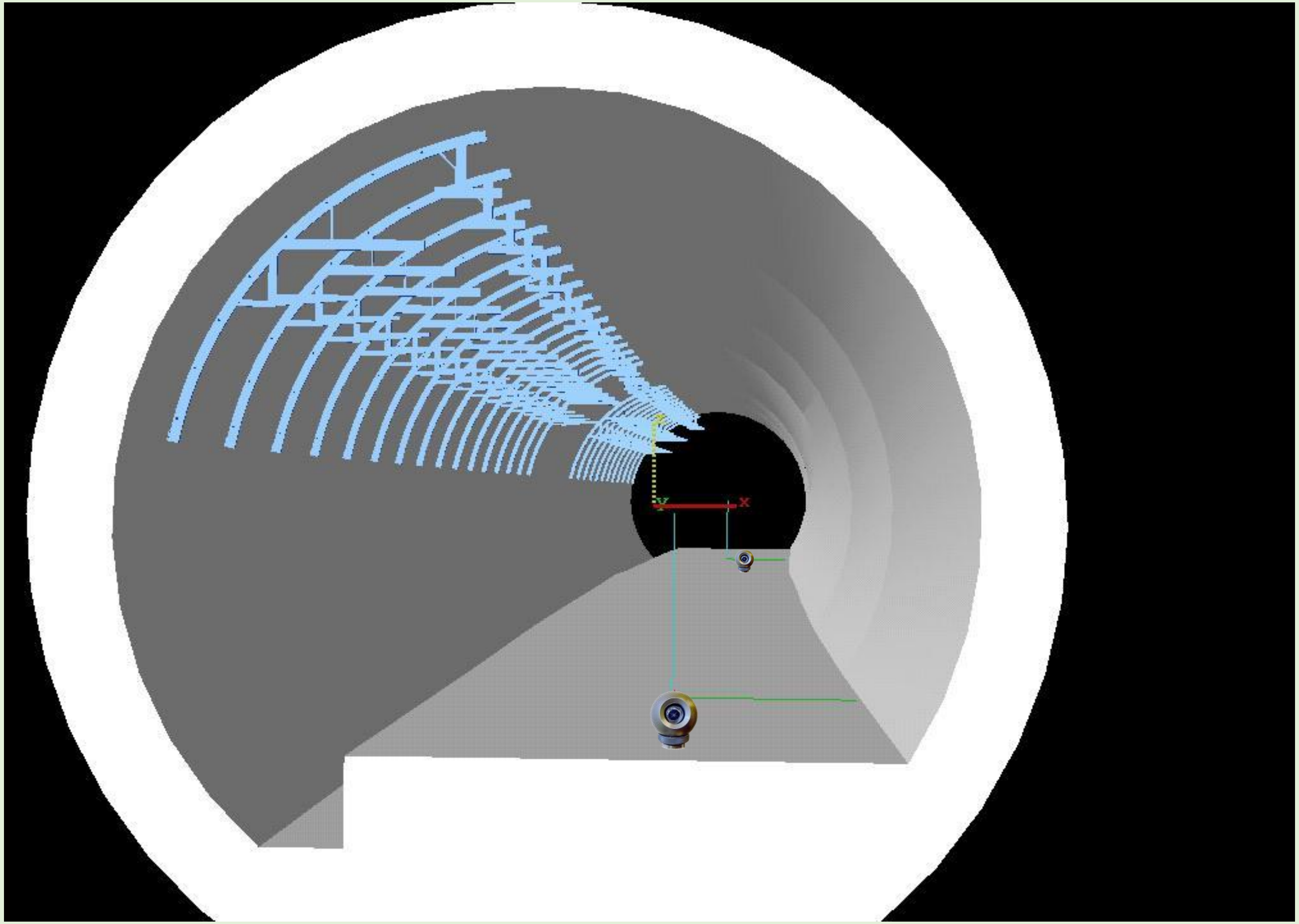
- Case 2:
    - A linac of 100 m,
    - 80 different components (quadrupoles, sextupoles, RF cavities),
    - Tolerance of alignment (1σ) of their reference axis: 0.2 mm

