Academic training
Geodetic Metrology for Future Colliders

Towards the Alignment of Future Colliders

Hélène Mainaud Durand

16 June 2022

Outlook

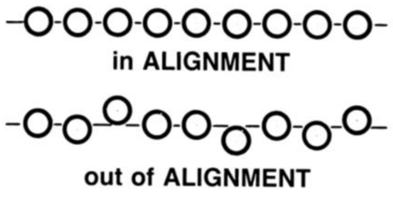
Introduction: a few definitions

The different steps of the alignment of colliders

State of the art

Towards the alignment of future colliders

Introduction: a few definitions – basics on alignment

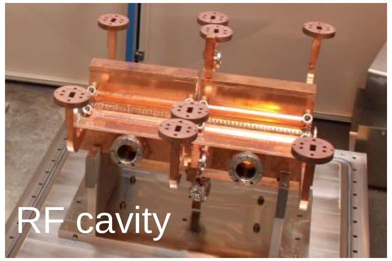


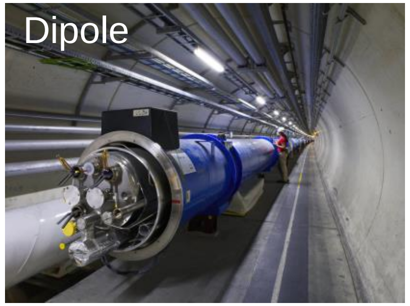
What does alignment mean?

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

In the context of accelerators;

- it is not always a straight line but a theoretical / nominal position. At CERN, we position w.r.t. smoothed line.
- the things are: beam instrumentation (Beam Position Monitors), vacuum devices, magnets (quadrupoles, dipoles, sextupoles), RF components (Accelerating cavities)





Introduction: a few definitions – basics on alignment

- **Why aligning components?**

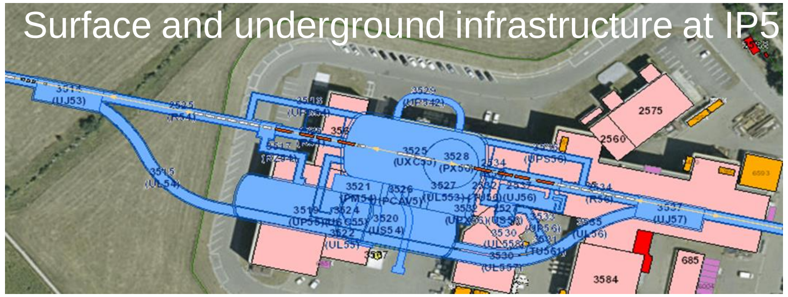
  The Earth on which we build accelerators is in constant motion.

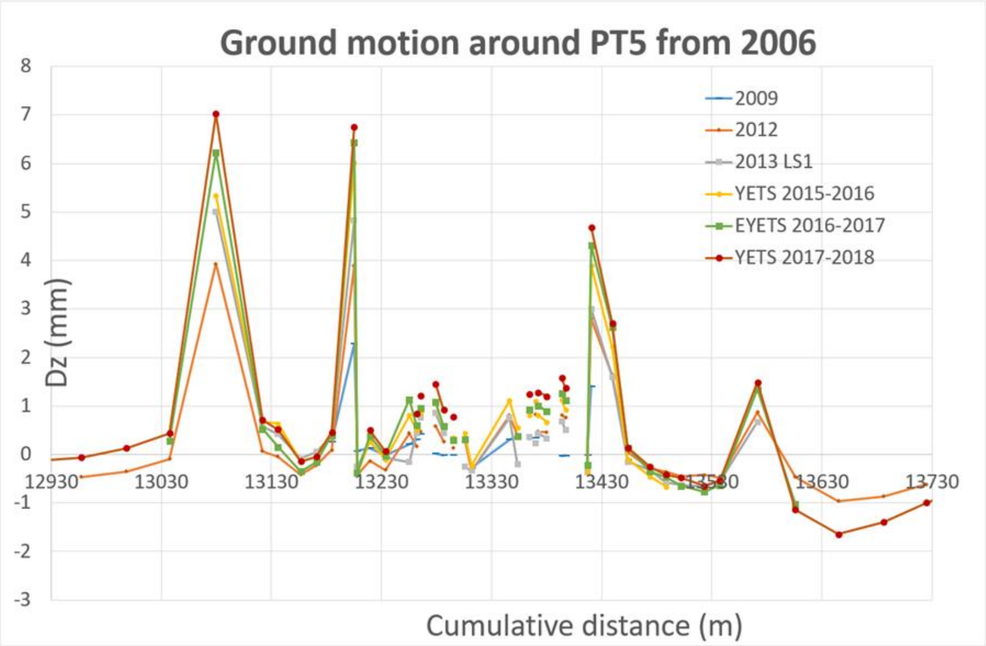
  There are mechanical constrains (vacuum, temperature, pressure) generating misalignments.

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

- **Alignment tolerances**

  Error of placement which, if exceeded, leads to a machine that is uncorrectable – with an "unacceptable loss of luminosity" (R. Ruland)





Introduction: a few definitions – alignment tolerances

Undesired position imperfections of accelerators components → perturbations of particle motion → limitations on accelerator performance.

In most of the particle accelerators built: a good **static alignment** to the level of 200-500 µm is sufficient to achieve the design performance.

Dynamic alignment “defined as an active and remote position control of accelerator components”. In order to be called dynamic, the position control should be possible **(1) at high frequencies,** certainly on time scales below a few hours but most typically below minutes; **(2) during the beam operation**, i.e. without human intervention in the vicinity of the accelerator (Redaelli).

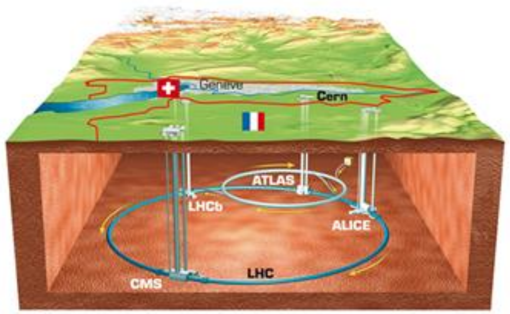
Static and dynamic alignment refer to **relative alignment** between several consecutive components.

This lecture will focus on **static alignment**.

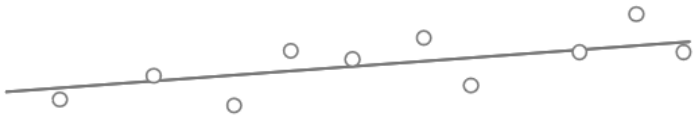
Introduction: a few definitions – basics on alignment

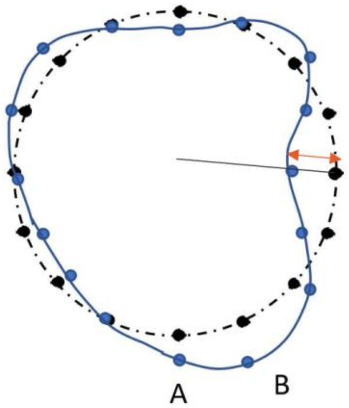
Absolute alignment refers to the «best possible absolute accuracy w.r.t. to the theoretical geometry»:

- In the vertical direction deviation from the theoretical plane of the collider



LHC collider


Alignment w.r.t. theoretical plane



Transverse plane variation of the collider

- In the transverse plane variation of its radius w.r.t. the theoretical value.