Let's summarize with the example of the LHC

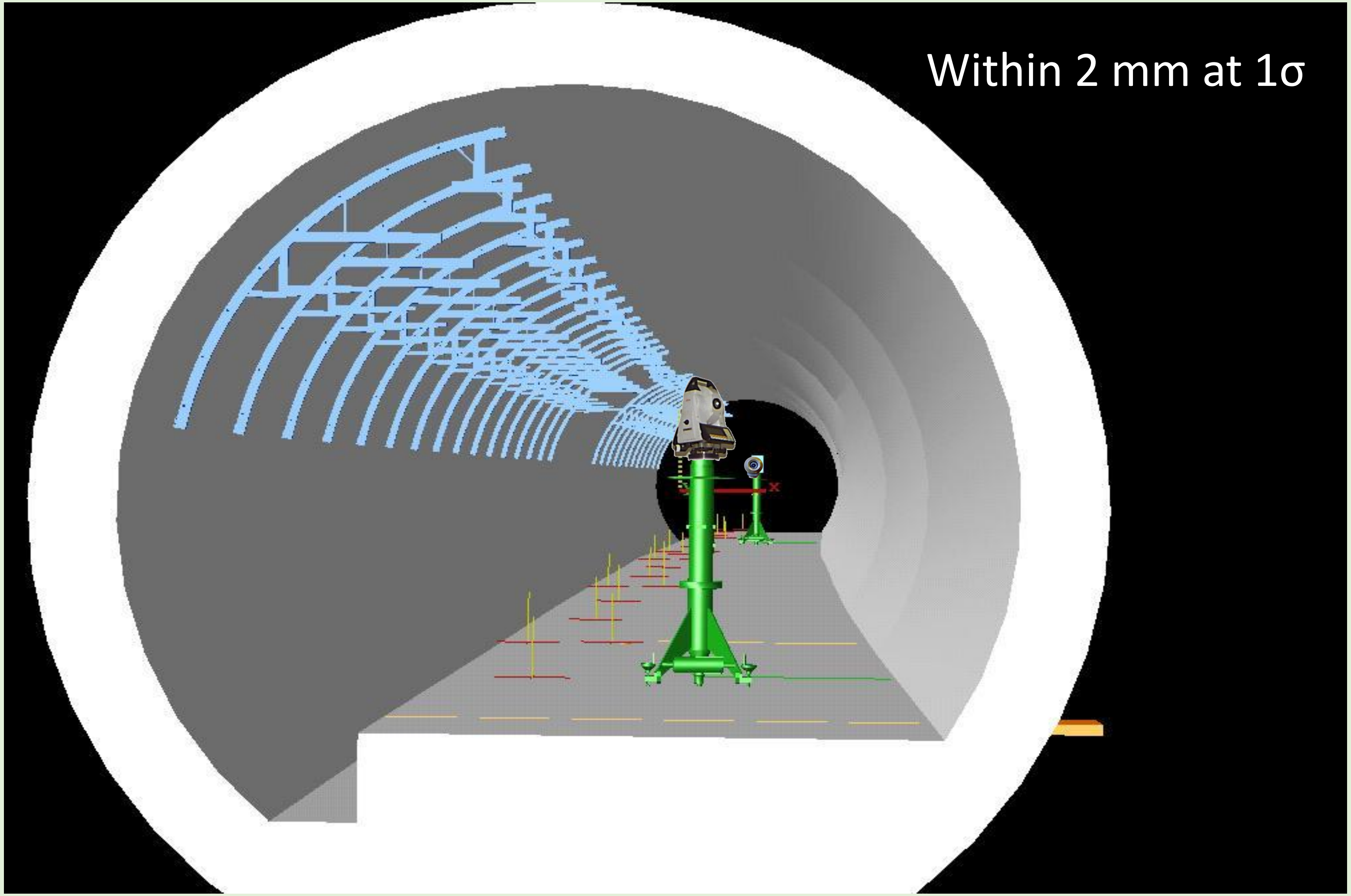
Tunnel empty



Determination of underground geodetic network

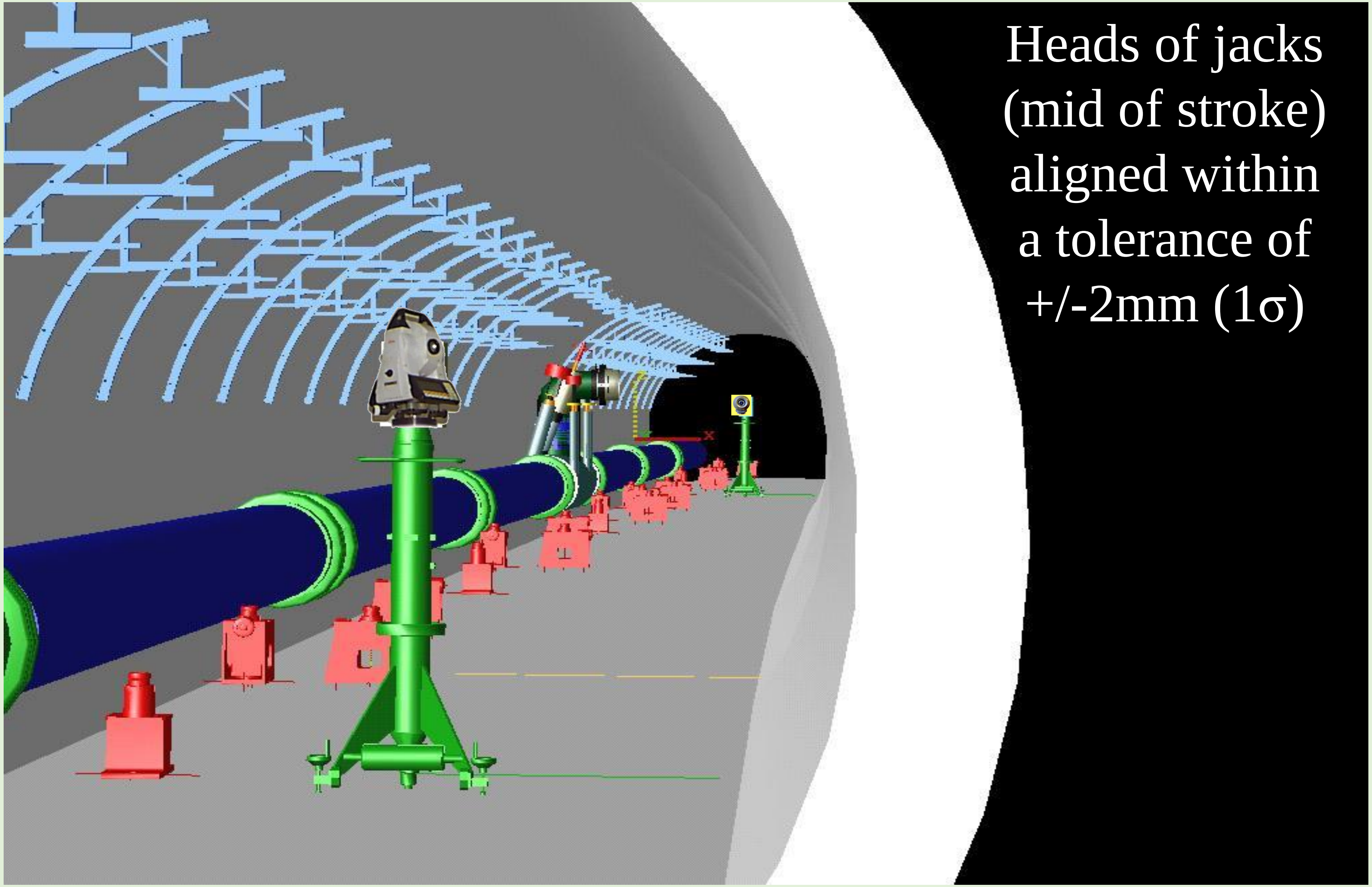


Marking on the floor



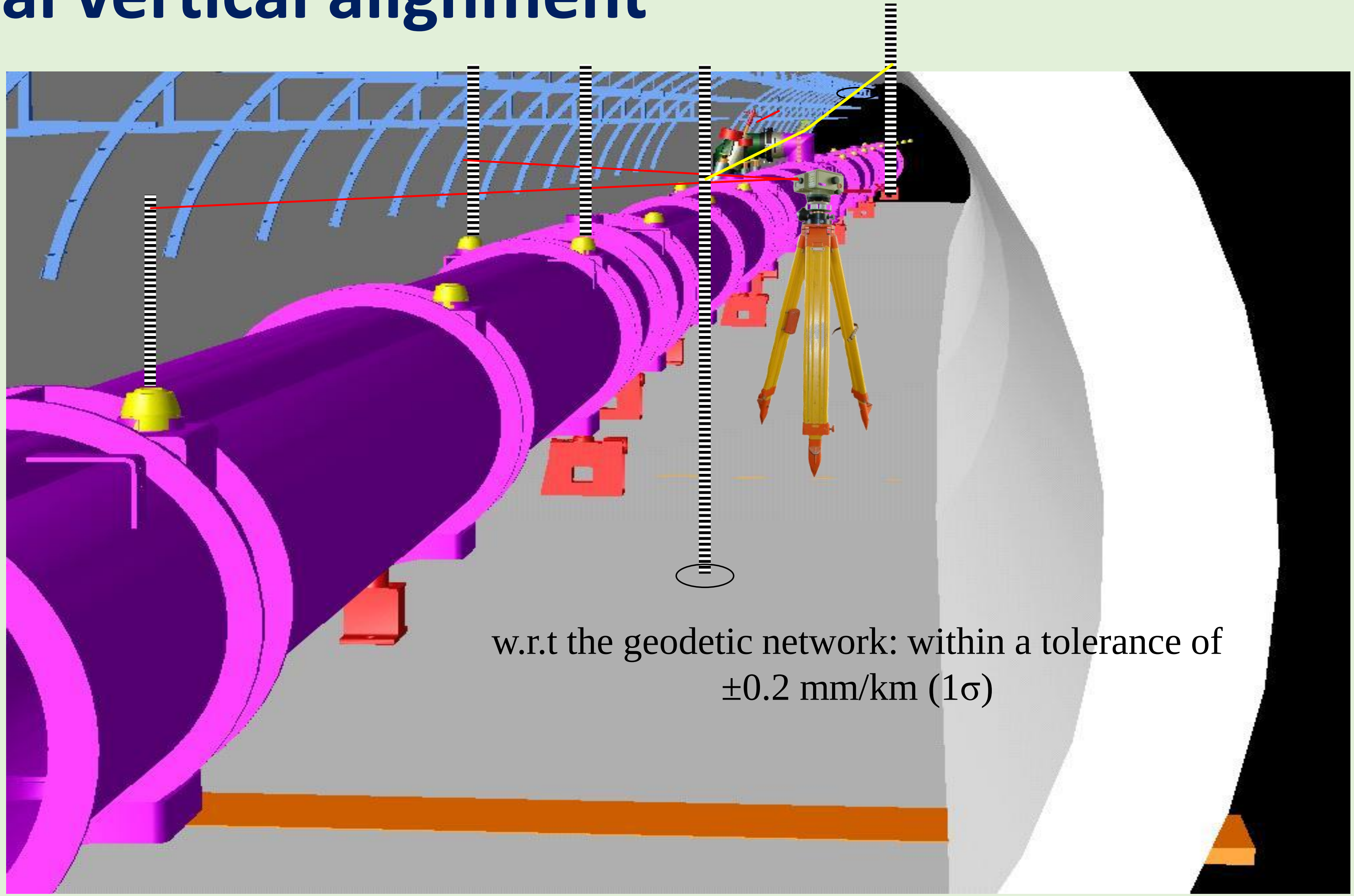
Within 2 mm at 1σ

Positioning of jacks



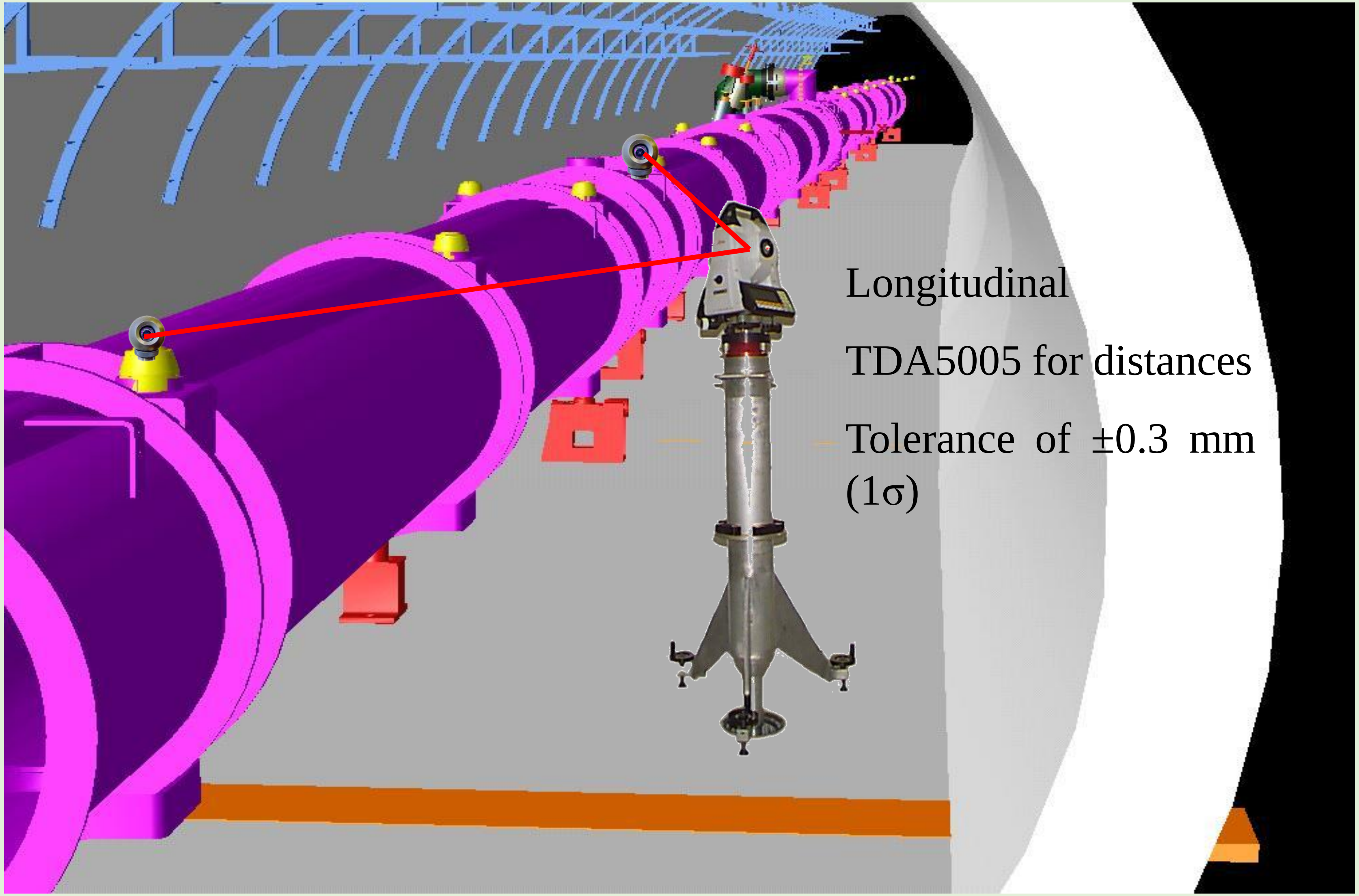
Heads of jacks (mid of stroke) aligned within a tolerance of +/-2mm (1σ)

Initial vertical alignment



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

Initial longitudinal alignment

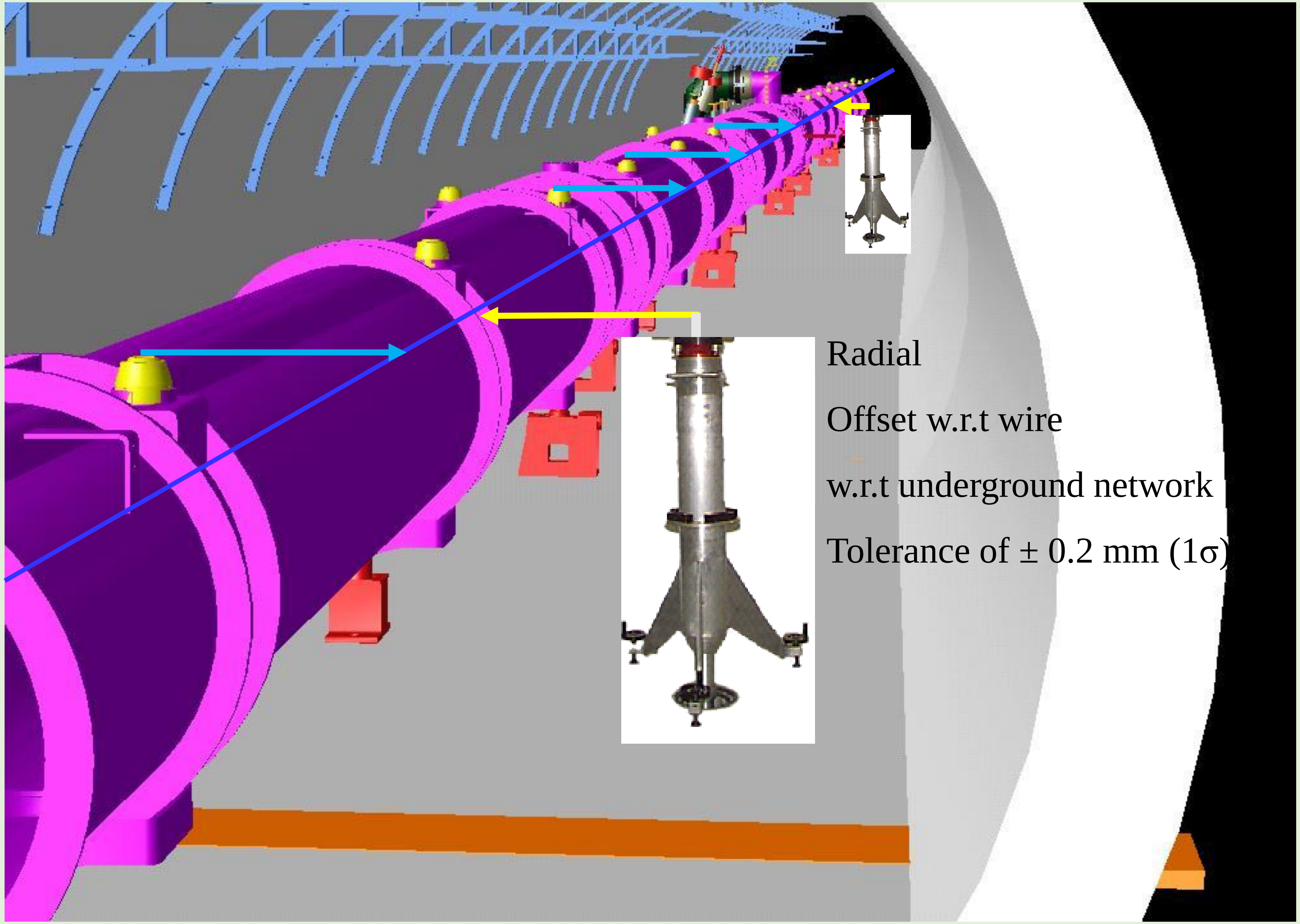


Longitudinal

TDA5005 for distances

Tolerance of ±0.3 mm (1σ)

Initial radial alignment



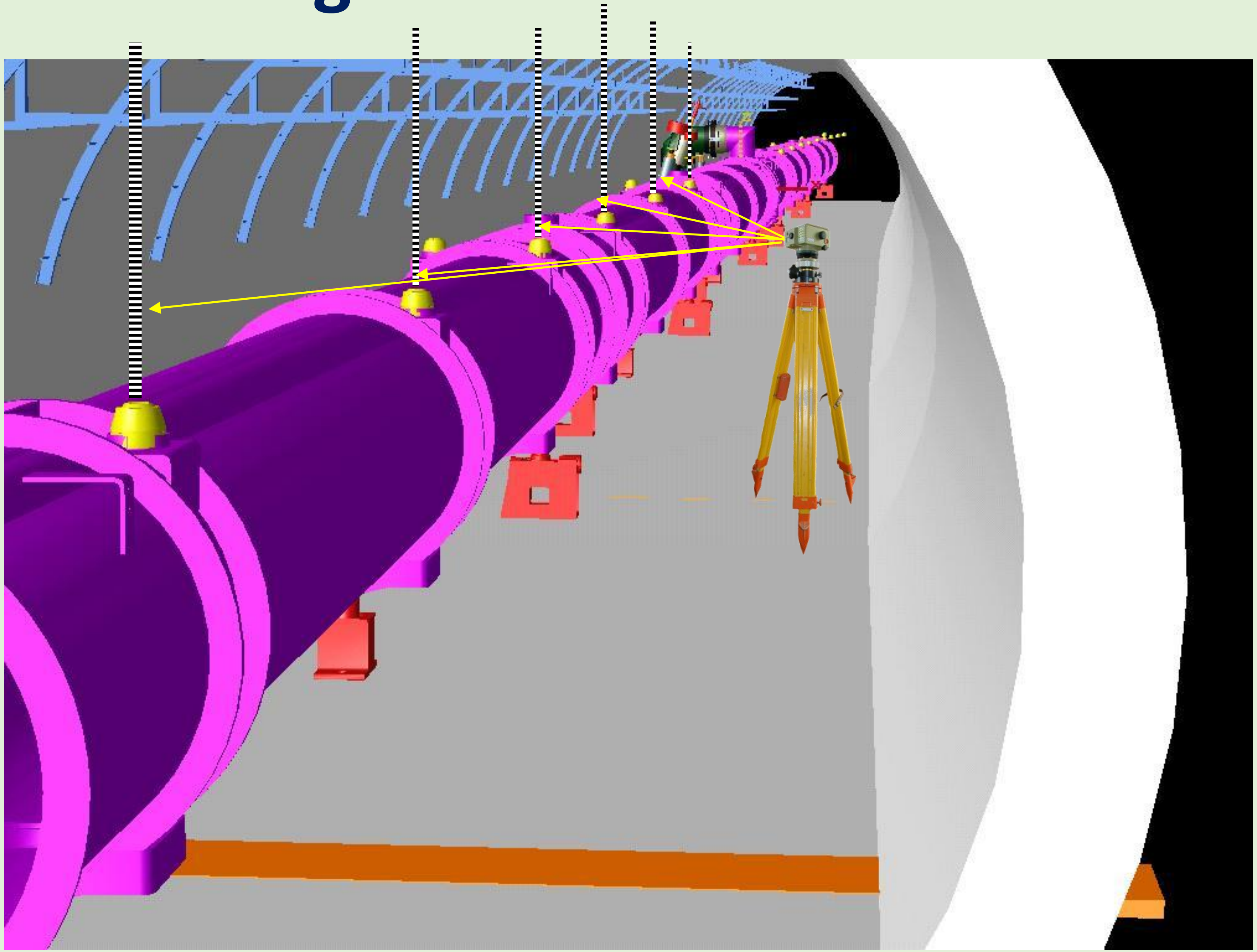
Radial

Offset w.r.t wire

w.r.t underground network

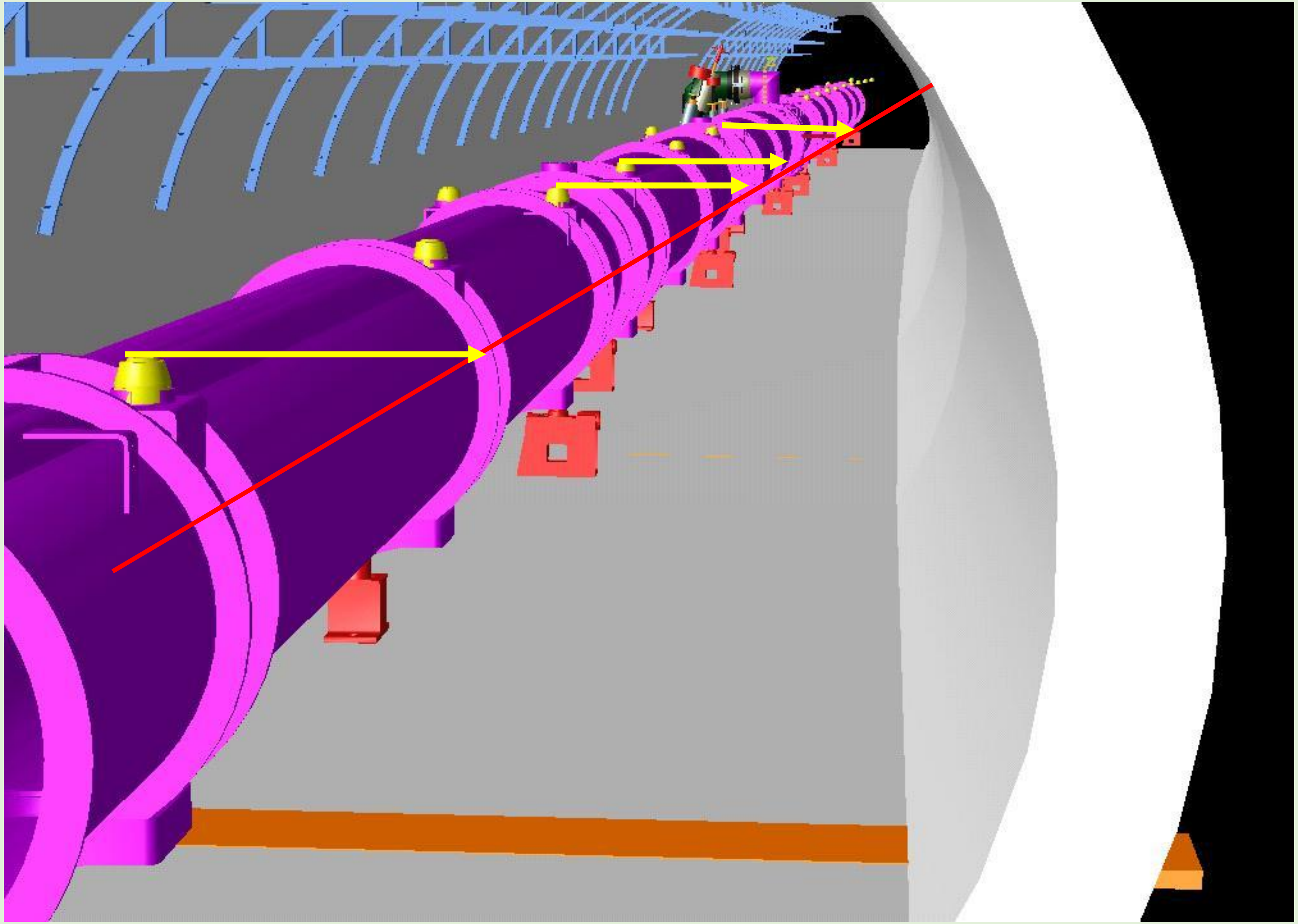
Tolerance of ± 0.2 mm (1σ)