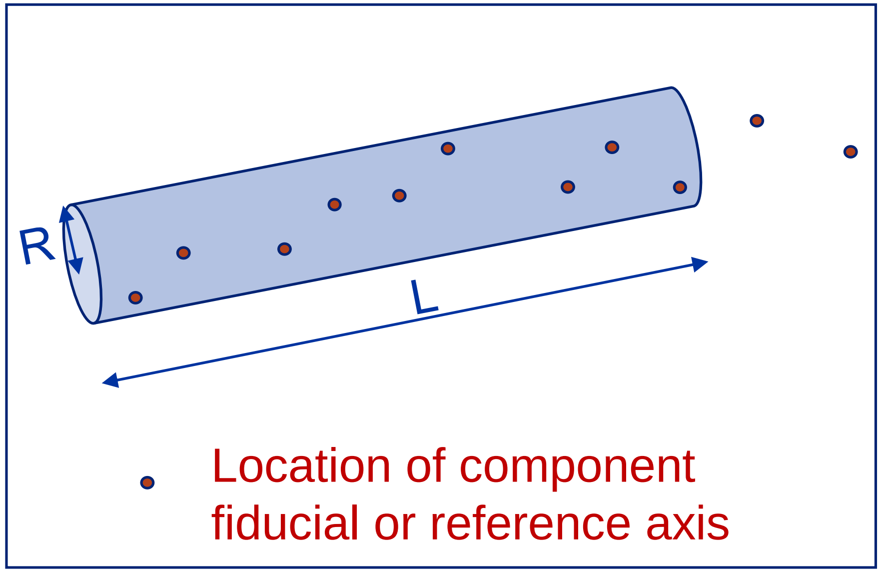
Introduction: a few definitions – basics on alignment

Tolerances vs uncertainty vs accuracy vs precision (simplified reminder):

- ***Precision:*** describes the repeatability of a measurement
- ***Accuracy :*** indicates the closeness of a measurement to its true value
- ***Tolerance:*** specifies the permissible deviations of the given value that can be accepted
- ***Uncertainty:*** quantification of the level of doubt we have about any measurement.

Common language put in place with physicists:

- R= Radius
- L= Overlapping length



Simplified representation of alignment tolerances

Outlook

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Steps of alignment

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

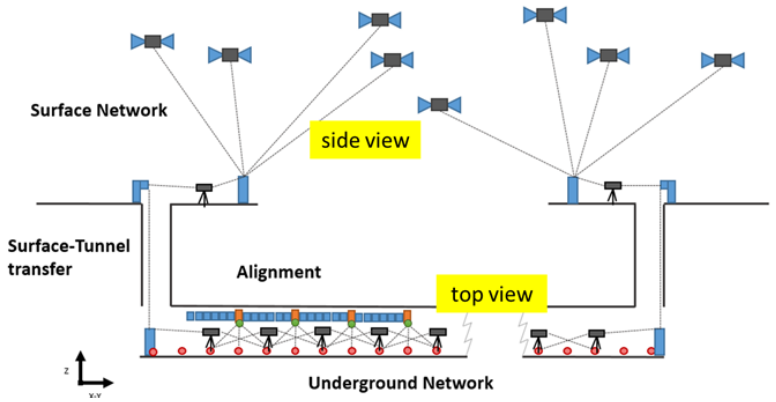
Definition of their theoretical trajectory

Time scale

Absolute alignment of the components

Relative alignment of the components

Maintenance of the alignment



Geodetic networks for a collider

Definition of alignment strategy

General constraints
- Access (installation, alignment, maintenance)
- Space
- Radiation level
- Thermal stability
- Stability of the tunnel floor, ground motion

Component & support design
- Impact of vibrations
- Eigen frequencies
- Rigidity of component & support
- Weight

Alignment of a component inside a tunnel

Beam requirements
- Fiducialisation requirements
- Component assembly on girder
- Girder alignment in the tunnel
- Relative / absolute alignment requirements

Project constraints
- Cost
- Manpower available
- Operation / maintenance time

Alignment methods & instrumentation available

- Takes several years!!!
- Different methods and solutions needed according to the area

Installation and determination of a surface geodetic network

Physical realization of points in an underlying reference system.

Absolute reference for all subsequent geodetic and survey work

- Civil engineering
- Infrastructure
- Alignment

Networks with different orders of precision.

Mixture of permanent GNSS stations and geodetic pillars

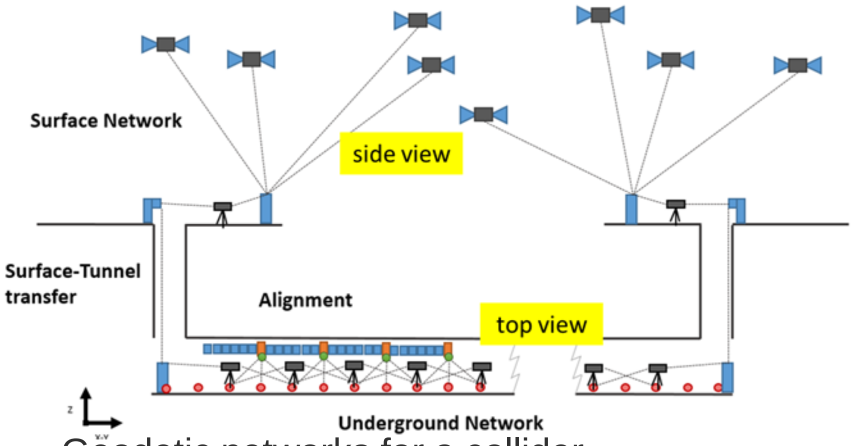
GNSS station

Geodetic pillar

LHC surface geodetic network and its pillars

Points determined from Global Navigation Satellite System (GNSS) observations (precision and accuracy below 2mm in planimetry and below 5 mm in altimetry). All points measured simultaneously twice, stationed during 48h each time with individually calibrated geodetic antennas.