Vertical smoothing

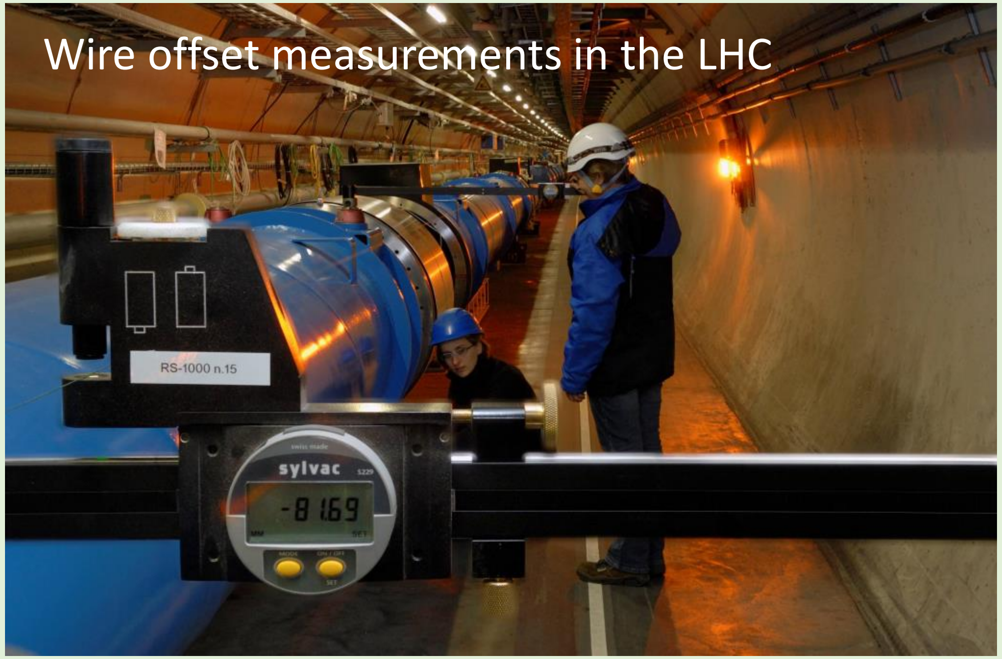


D. Missiaen

Radial smoothing



Wire offset measurements in the LHC

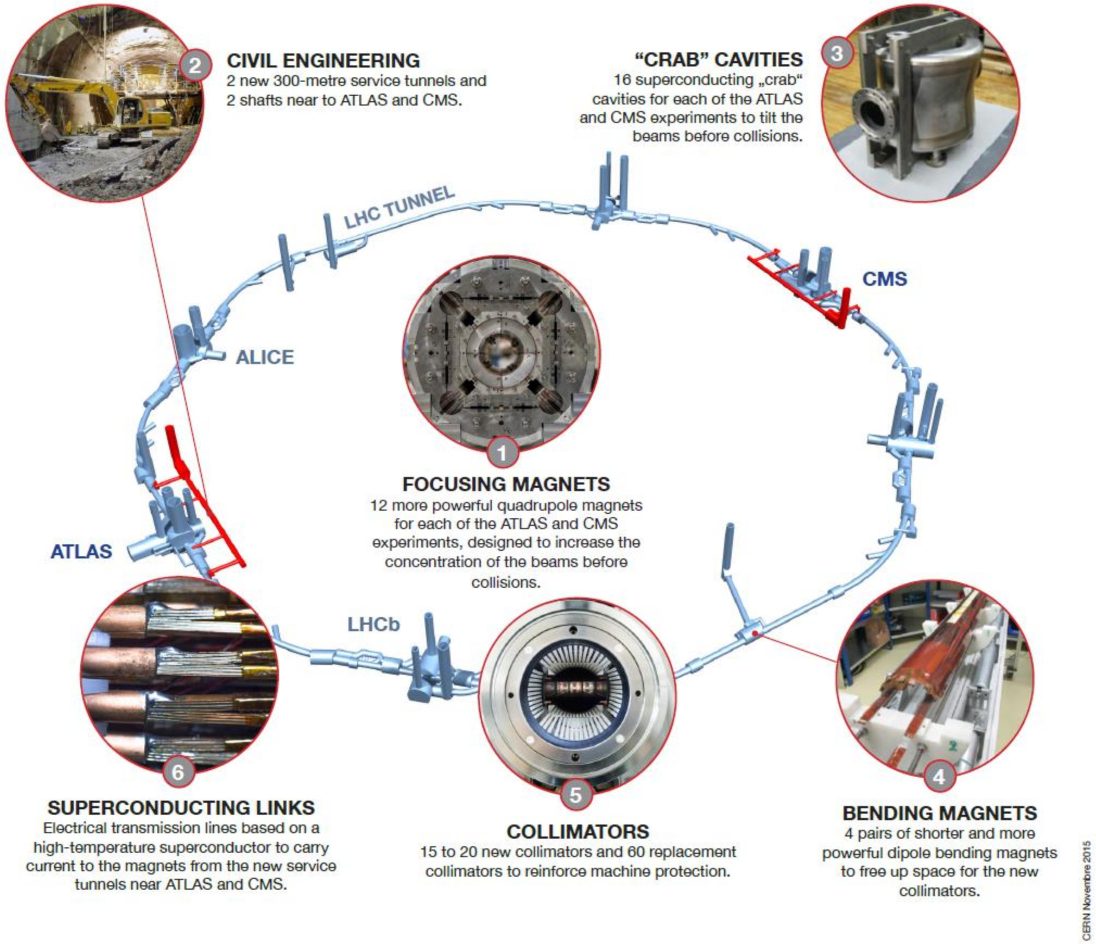



Wire protection pipe

Current challenges on HL-LHC

- Internal monitoring of cold masses
- Full Remote Alignment

HL-LHC: introduction



CIVIL ENGINEERING
2 new 300-metre service tunnels and 2 shafts near to ATLAS and CMS.

"CRAB" CAVITIES
16 superconducting „crab“ cavities for each of the ATLAS and CMS experiments to tilt the beams before collisions.

FOCUSING MAGNETS
12 more powerful quadrupole magnets for each of the ATLAS and CMS experiments, designed to increase the concentration of the beams before collisions.

SUPERCONDUCTING LINKS
Electrical transmission lines based on a high-temperature superconductor to carry current to the magnets from the new service tunnels near ATLAS and CMS.

COLLIMATORS
15 to 20 new collimators and 60 replacement collimators to reinforce machine protection.

BENDING MAGNETS
4 pairs of shorter and more powerful dipole bending magnets to free up space for the new collimators.

CERN Novembre 2015

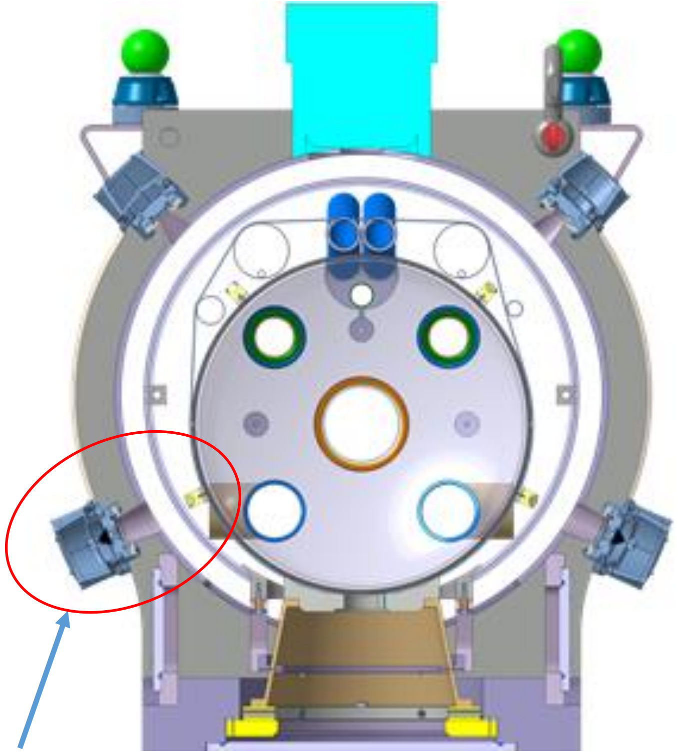
- ✓ **New IR-quads Nb3Sn (inner triplets)**
- ✓ **New 11 T Nb3Sn (short) dipoles**
- ✓ **Collimation upgrade**
- ✓ **Cryogenics upgrade**
- ✓ **Crab Cavities**
- ✓ **Cold powering**
- ✓ **Machine protection**
- ✓ **…**

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



FSI based monitoring

HL-LHC quadrupole cross-section

HL-LHC: internal monitoring system

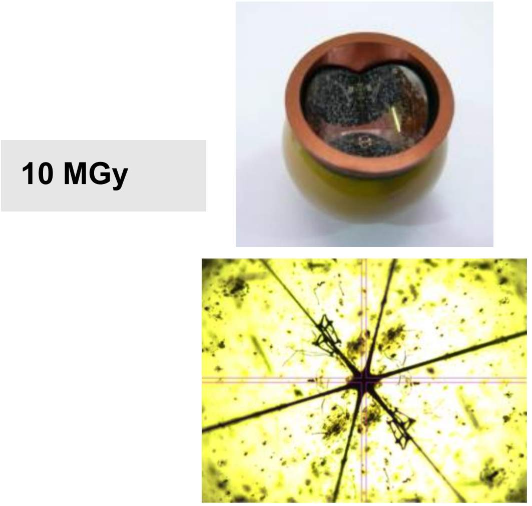
Validation on independent benches
Performance of one line FSI & study of an alternative
- Irradiation tests
- Thermal tests
- Precision, accuracy,…

→

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

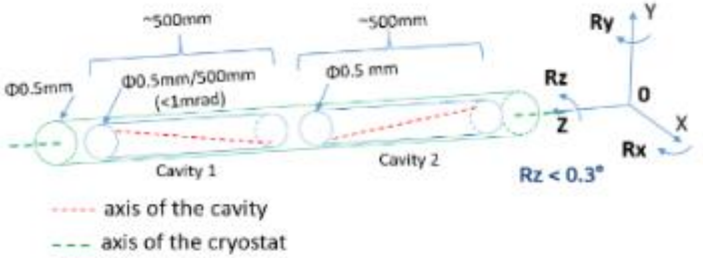
→

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

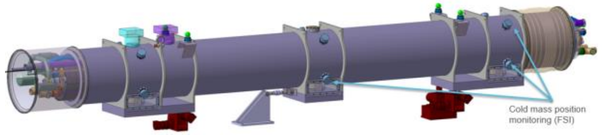


CCR after 10 MGy irradiation

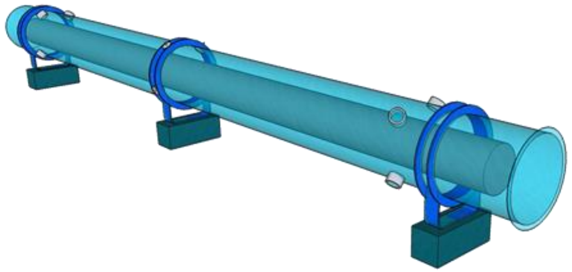
Crab cavity section



Crab cavities alignment requirements

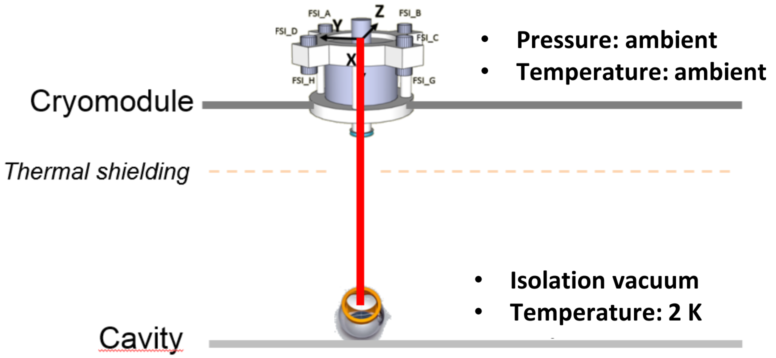


HL-LHC inner triplet



[Mainaud Durand2]

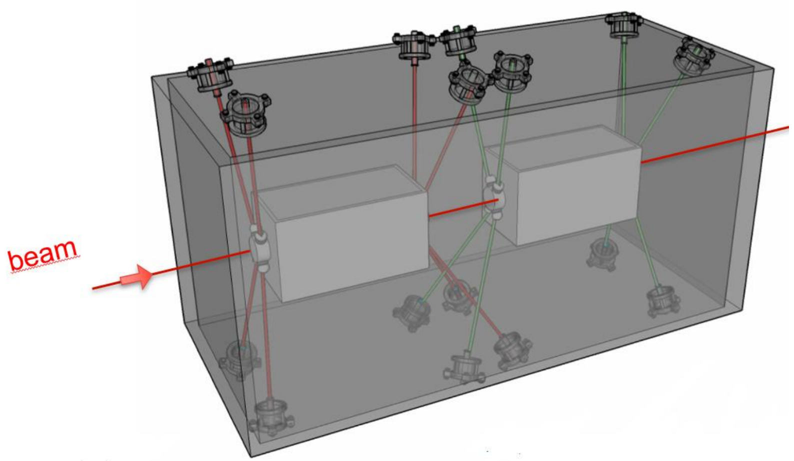
HL-LHC: internal monitoring system



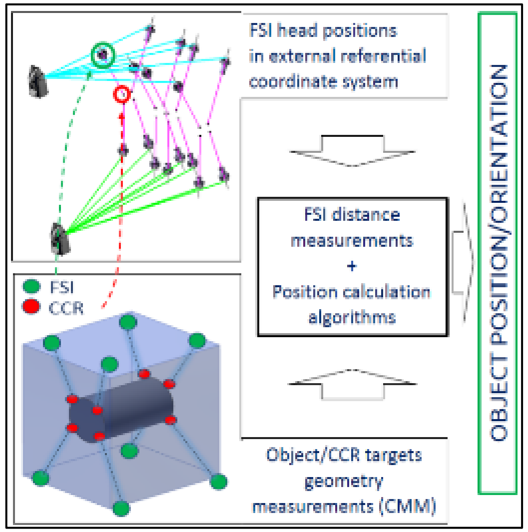
- **Pressure: ambient**
- **Temperature: ambient**

- **Isolation vacuum**
- **Temperature: 2 K**

FSI measurement concept



FSI measurement configuration in crab cavity cryostat



FSI head positions in external referential coordinate system

FSI distance measurements + Position calculation algorithms

Object/CCR targets geometry measurements (CMM)

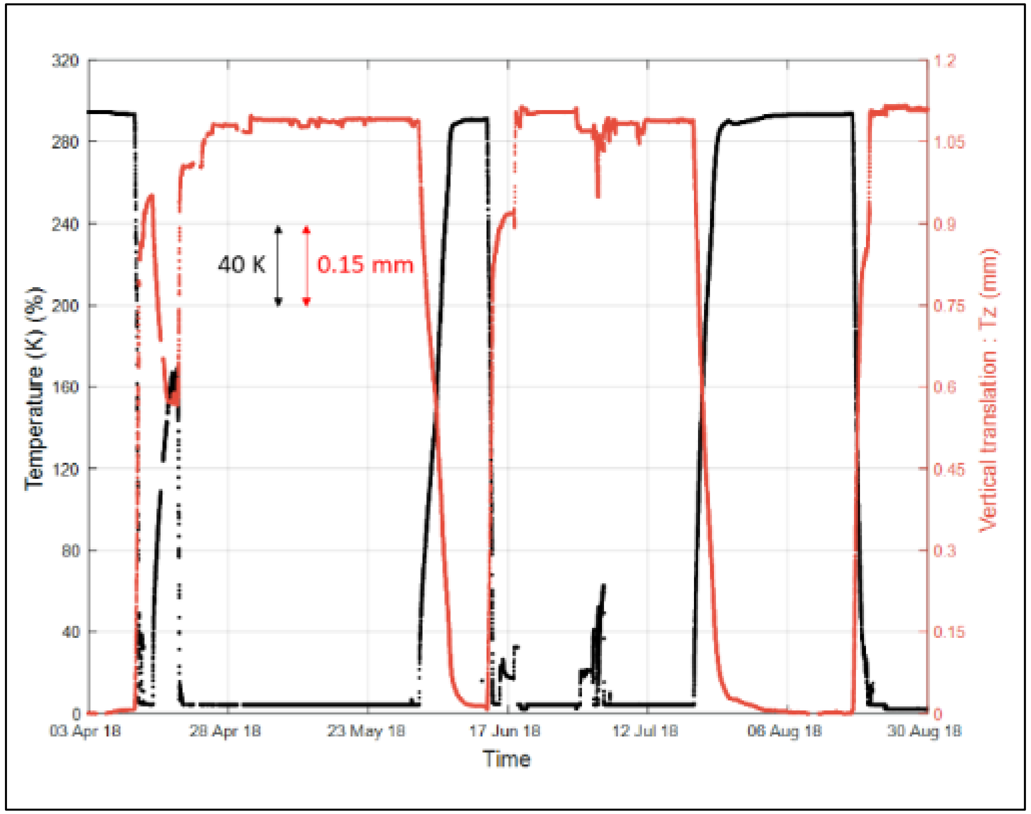
Feedthrough

CCR

[Rude]

HL-LHC: internal monitoring system

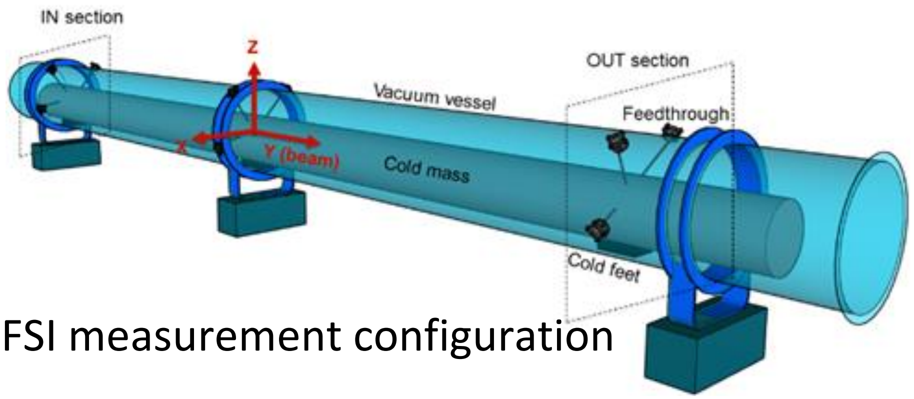
Crab cavity prototype installed in SPS



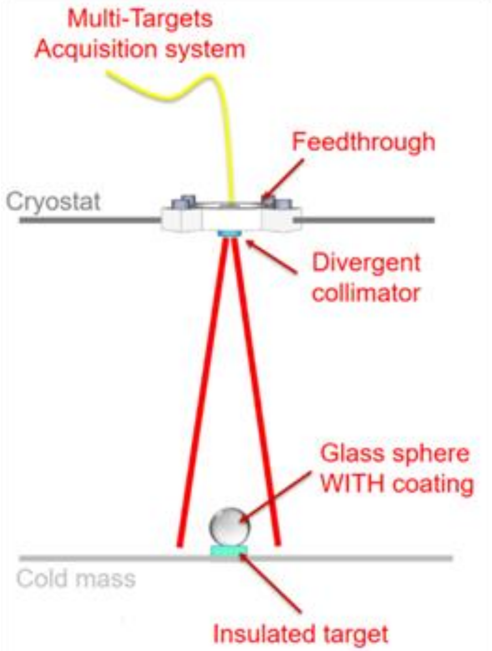
FSI measurements in the SPS prototype

- 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



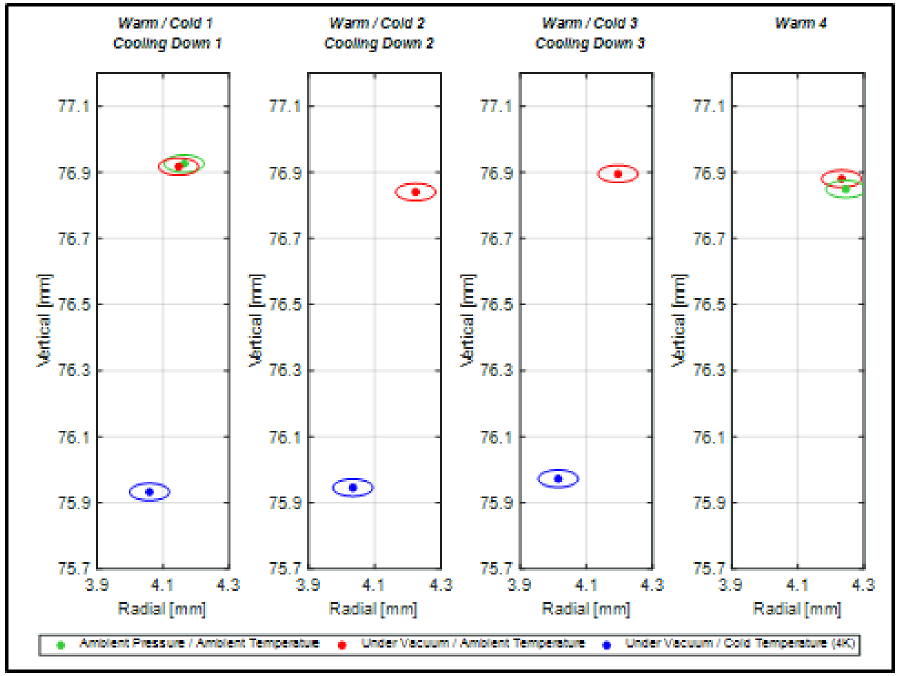
FSI measurement configuration



FSI measurement concept

Simplified feedthrough

Target support

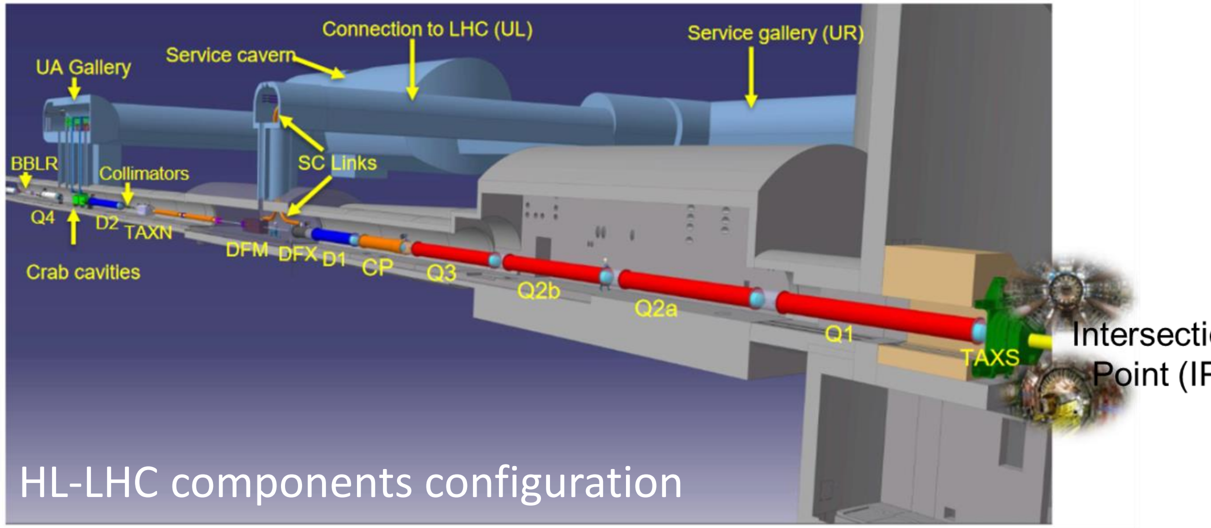


Coordinates after 3 thermal cycles

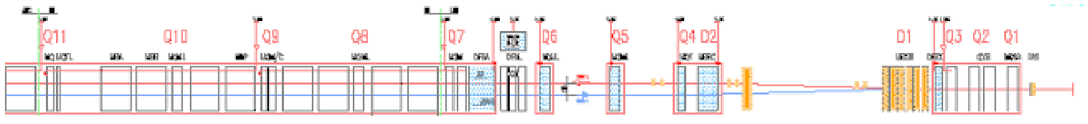
Accuracy of section determination

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

HL-LHC: Full Remote Alignment System (FRAS)



HL-LHC components configuration

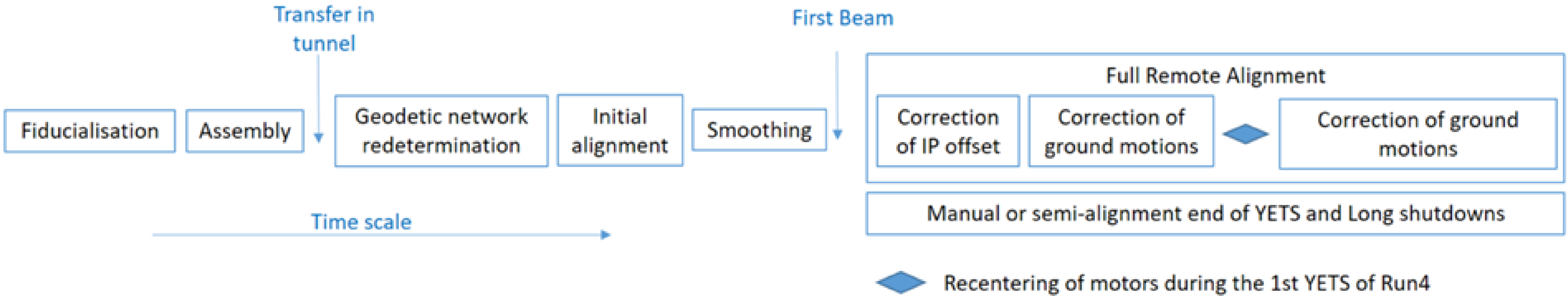


The Full Remote Alignment System (FRAS) will allow aligning rigidly (as a block, simultaneously) and remotely from the CERN Control Centre, all the components from Q1 to Q5 on both sides of the IP within a range of ± 2.5 mm.

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.

HL-LHC: Full Remote Alignment System



Transfer in tunnel

First Beam

Fiducialisation

Assembly

Geodetic network redetermination

Initial alignment

Smoothing

Full Remote Alignment

Correction of IP offset

Correction of ground motions

◆

Correction of ground motions

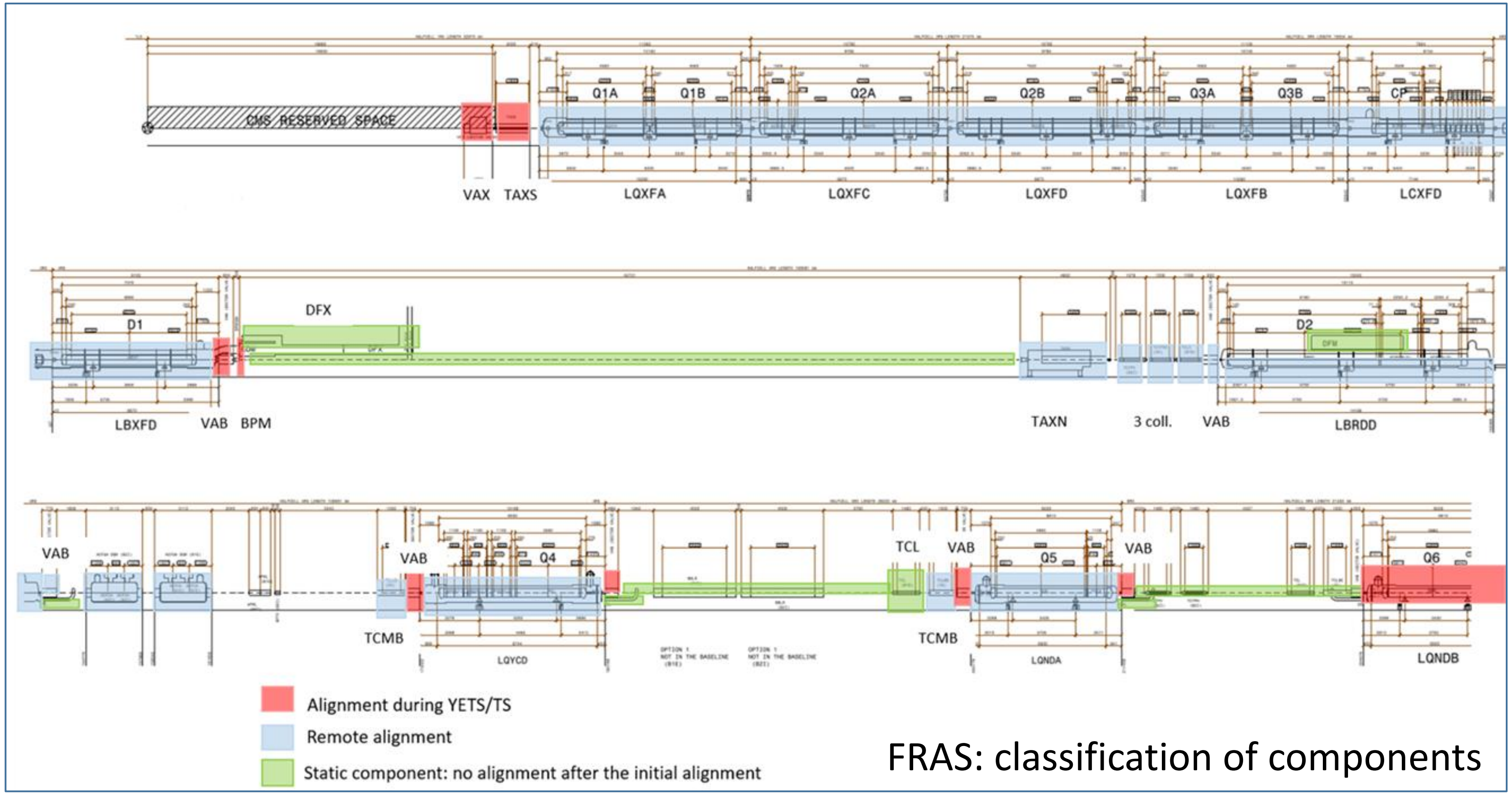
Manual or semi-alignment end of YETS and Long shutdowns

Time scale

◆ Recentering of motors during the 1st YETS of Run4

- 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 re-centered 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



FRAS: classification of components

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

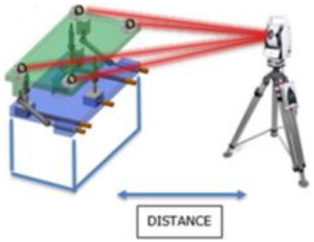
HL-LHC: Full Remote Alignment System

Solution proposed for the position determination

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

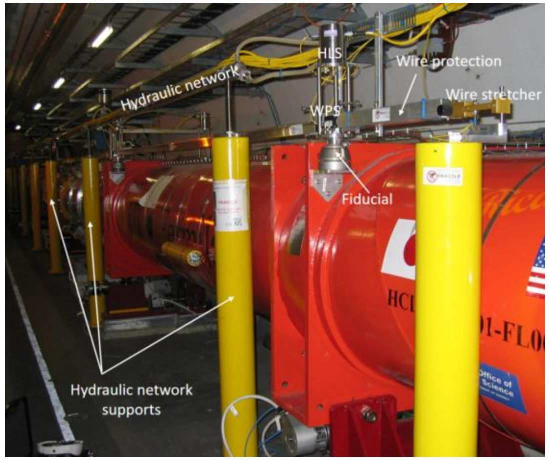
Laser tracker

Glass sphere



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

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

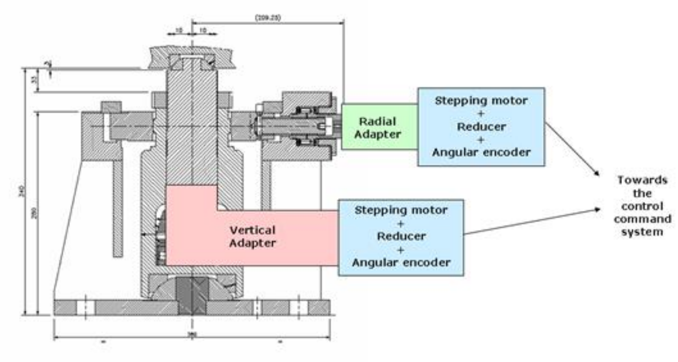


- ✓ Continuous and remote measurements
- ✓ From the CCC

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

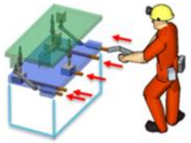


Fig. 8a. Manual adjustment: the operator turns adjustment knobs

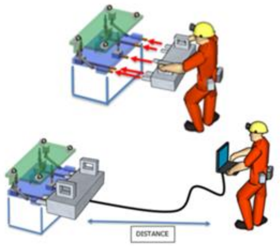


Fig. 8b. Semi/manual adjustment using temporary plug-in motors

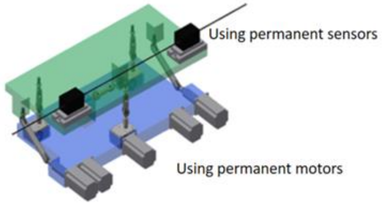
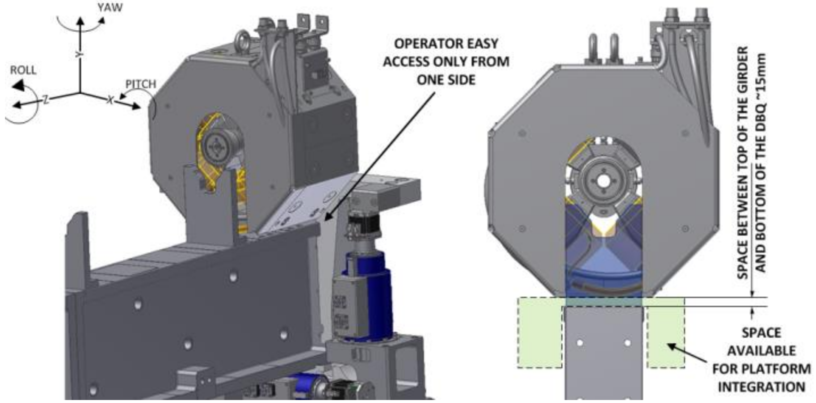


Fig. 8c. Remote alignment

Adjustment possibilities using a platform

Full Remote Alignment System

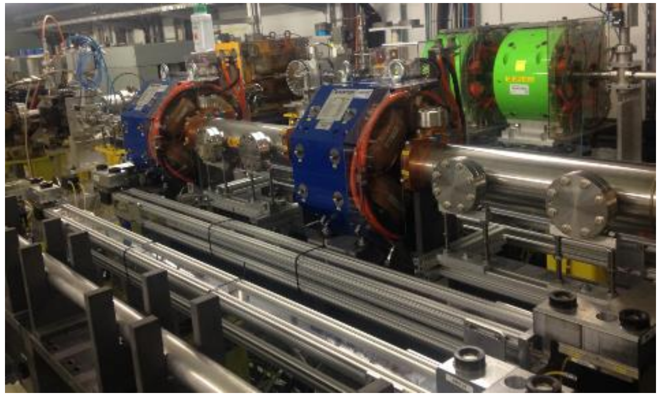
«Standardized» adjustment platform



CLIC adjustment: space constrain

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.