Transfer of reference in the tunnel

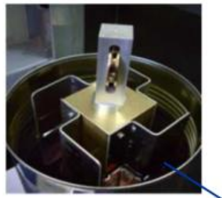


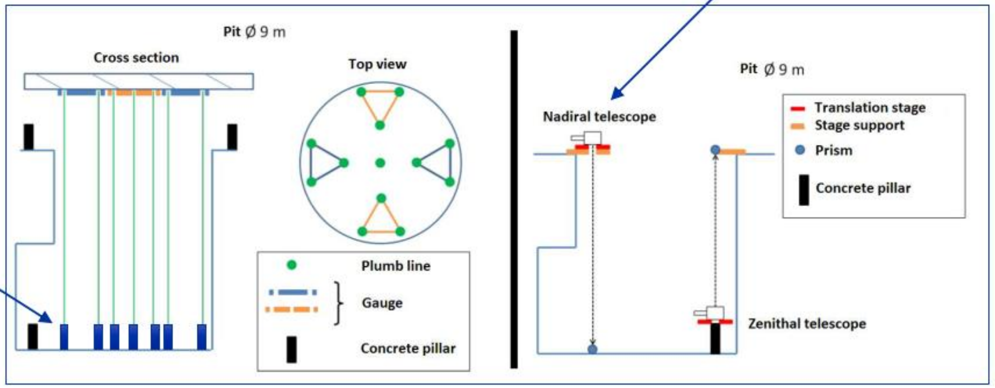
Geodetic networks for a collider

Survey monuments are installed close to each pit on the surface, measured by GPS means.

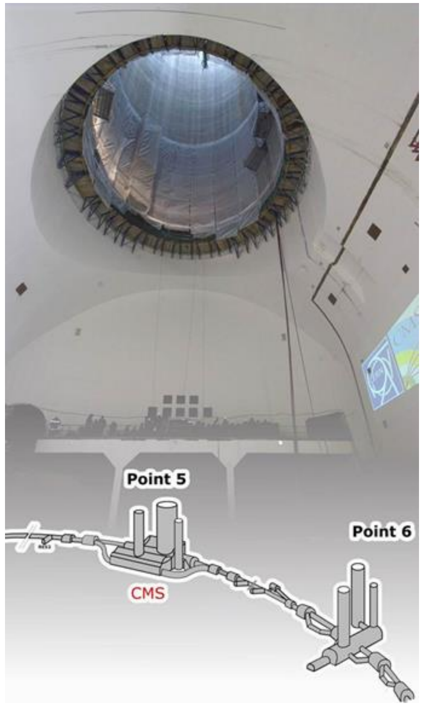
These reference points will be transferred from the surface to the tunnel through pits, using a combination of:

- 3D triangulation and trilateration measurements
- angular measurements w.r.t. plumb line.
- Nadiro-zenithal telescope
- 3D measurements.





Transfer of reference using plumb line (left) nadiral telescope (right)



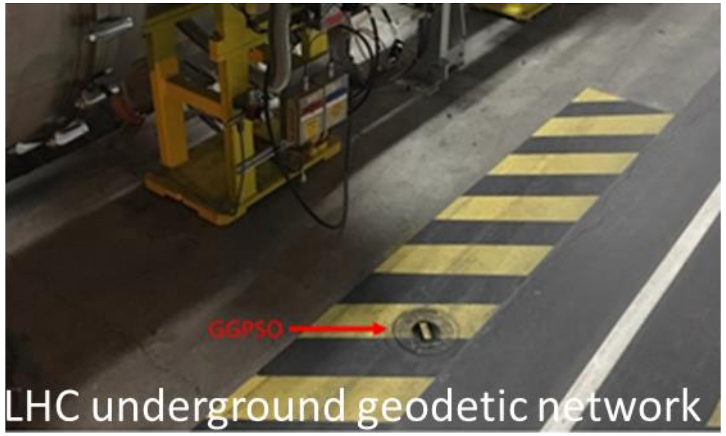
Transfer through shaft

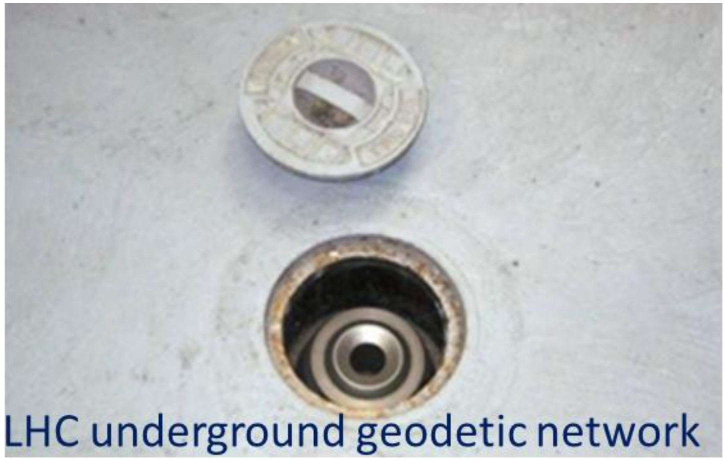
Installation & determination of an underground geodetic network

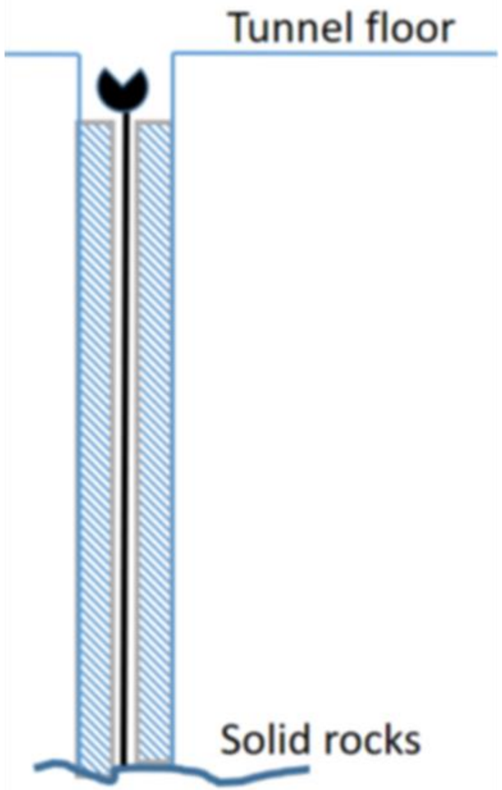
The **underground geodetic network** consists of dense networks of monuments, preferably in the floor or on the walls.