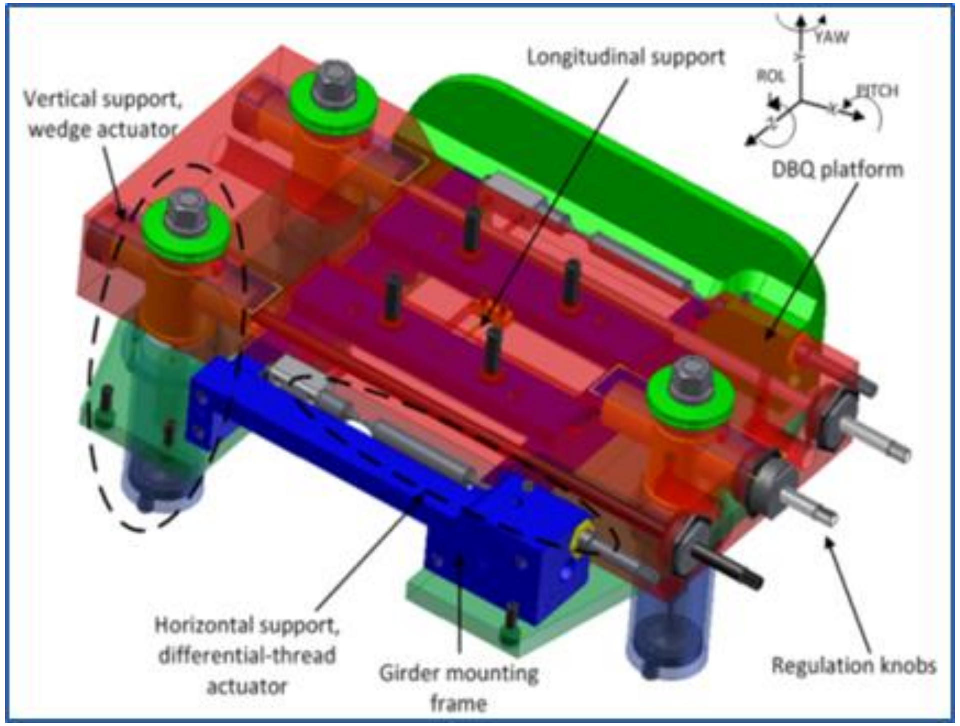
CLEAR components

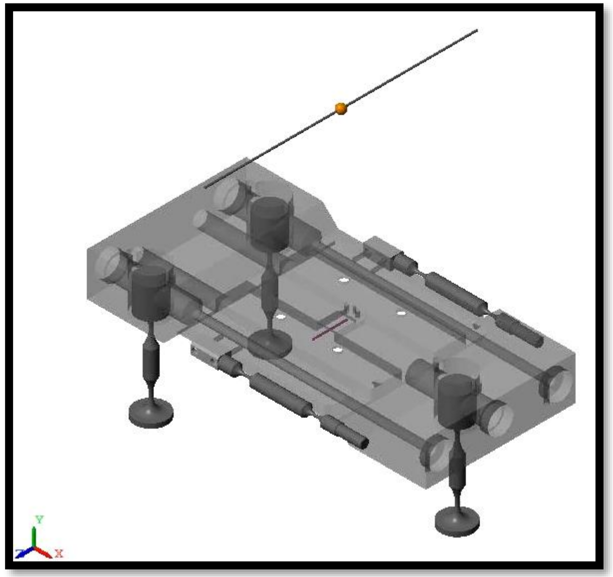
Requirements:

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

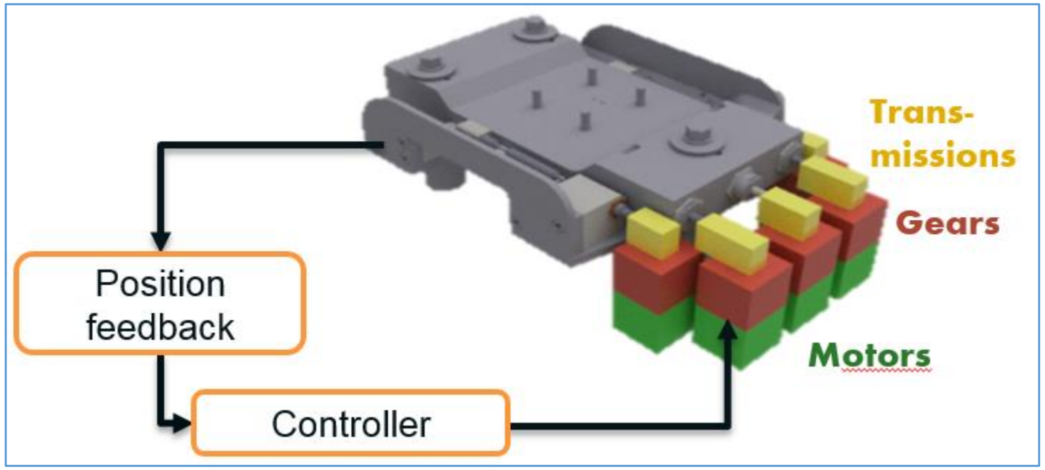
Full Remote Alignment System

«Standardized» adjustment platform





Kinematic of adjustment



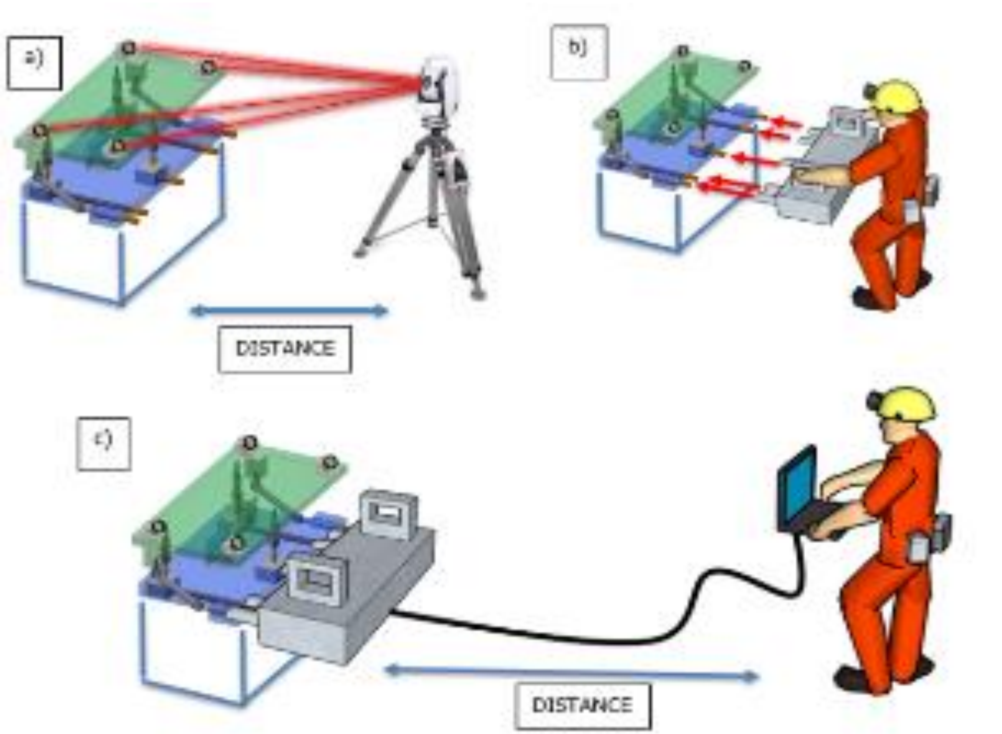
Control concept

Full Remote Alignment System

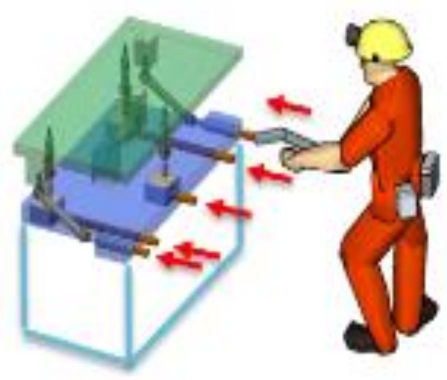
«Standardized» adjustment platform with plug-in motors

Full Remote Alignment System

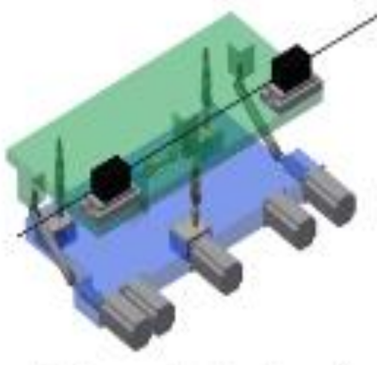
«Standardized» adjustment platform



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.



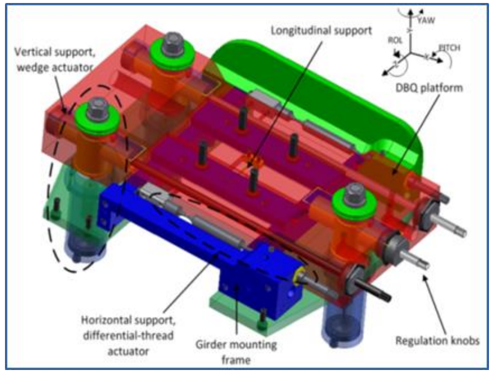
Universal adjustment platform – manual operation concept

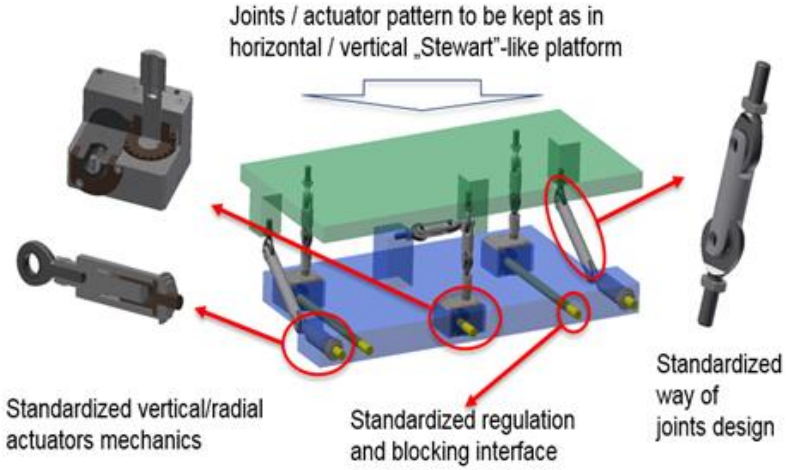


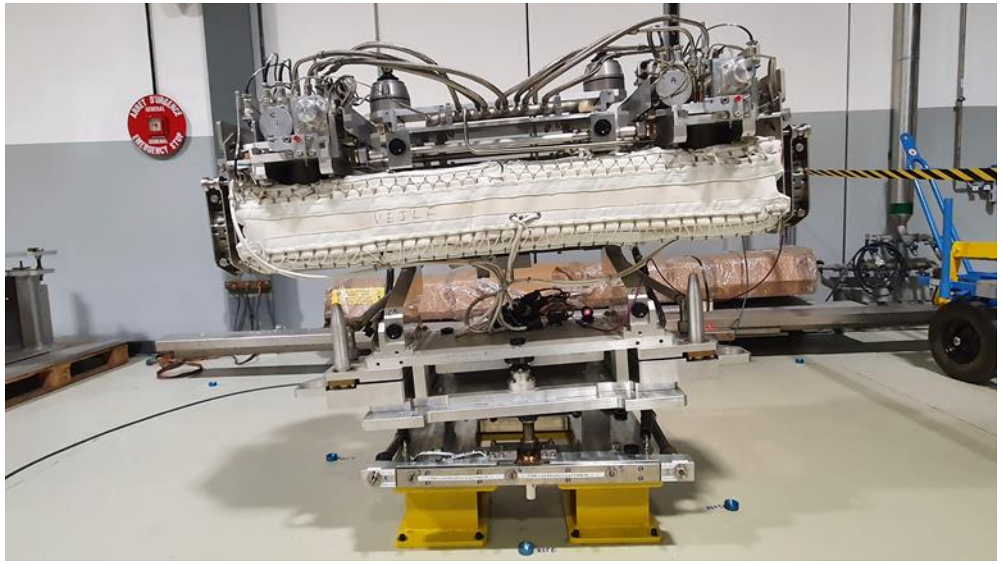
Universal adjustment solution - permanent motors version concept

Full Remote Alignment System

«Standardized» adjustment platform





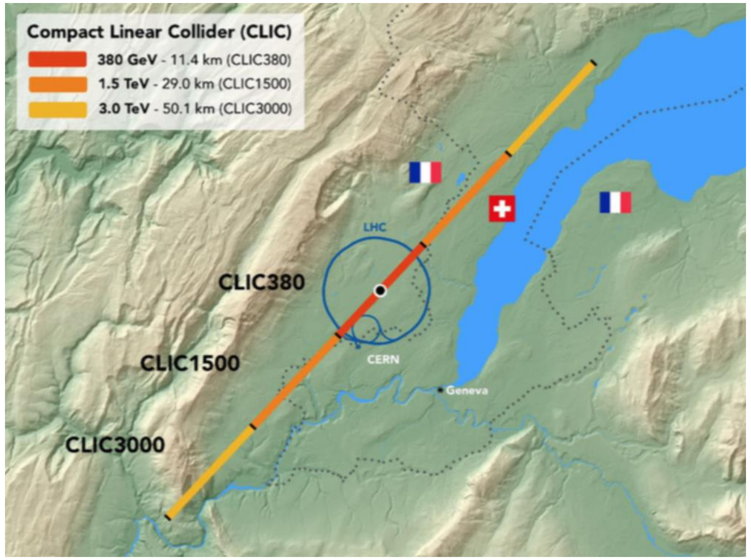


R&D in survey & alignment:

Case of CLIC project

CLIC: introduction

- CLIC= Compact LInear Collider



Footprint of the CLIC

CLIC: introduction

Beam off

Mechanical pre-alignment ~0.2 - 0.3 mm over 200 m

Active pre-alignment 14 - 17 µm over 200 m

Beam on

Beam based Alignment & Beam based feedbacks

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

→ **Minimization of the emittance growth**

CLIC: introduction

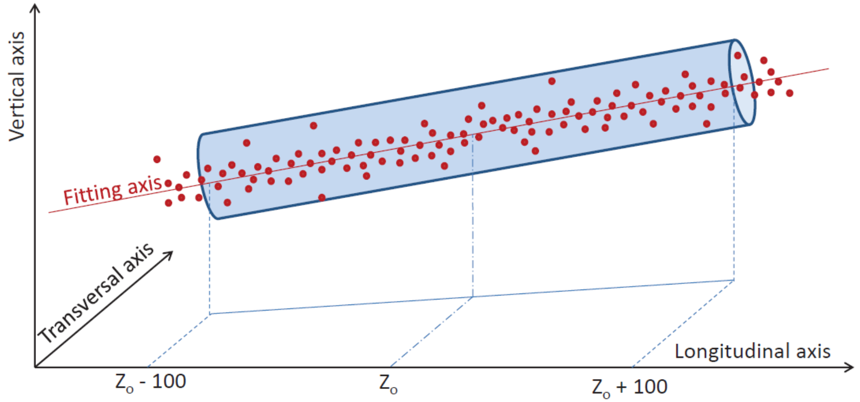
- Considering the number of components to be aligned, ground motion, such tight tolerances can not be obtained by a static on-time alignment system.
- Active pre-alignment: association of movers and sensors to the components to maintain them in place.