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

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







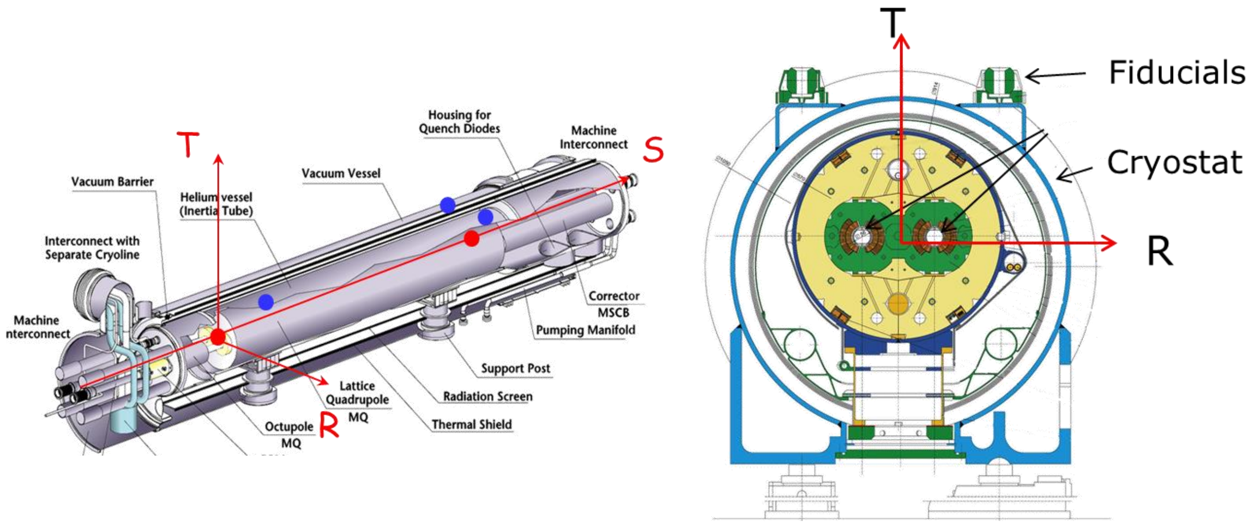
Deep reference concept

Fiducialisation

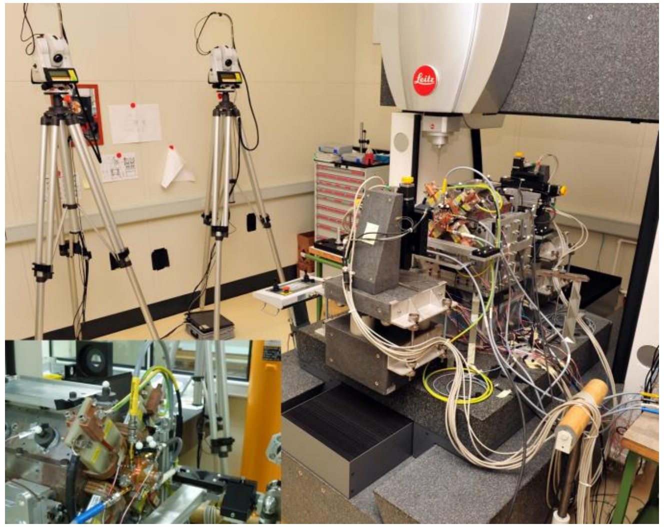
Fiducialisation: the determination of the reference axis of the component w.r.t. its external alignment targets (fiducials) accessible to survey measurements.

3 types of measurements according to the accuracy needed:

- Mechanical measurements using a gauge (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.



Fiducials in blue, w.r.t. the component reference axis in red

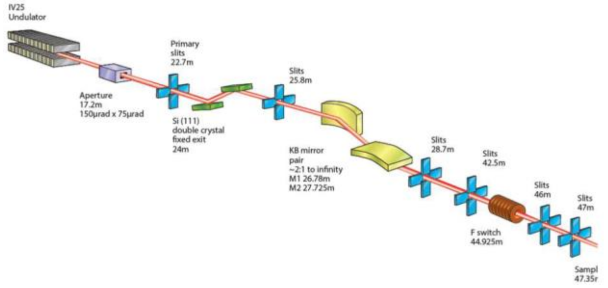


Fiducialisation of a CLIC quadrupole in a CMM

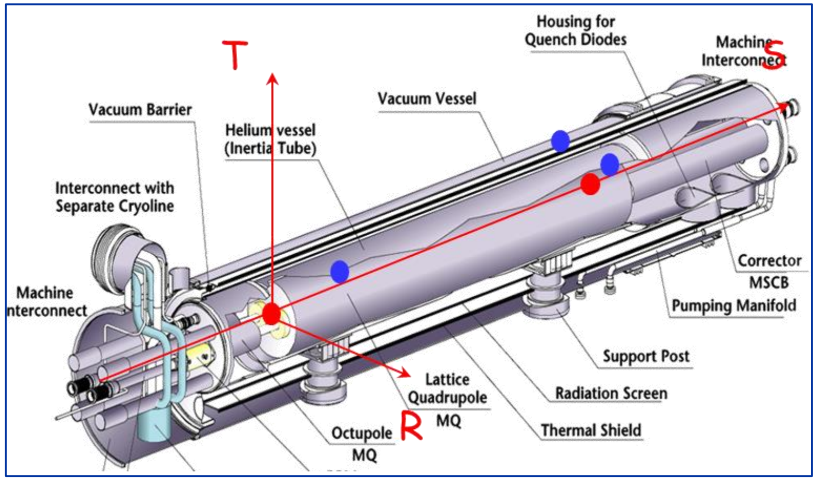
Definition of their theoretical trajectory

To align components, their position on the theoretical trajectory is needed:

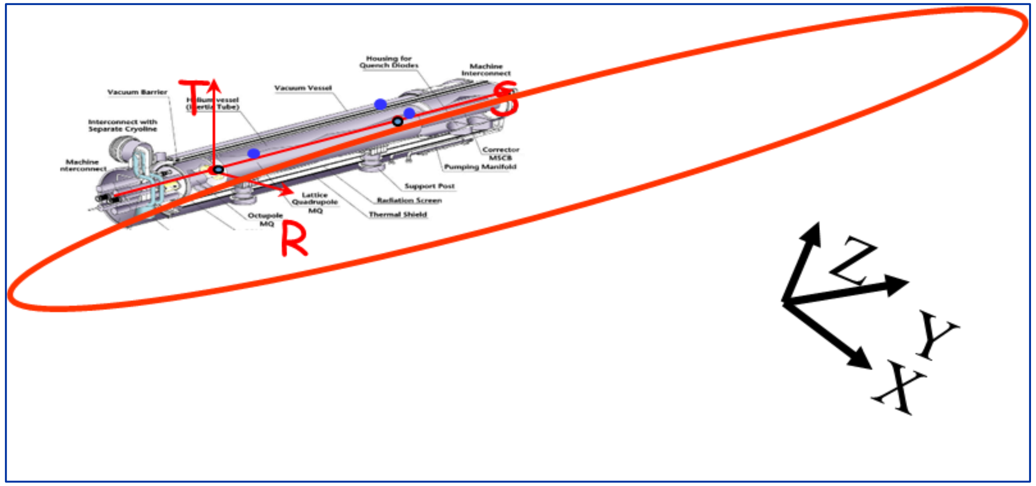
- Defined by physicists, using the MAD-X software (general purpose tool for charged particle optics design and studies in accelerators and beam lines)
- The component positions are given in an optics local coordinate system
- They are then transformed in the CERN Coordinate System (CCS) (for this, the definition of a start point and orientation known in both systems is needed)