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

Along BDS:

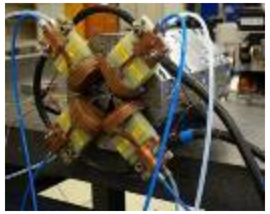
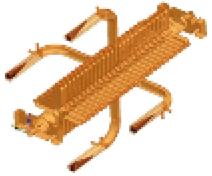
Radius equals to 10 µm over sliding windows of 500 m

Along Main Linac: over sliding windows of 200 m

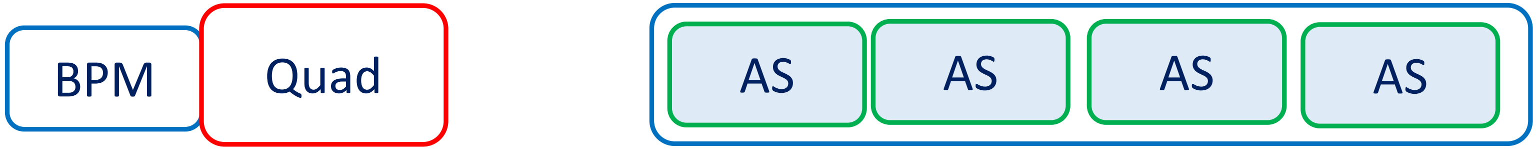


Component type	AS	BPM	MB Quad	DB quad
Radius (µm)	14	14	17	20

CLIC: introduction

Components to be aligned:			
Number of components	~ 4000	~ 4000	~ 140 000
Budget of error	14 µm	17 µm	17 µm
	BPM	Quad	AS

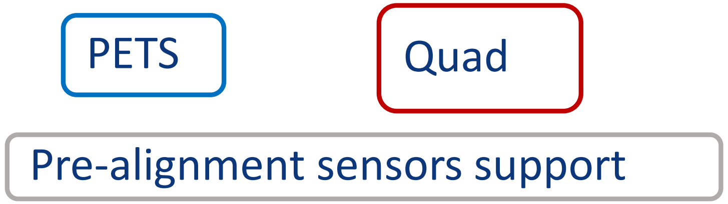
Strategy:



2 steps:

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

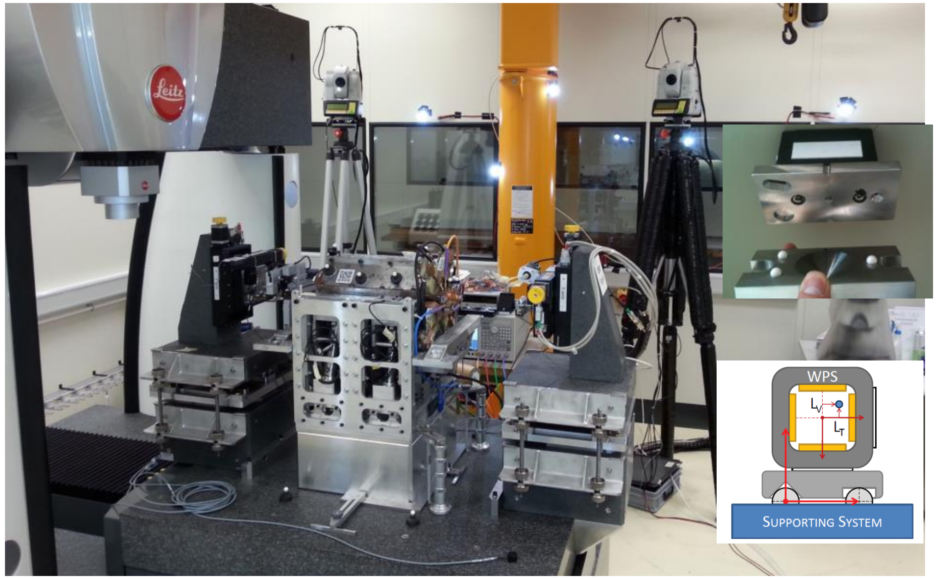
CLIC: alignment strategy


PETS

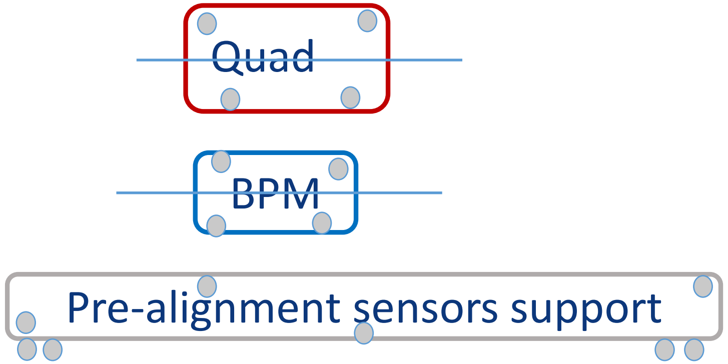
Quad

Pre-alignment sensors support

Initial alignment:



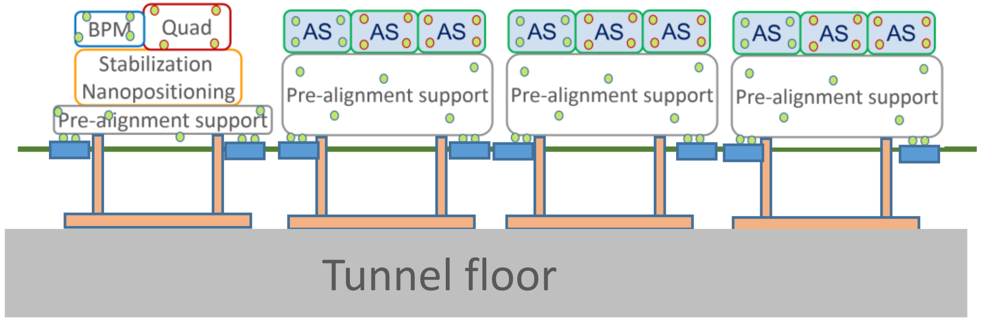
Fiducialisation:


Quad

BPM

Pre-alignment sensors support

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

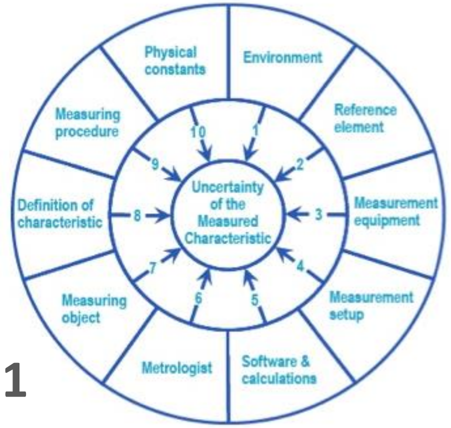
PACMAN = a study on Particle Accelerator Components' Metrology and Alignment to the Nanometre scale
It is an **Innovative Doctoral Program**, hosted by CERN, providing training to **10 Early Stage Researchers**.


ESR 3.3

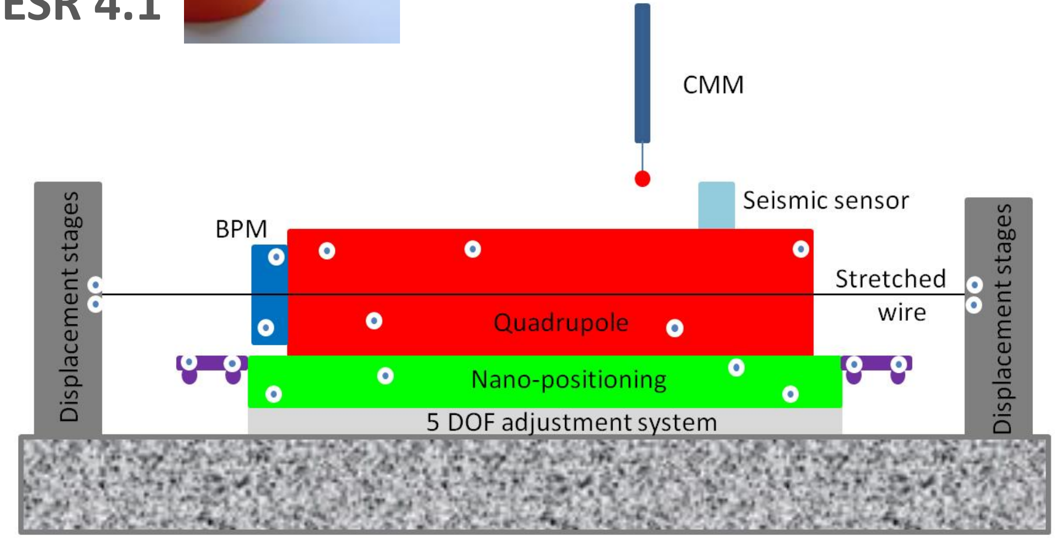

ESR 4.1


ESR 3.2


ESR 1.1



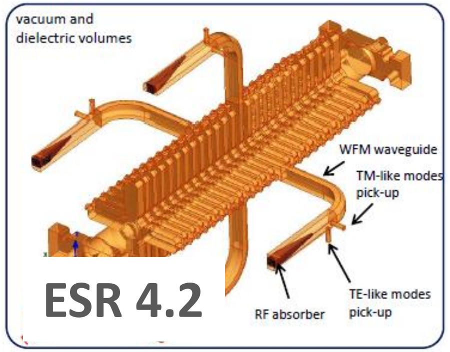
ESR 3.1



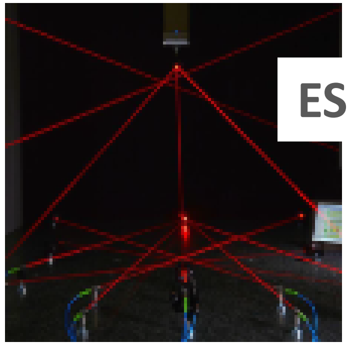

ESR 1.3

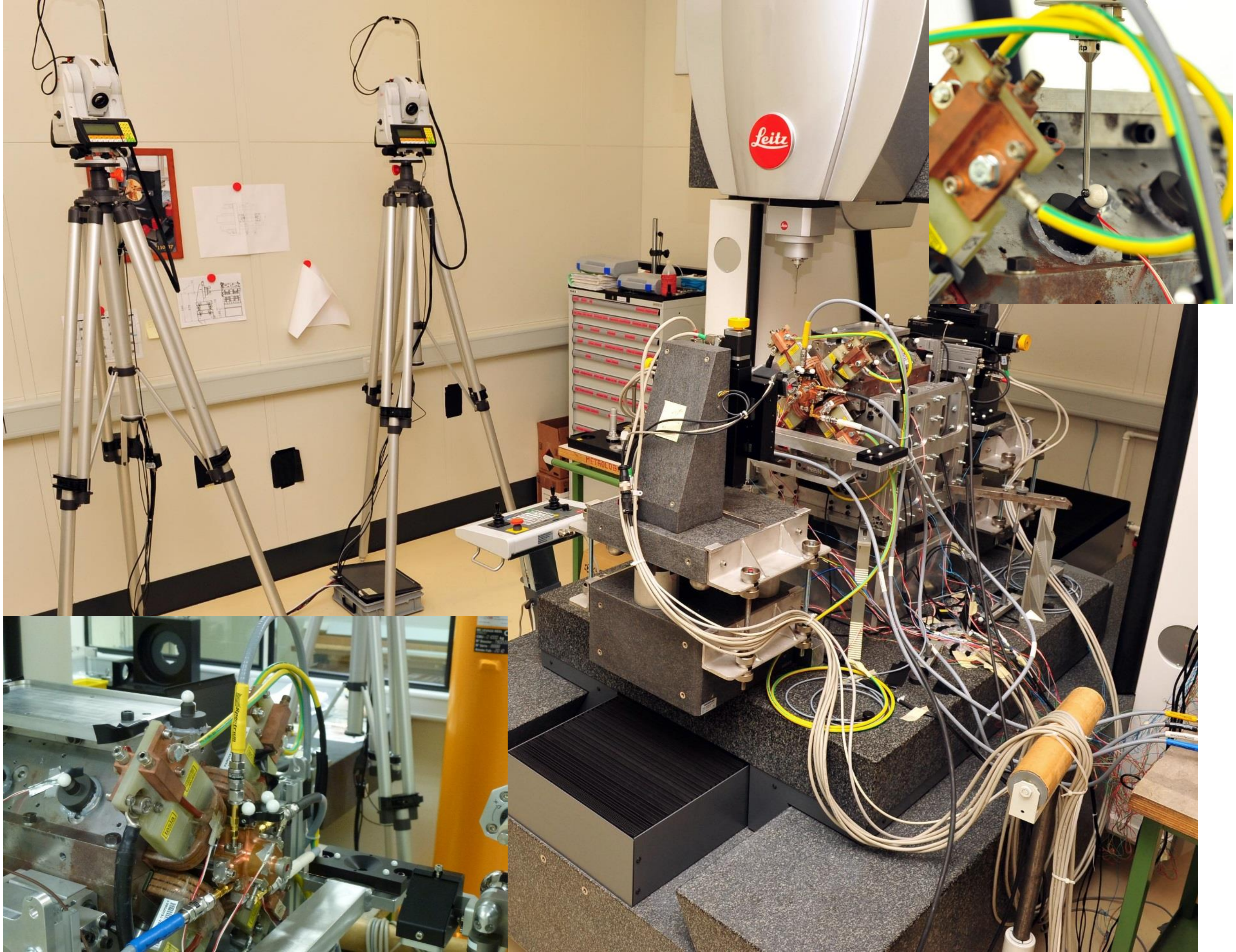

ESR 2.1


ESR 2.2



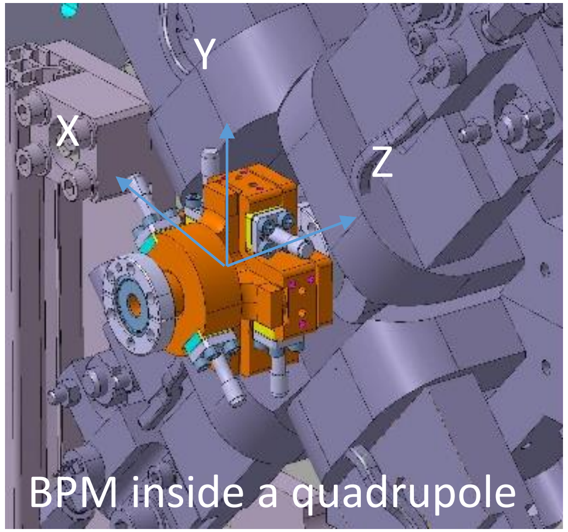
ESR 4.2


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.



BPM inside a quadrupole

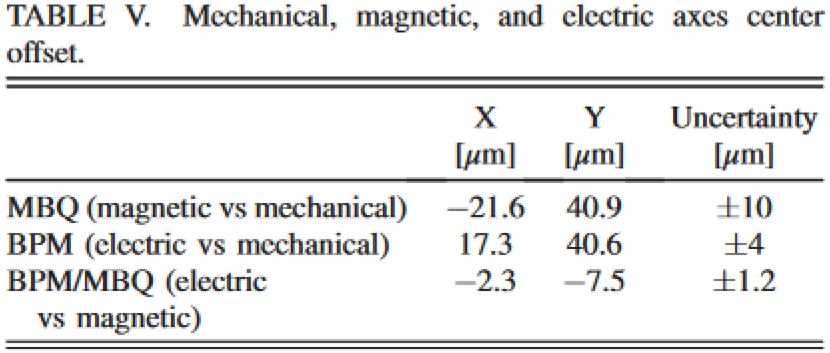


TABLE V. Mechanical, magnetic, and electric axes center offset.

	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

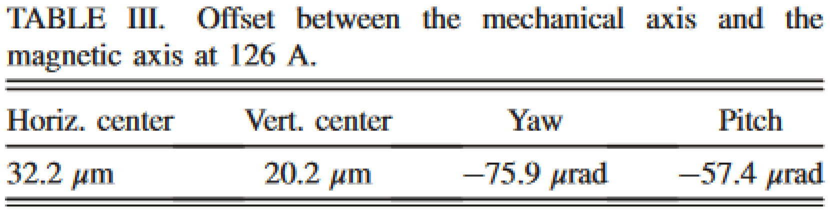


TABLE III. Offset between the mechanical axis and the magnetic axis at 126 A.