* NAME	S	L	ANGLE	X	Y	Z	THETA	PHI	PSI	GLOBALTILT
$ %s	%le	%le	%le	%le	%le	%le	%le	%le	%le	%le
"IP.1"	0.000000000	0.000000000	0.000000000	-2202.210270000	2359.006560000	2710.638820000	-4.315508007	0.012427956	-0.006530924	-0.006530924
"MBAS2.1R1"	3.000000000	3.000000000	0.000000000	-2199.443670316	2359.043842909	2709.479278637	-4.315508007	0.012427956	-0.006530924	-0.006530924
"DRIFT_0"	19.050000000	16.050000000	0.000000000	-2184.642362007	2359.243306475	2703.275732343	-4.315508007	0.012427956	-0.006530924	-0.006530924
"TAS.1R1"	20.850000000	1.800000000	0.000000000	-2182.982402156	2359.265676221	2702.580007525	-4.315508007	0.012427956	-0.006530924	-0.006530924
"DRIFT_1"	21.564000000	0.714000000	0.000000000	-2182.323951472	2359.274549553	2702.304036680	-4.315508007	0.012427956	-0.006530924	-0.006530924
"BPMSW.1R1.B1"	21.564000000	0.000000000	0.000000000	-2182.323951472	2359.274549553	2702.304036680	-4.315508007	0.012427956	-0.006530924	-0.006530924
"DRIFT_2"	21.697000000	0.133000000	0.000000000	-2182.201298886	2359.276202429	2702.252630347	-4.315508007	0.012427956	-0.006530924	-0.006530924
"BPMWF.A1R1.B1"	21.697000000	0.000000000	0.000000000	-2182.201298886	2359.276202429	2702.252630347	-4.315508007	0.012427956	-0.006530924	-0.006530924
"DRIFT_3"	22.965000000	1.268000000	0.000000000	-2181.031949419	2359.291960672	2701.762530864	-4.315508007	0.012427956	-0.006530924	-0.006530924
"MQXA.1R1"	29.335000000	6.370000000	0.000000000	-2175.157536090	2359.371124716	2699.300438036	-4.315508007	0.012427956	-0.006530924	-0.006530924
"DRIFT_4"	29.842000000	0.507000000	0.000000000	-2174.689980744	2359.377425528	2699.104475545	-4.315508007	0.012427956	-0.006530924	-0.006530924
"MCBXH.1R1"	29.842000000	0.000000000	0.000000000	-2174.689980744	2359.377425528	2699.104475545	-4.315508007	0.012427956	-0.006530924	-0.006530924
"MCBXV.1R1"	29.842000000	0.000000000	0.000000000	-2174.689980744	2359.377425528	2699.104475545	-4.315508007	0.012427956	-0.006530924	-0.006530924



Local coordinate system defined with a component

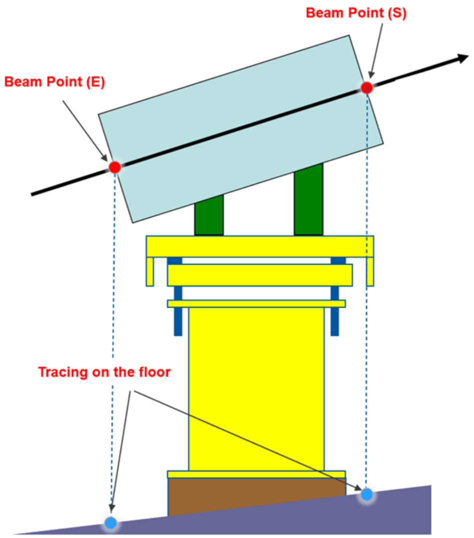


Position of the component expressed in the CCS

Absolute alignment of the components

The absolute alignment is divided into 3 tasks:

- **Marking on the floor**: vertical projection of the geometrical mean (Start / End points) of the beam line
- **Positioning of the supporting structures** (jacks or adjustment platform): the stroke of the supporting structures compensates the errors of the floor, the errors in their positioning, cryostat construction errors and ground motion during the life of the accelerator. Jacks or adjustment platforms are positioned within ± 2mm, w.r.t. underground geodetic network. Then, they are sealed on the floor.
- **First positioning** of the component w.r.t. underground network