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

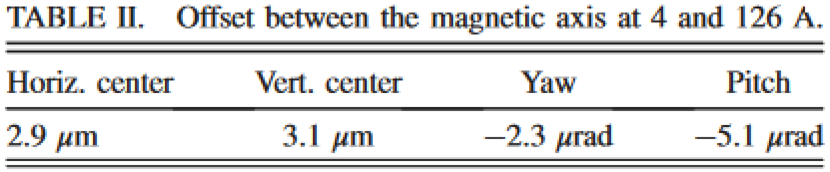
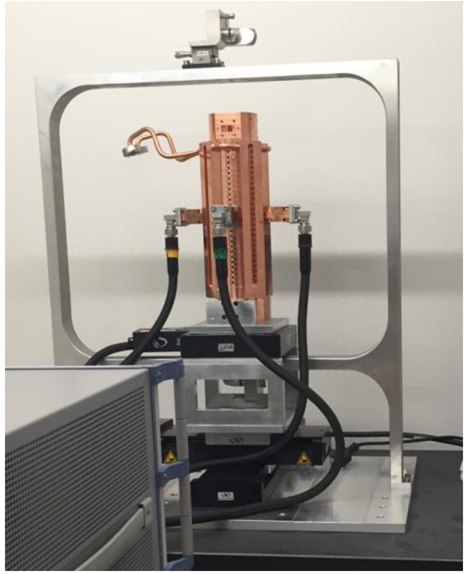


TABLE II. Offset between the magnetic axis at 4 and 126 A.

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

[Caiazza]

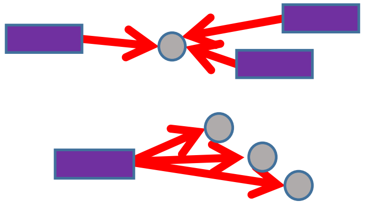


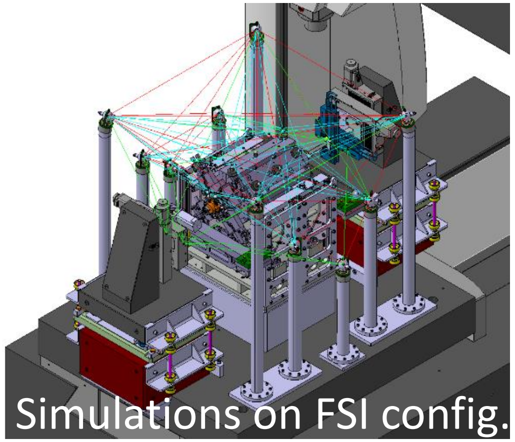
PACMAN: a few interesting results

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 is < 2.5 µm. Portable & self calibrating method!




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.

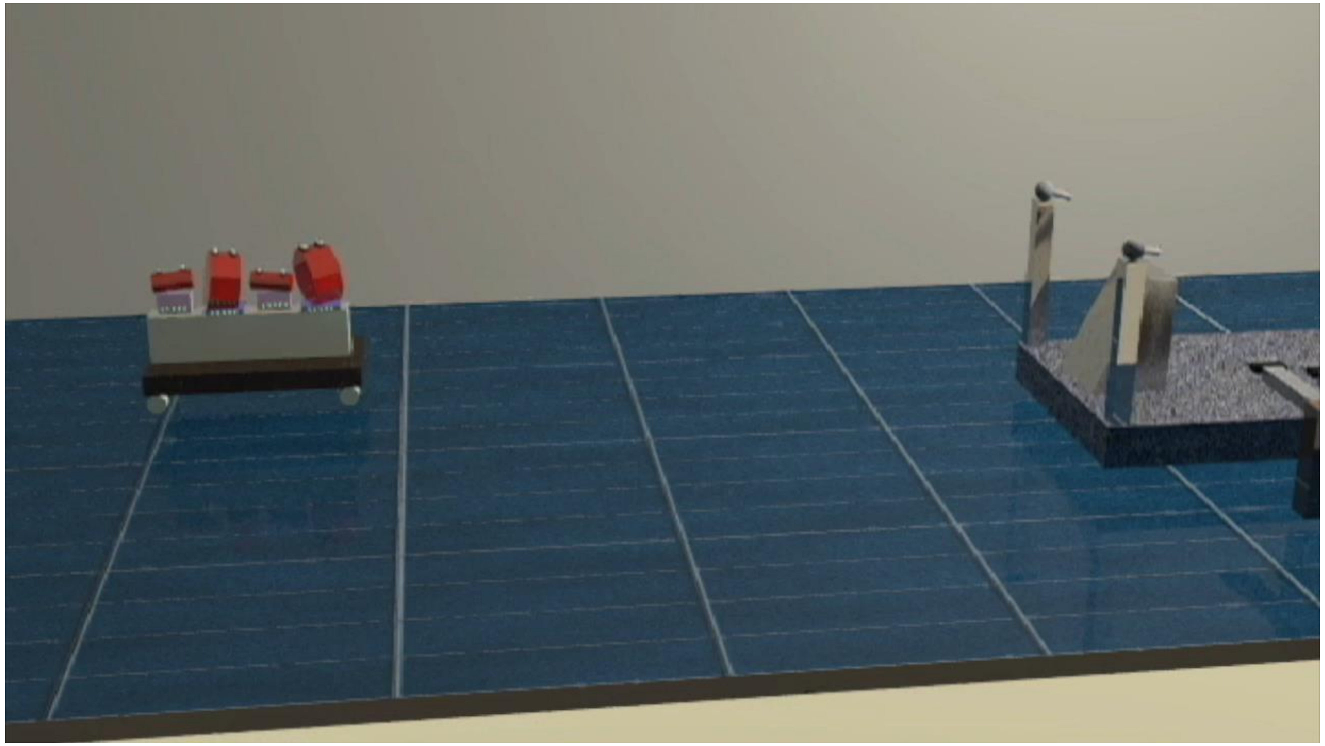
PACMAN: scenario 1

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



Conclusion

Do not forget Survey & Alignment in your project, you will save:

- 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;
- to choose the most appropriate solutions and instrumentation.

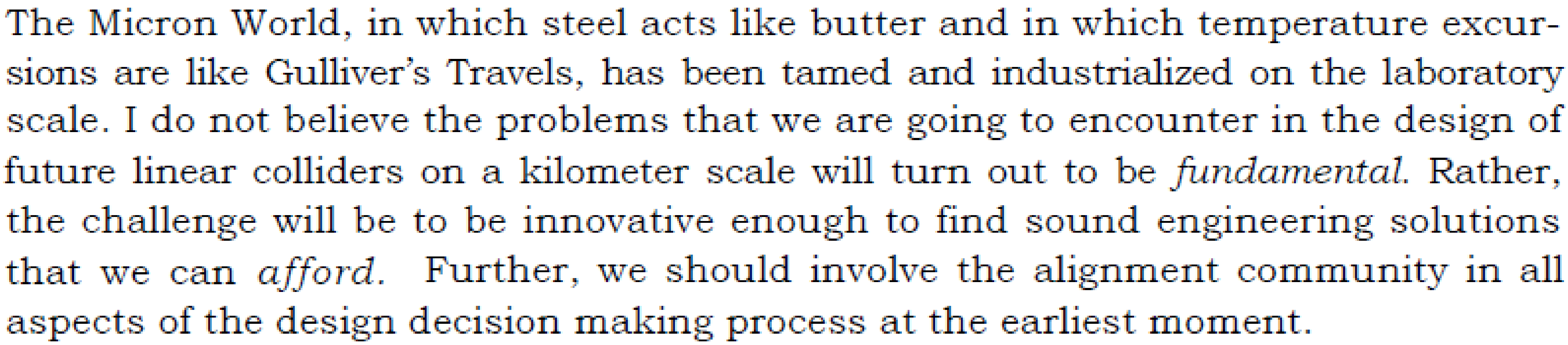
Conclusion

For the next generation of colliders:

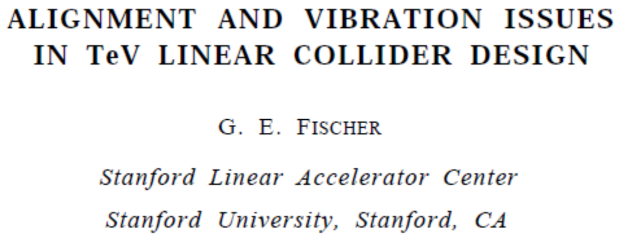
- there is a need to develop robust, performant and low cost alignment sensors, optimizing also associated cables.

Automated standardized operation will be needed, due to:

- the limited access in the tunnel;
- the large 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

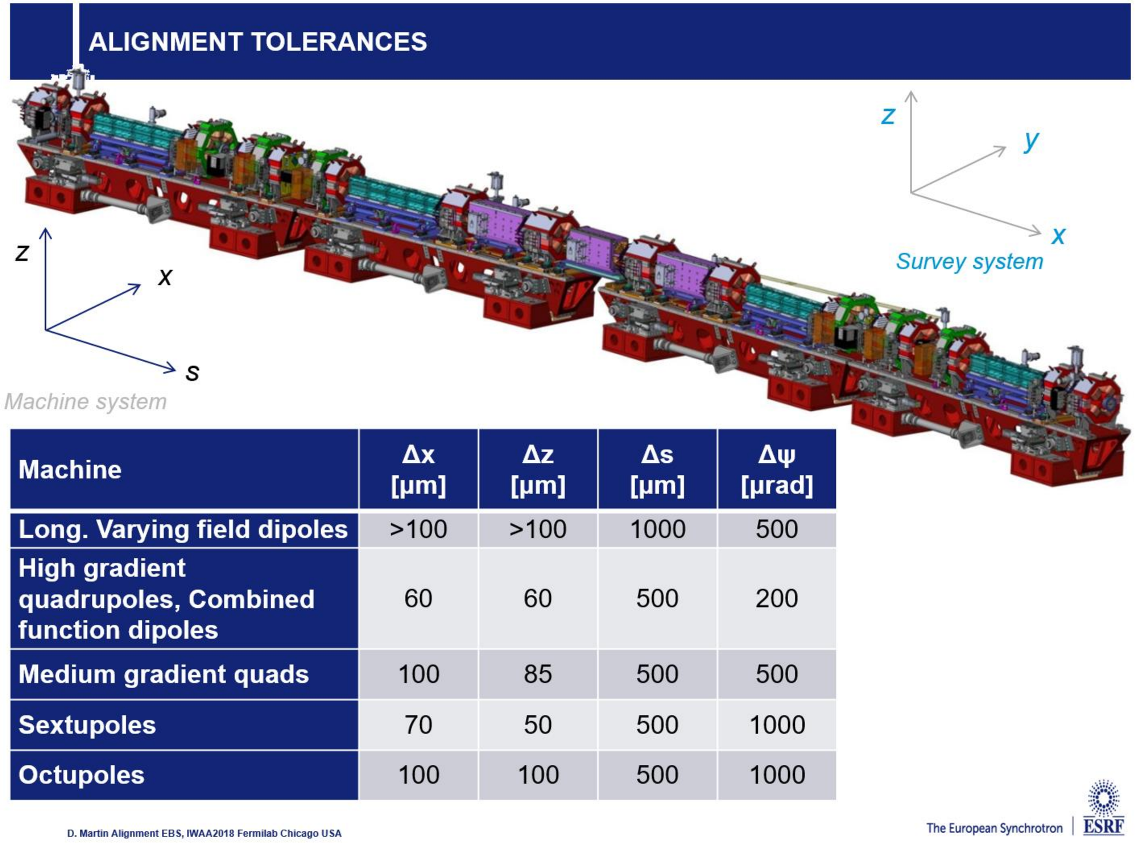
G. E. Fischer

Stanford Linear Accelerator Center
Stanford University, Stanford, CA

Final study case

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

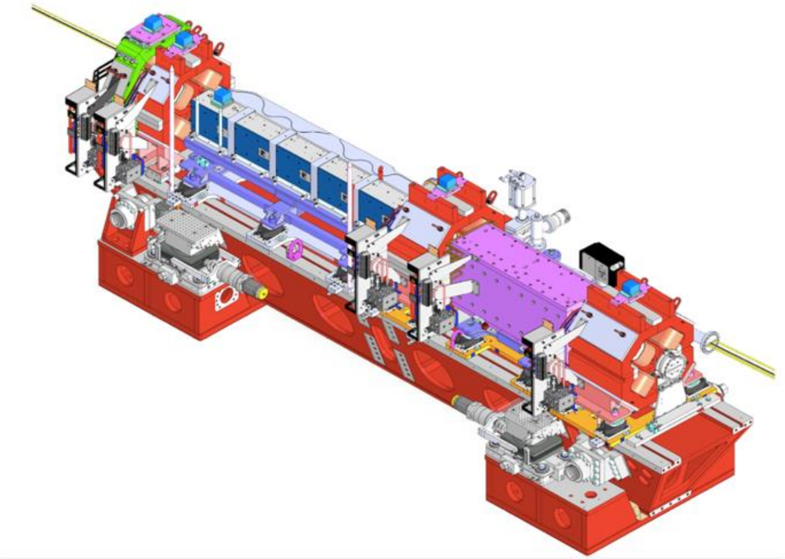
All info from this (very interesting) presentation:

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

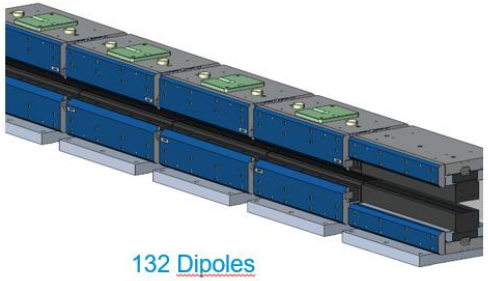


Four girders per cell :
- Magnet supports
- Magnets
- Vacuum equipment
- Diagnostics

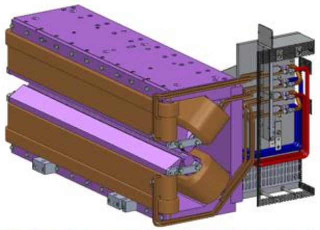
128 girders

6T empty
12-13T fully equipped

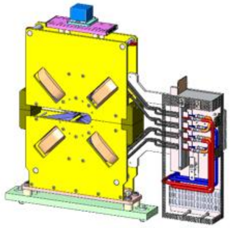
MAGNETS



132 Dipoles

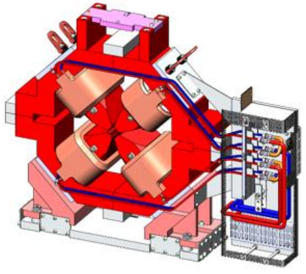


100 Combined function-quadrupoles

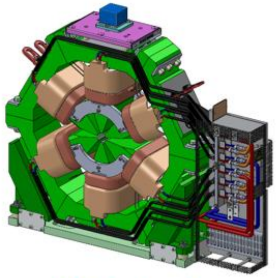


66 Octupoles

More than 1000 Magnets have been manufactured



524 Quadrupoles
(132 HG, 392 MG)



196 Sextupoles

98 Correctors

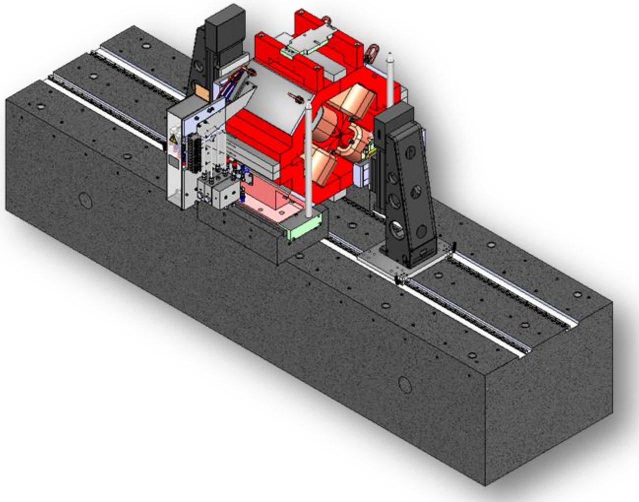
Study case: ESRF

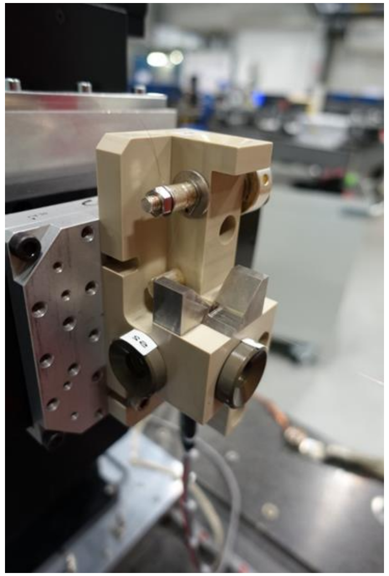
FIDUCIALISATION UNCERTAINTY

	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.

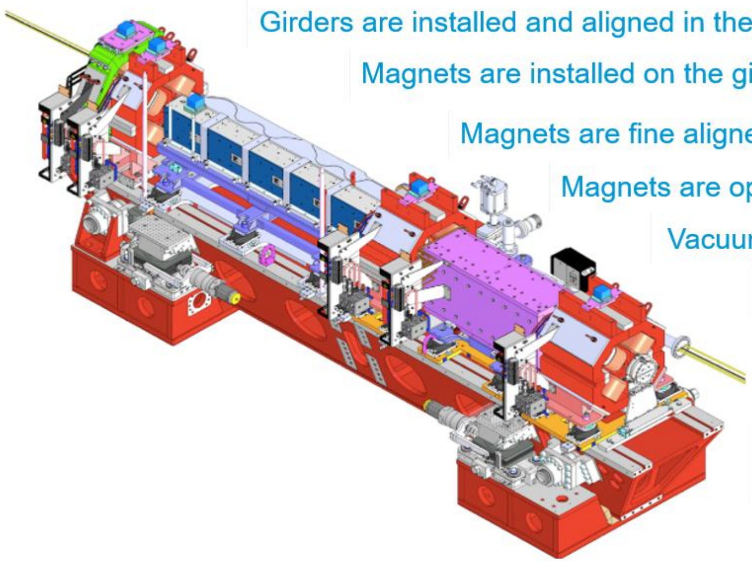
This is just one of many contributions to the overall alignment uncertainty…





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

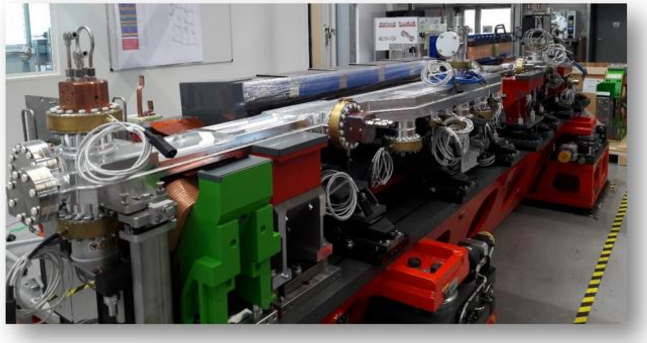
THE MAGNETS ARE OPENED AND THE VACUUM STRING IS INSTALLED.

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.*

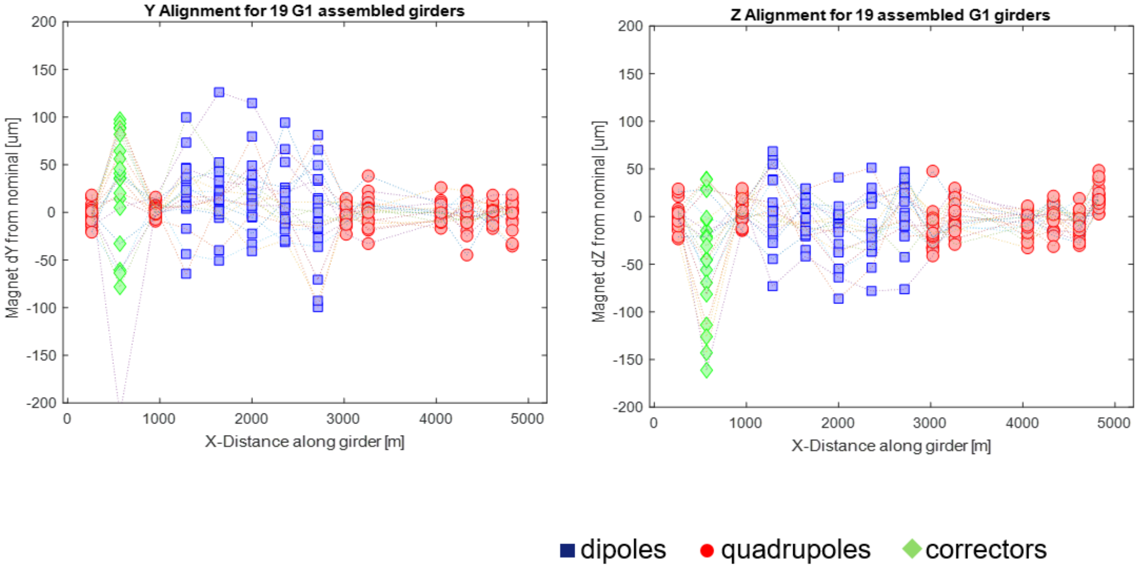
Study case: ESRF

THE VACUUM STRING IS ALIGNED AND THE FINAL ALIGNMENT MADE



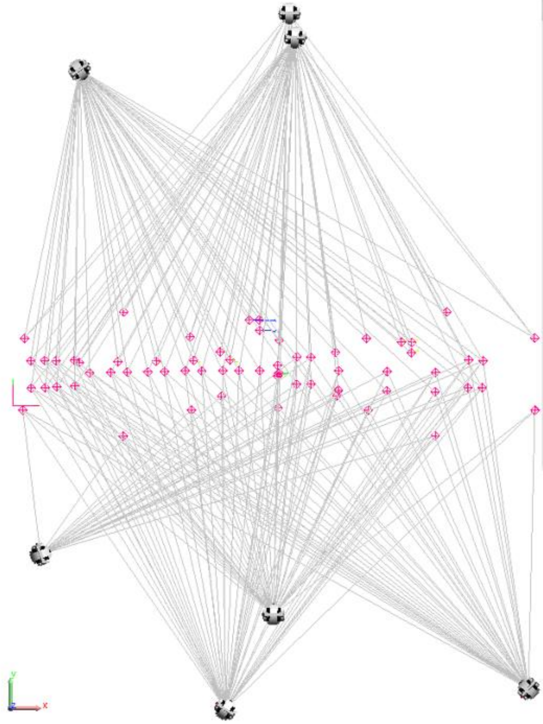
The vacuum chambers/BPMs are aligned, the magnets closed and the final alignment survey is made

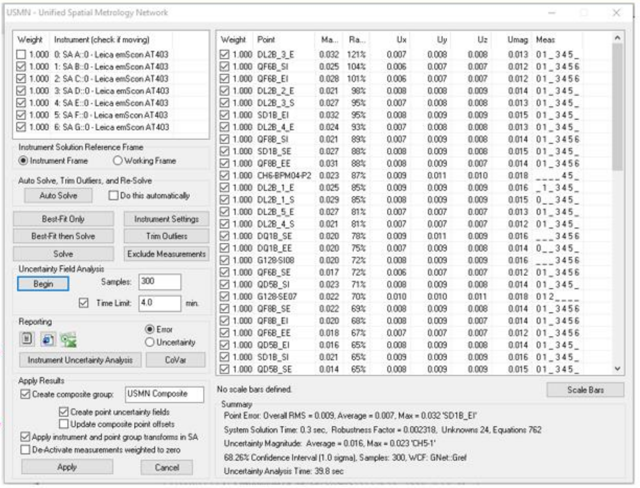
ALIGNMENT SUMMARY FOR 19 ASSEMBLED G1 GIRDERS



Study case: ESRF

GIRDER ALIGNMENT UNCERTAINTY





USMN - Unified Spatial Metrology Network

Weight	Instrument (check if moving)
☐ 1.000	0: SA A::0 - Leica emScon AT403
☑ 1.000	1: SA B::0 - Leica emScon AT403
☑ 1.000	2: SA C::0 - Leica emScon AT403
☑ 1.000	3: SA D::0 - Leica emScon AT403
☑ 1.000	4: SA E::0 - Leica emScon AT403
☑ 1.000	5: SA F::0 - Leica emScon AT403
☑ 1.000	6: SA G::0 - Leica emScon AT403

Instrument Solution Reference Frame
● Instrument Frame ○ Working Frame

Auto Solve, Trim Outliers, and Re-Solve
☐ Do this automatically

Uncertainty Field Analysis
Samples: 300
☑ Time Limit: 4.0 min.

Reporting
● Error
○ Uncertainty

Apply Results
☑ Create composite group: USMN Composite
☑ Create point uncertainty fields
☐ Update composite point offsets
☑ Apply instrument and point group transforms in SA
☐ De-Activate measurements weighted to zero

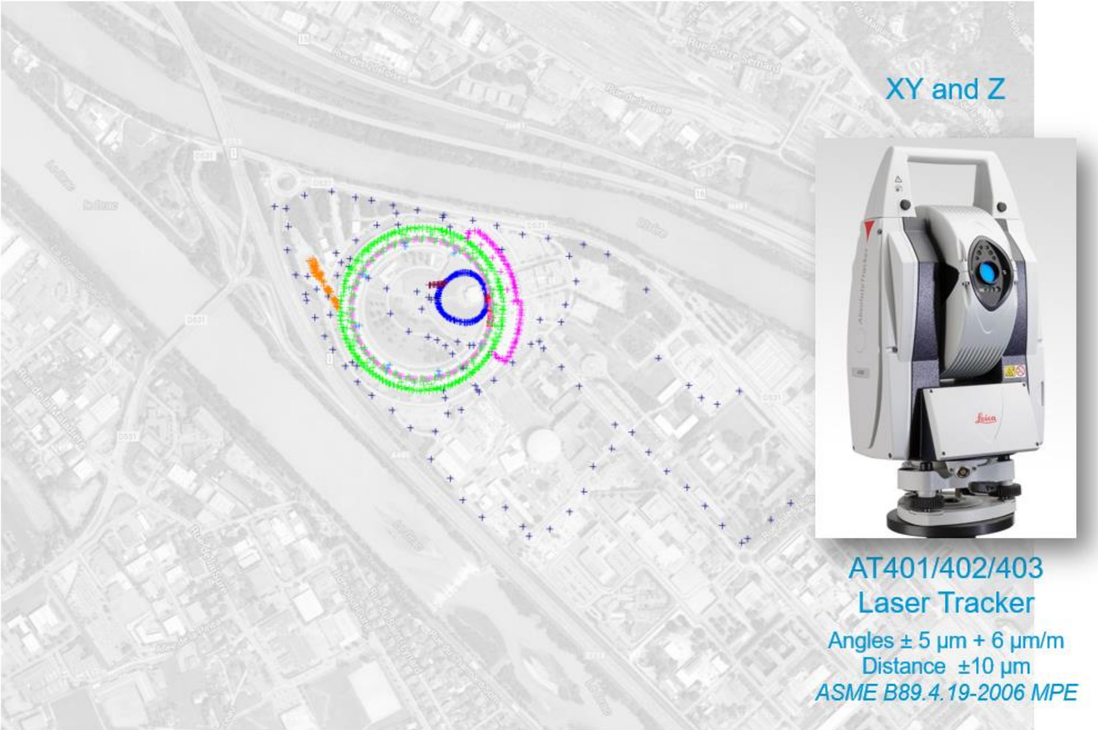
Weight	Point	Ma...	Ra...	Ux	Uy	Uz	Umag	Meas
☑ 1.000	DL2B_3_E	0.032	121%	0.007	0.008	0.008	0.013	01_345_
☑ 1.000	QF6B_SI	0.025	104%	0.006	0.007	0.007	0.012	01_3456
☑ 1.000	QF6B_EI	0.028	101%	0.006	0.007	0.007	0.012	01_3456
☑ 1.000	DL2B_2_E	0.021	98%	0.008	0.008	0.009	0.014	01_345_
☑ 1.000	DL2B_3_S	0.027	95%	0.007	0.008	0.008	0.013	01_345_
☑ 1.000	SD1B_EI	0.032	95%	0.008	0.009	0.009	0.015	01_345_
☑ 1.000	DL2B_4_E	0.024	93%	0.007	0.008	0.008	0.013	01_345_
☑ 1.000	QF8B_SI	0.021	89%	0.007	0.009	0.008	0.014	01_3456
☑ 1.000	SD1B_SE	0.027	88%	0.008	0.009	0.008	0.015	01_345_
☑ 1.000	QF8B_EE	0.031	88%	0.008	0.009	0.007	0.014	01_3456
☑ 1.000	CH6-BPM04-P2	0.023	87%	0.009	0.011	0.010	0.018	____45_
☑ 1.000	DL2B_1_E	0.025	85%	0.009	0.009	0.009	0.016	_1_345_
☑ 1.000	DL2B_1_S	0.029	85%	0.008	0.009	0.009	0.015	0__345_
☑ 1.000	DL2B_5_E	0.027	81%	0.007	0.007	0.007	0.013	01_345_
☑ 1.000	DL2B_4_S	0.021	81%	0.007	0.007	0.007	0.012	01_345_
☑ 1.000	DQ1B_SE	0.020	78%	0.009	0.011	0.009	0.016	___3456
☑ 1.000	DQ1B_EE	0.020	75%	0.007	0.009	0.008	0.014	0__345_
☑ 1.000	G128-SI08	0.020	72%	0.008	0.009	0.009	0.016	___3456
☑ 1.000	QF6B_SE	0.017	72%	0.006	0.007	0.007	0.012	01_3456
☑ 1.000	QD5B_SI	0.023	71%	0.008	0.009	0.008	0.014	01_345_
☑ 1.000	G128-SE07	0.022	70%	0.010	0.010	0.011	0.018	012____
☑ 1.000	QF8B_SE	0.022	69%	0.008	0.009	0.008	0.014	01_3456
☑ 1.000	QF8B_EI	0.020	68%	0.008	0.009	0.007	0.014	01_3456
☑ 1.000	QF6B_EE	0.018	67%	0.007	0.007	0.007	0.012	01_3456
☑ 1.000	QD5B_EI	0.016	65%	0.008	0.009	0.008	0.014	01_345_
☑ 1.000	SD1B_SI	0.021	65%	0.009	0.009	0.009	0.016	01_345_
☑ 1.000	QD5B_SE	0.014	65%	0.008	0.009	0.009	0.015	01_345_

No scale bars defined.

Summary
Point Error: Overall RMS = 0.009, Average = 0.007, Max = 0.032 'SD1B_EI'
System Solution Time: 0.3 sec., Robustness Factor = 0.002318, Unknowns 24, Equations 762
Uncertainty Magnitude: Average = 0.016, Max = 0.023 'CH5-1'
68.26% Confidence Interval (1.0 sigma), Samples: 300, WCF: GNet::Gref
Uncertainty Analysis Time: 39.8 sec

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

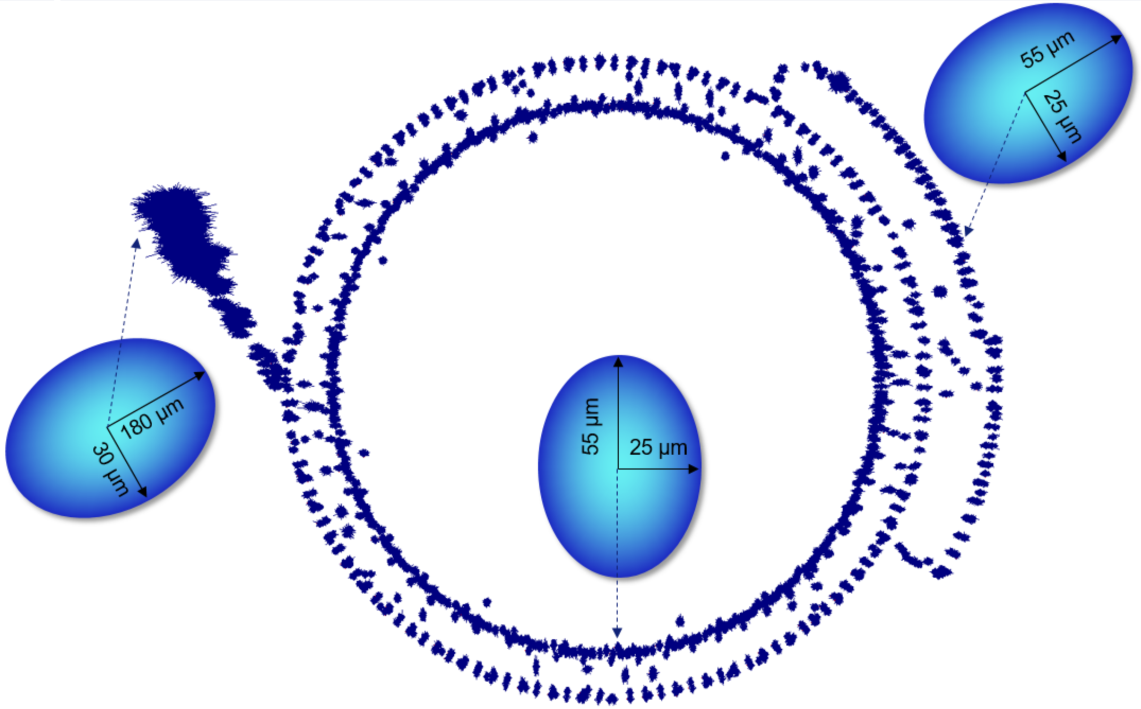
THE ESRF SURVEY NETWORKS



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

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