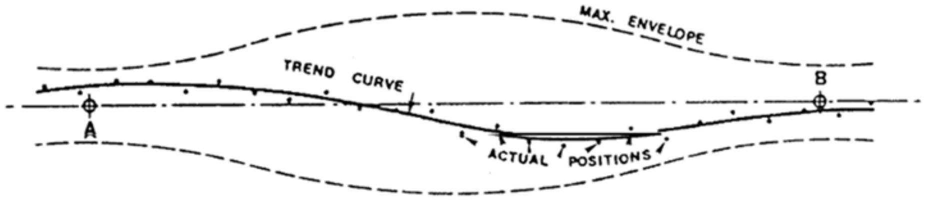


Marking on the floor

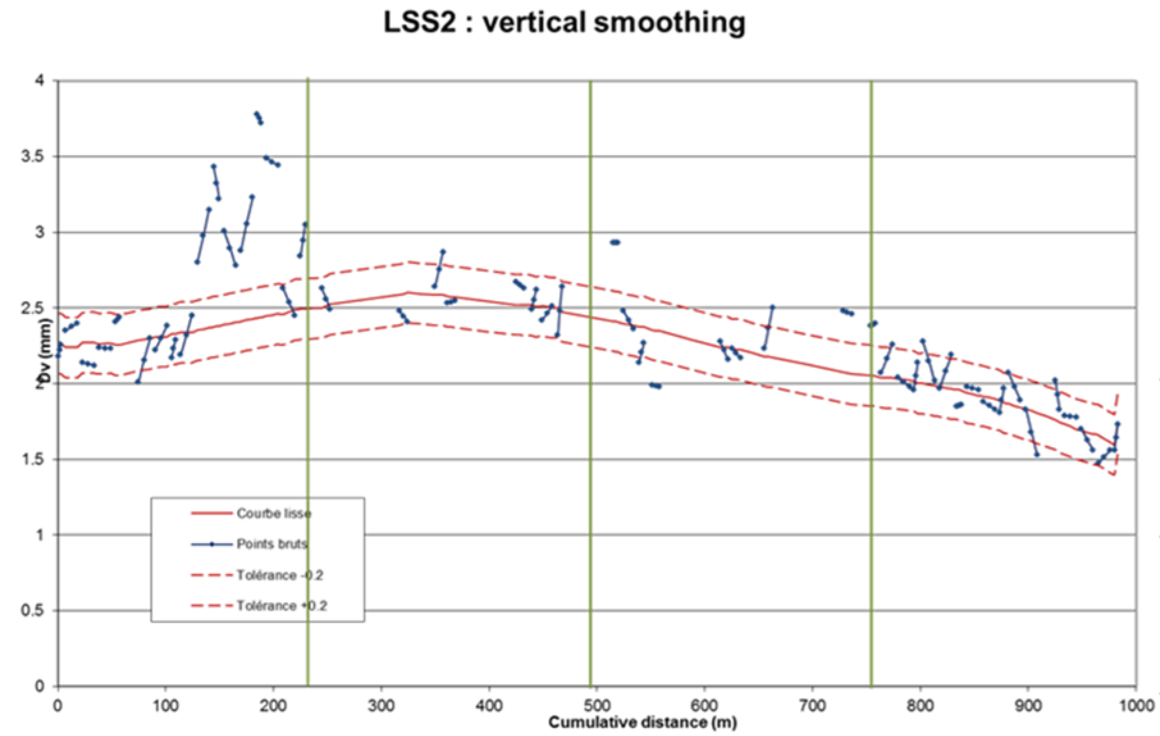

Component on its jacks

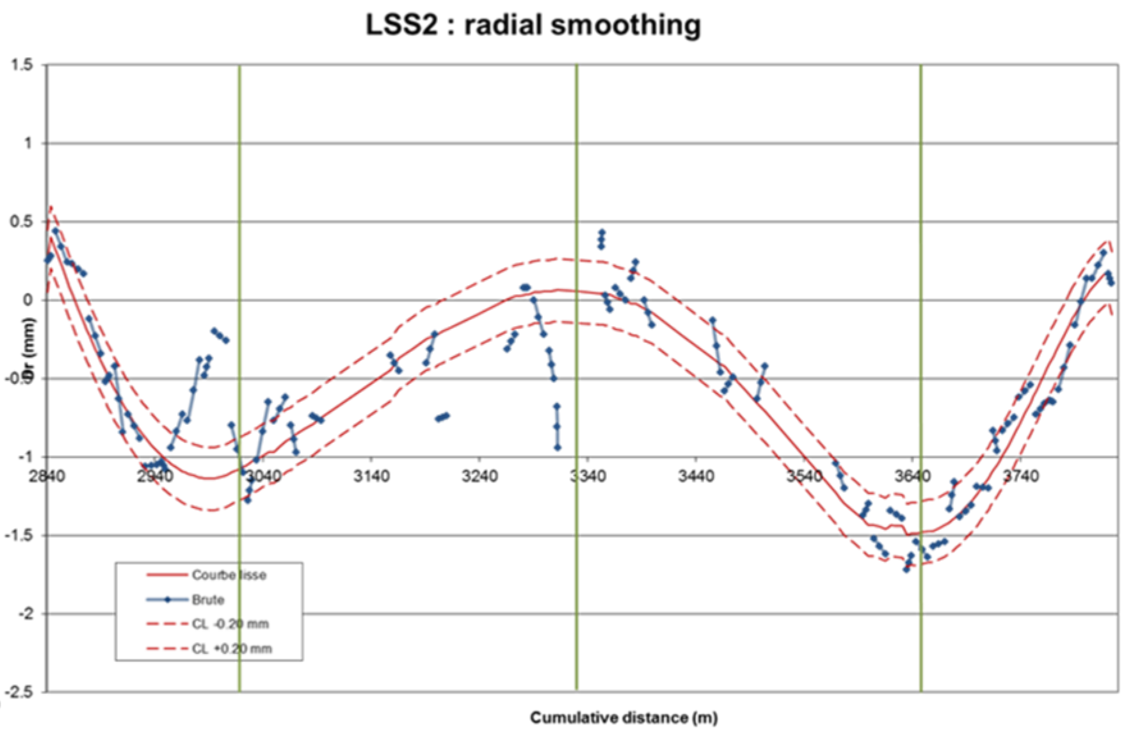
Relative alignment → smoothing

The smoothing process: only start once the magnets are connected, under vacuum and are at cold (if supra), to take all the mechanical forces into account.



Position of magnets with respect to theoretical orbit



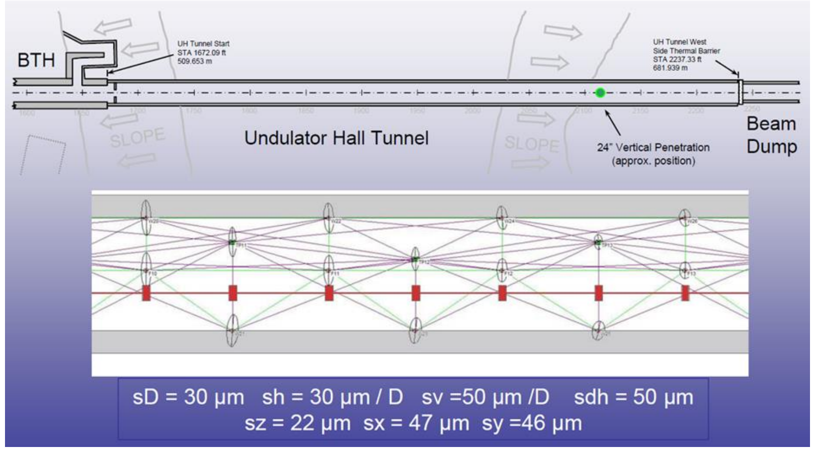


Relative alignment of the components

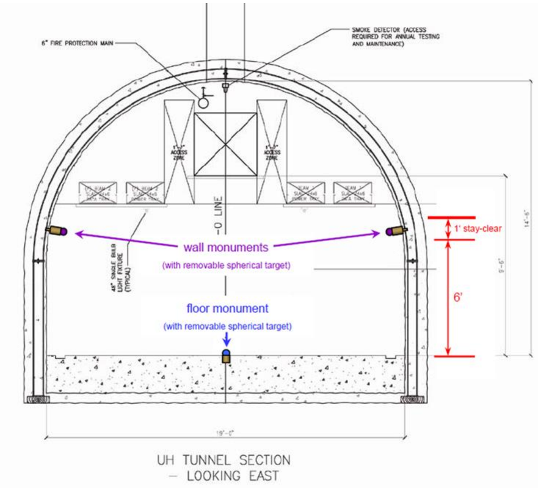
At CERN, we perform **smoothing measurements: we measure the relative position of components,** independently from the geodetic network. The geodetic network is not remeasured anymore after the initial alignment of components.

In other labs, an alternative strategy is performed: the geodetic network is remeasured before each alignment, and then a relative alignment of each component w.r.t. geodetic network is performed:

- A denser underground geodetic network is needed
- Only applicable for machines within a few kilometres.



Underground network (SLAC undulator hall tunnel)



Underground network configuration (SLAC)

Maintenance of the alignment

The performance of any collider depends not only **on the initial placement of its components after construction, but also of their alignment during the operation and maintenance.**

The **maintenance of the alignment** is a **key parameter**, even if does not appear in the initial costs of the project; it is function of the tolerance of alignment, ground motion and duration of the maintenance shutdowns.

A few examples:

- The maintenance of the alignment of the LHC main and secondary components takes more than 2 years with an average of 10 persons.
- The maintenance of the alignment of the ESRF main ring is performed 5 times a year, during 8 hours, with 4 teams of 2 persons (131 girders)
- For the CLIC collider study, considering the number of components, the tight tolerances, and expected ground motion, it was decided to perform it remotely using sensors and actuators.

Outlook

Introduction: a few definitions

The different steps of the alignment of colliders

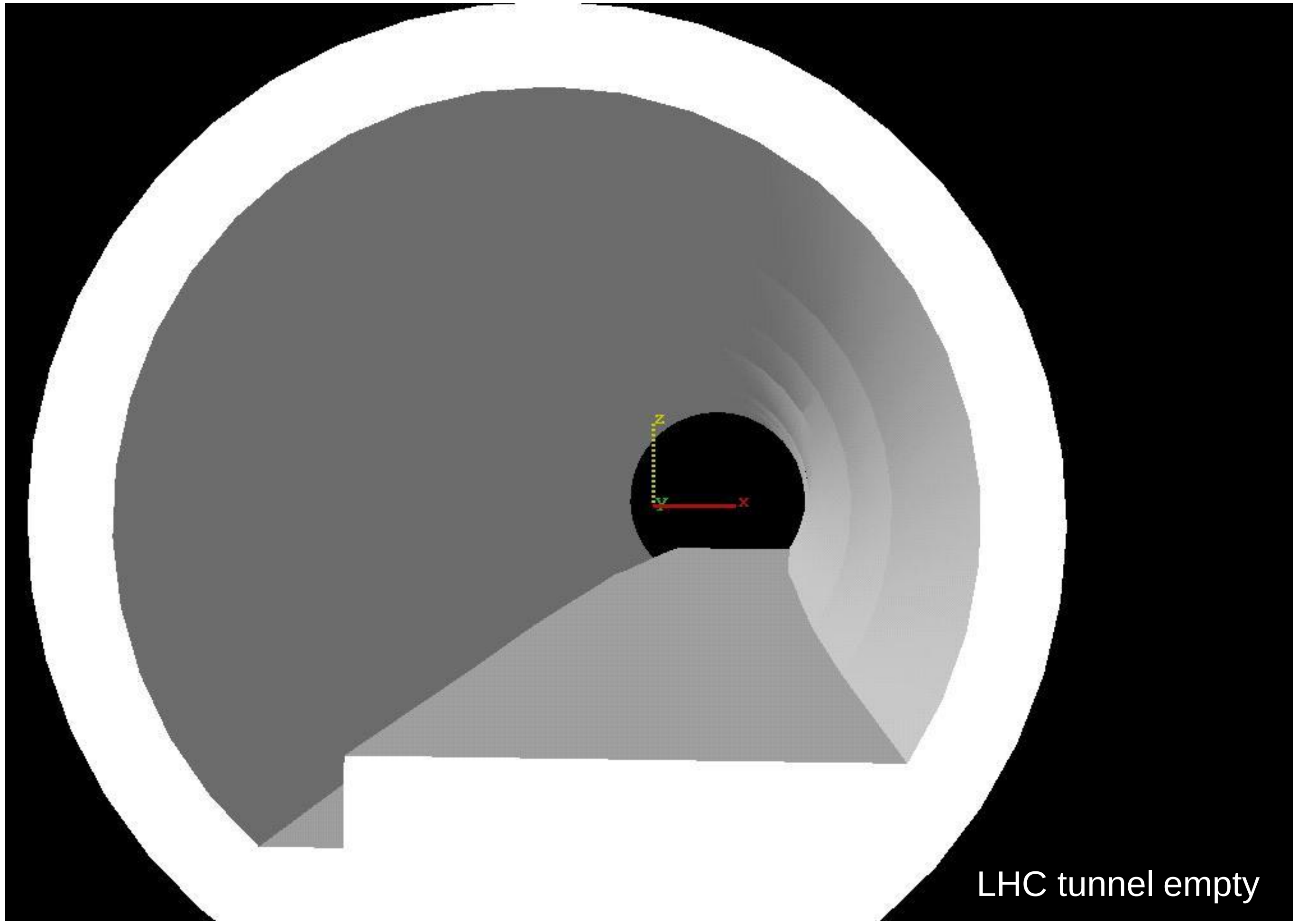
State of the art

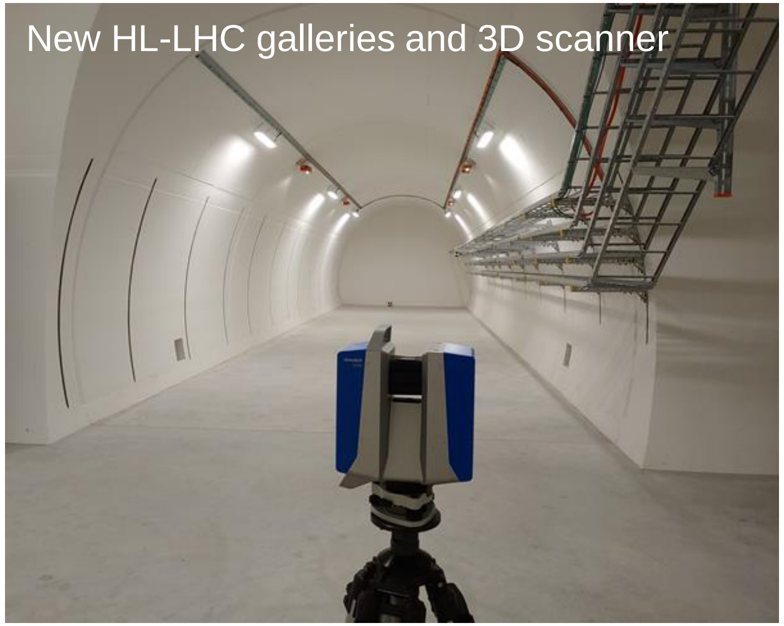
- Case of the LHC
- Case of synchrotrons and other colliders

Towards the alignment of future colliders

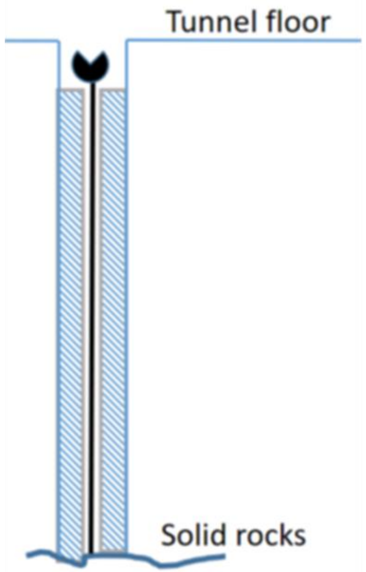
LHC tunnel

LHC tunnel empty



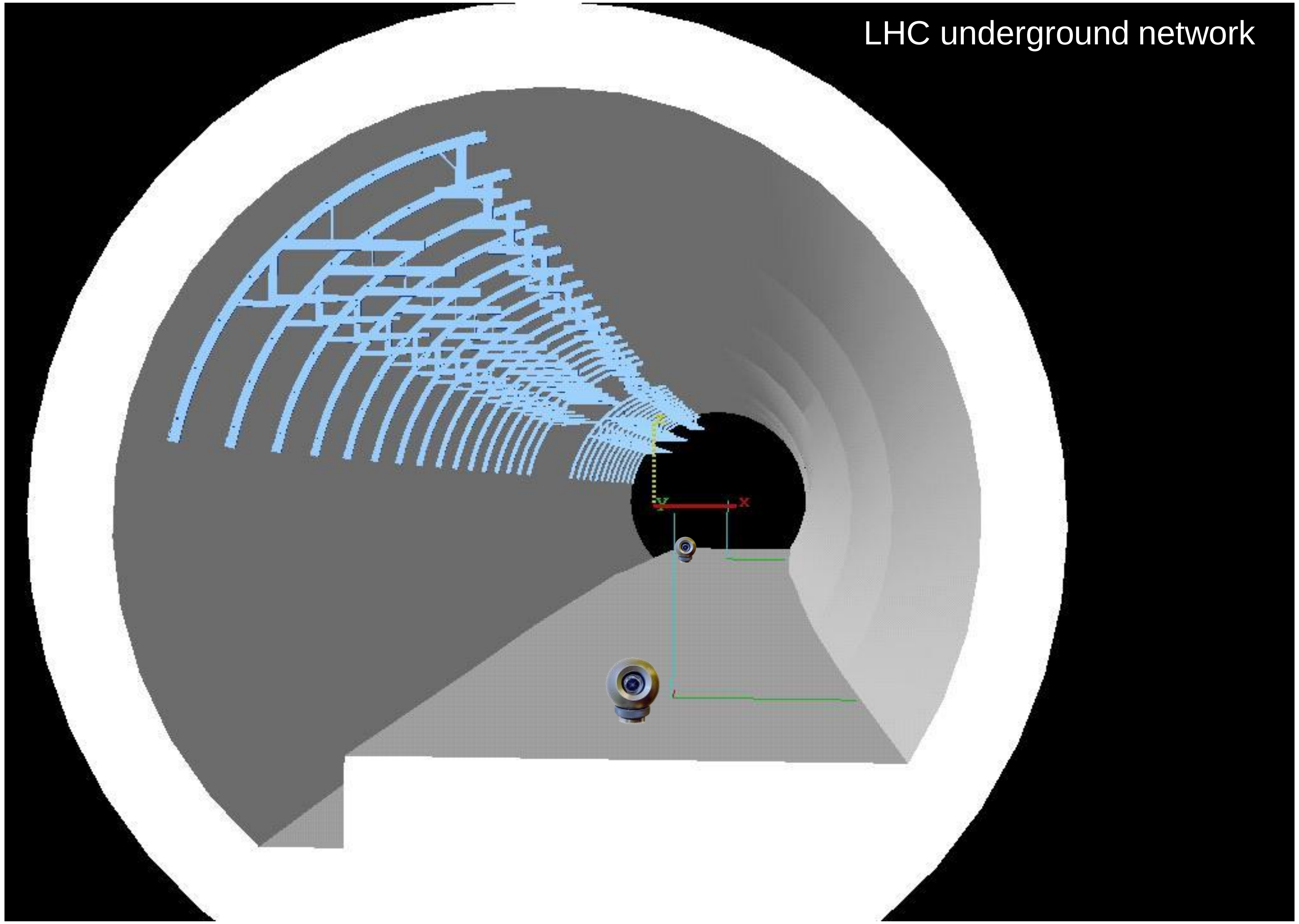


Determination of underground geodetic network



Deep reference concept

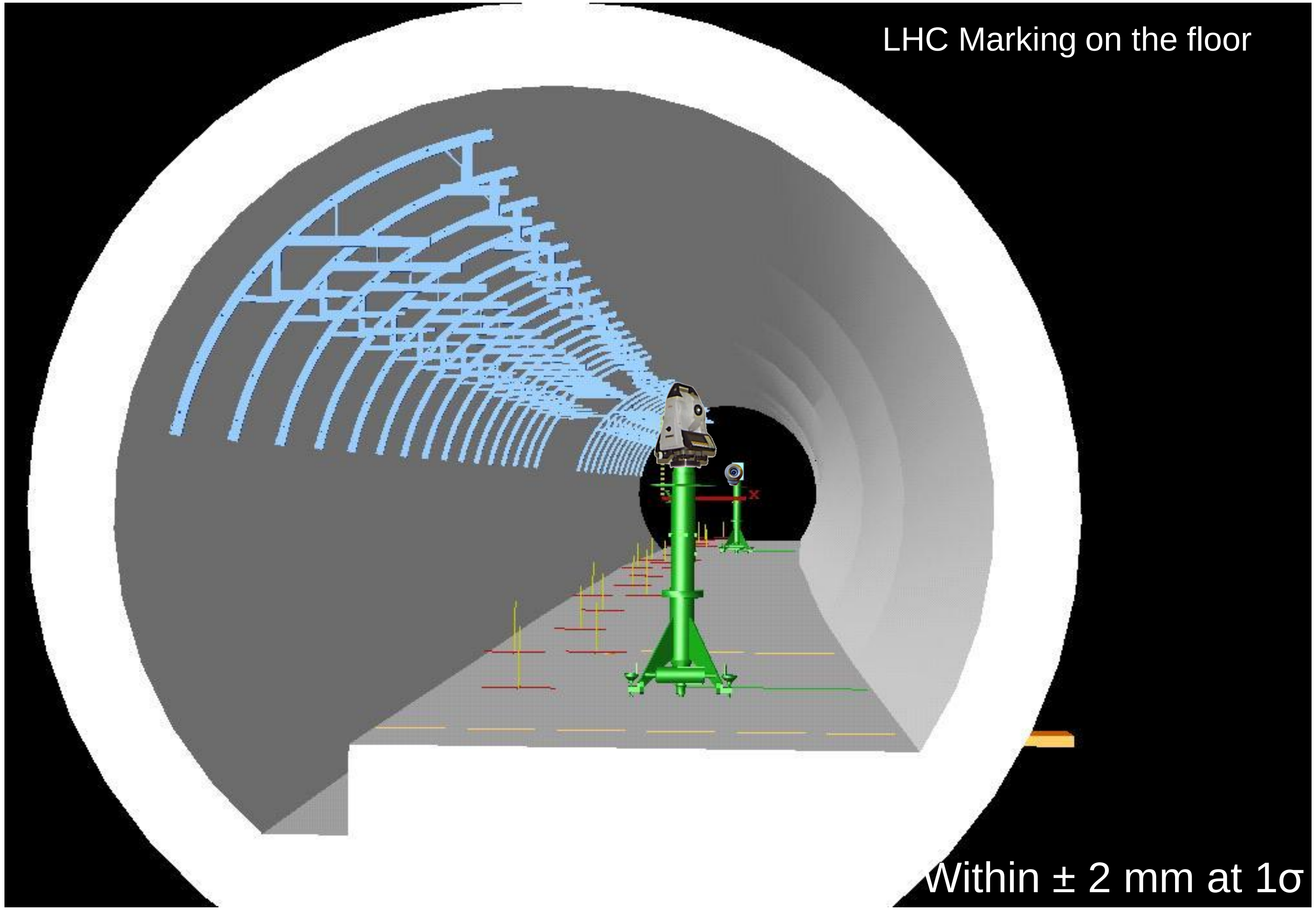

Conical interface of a deep reference

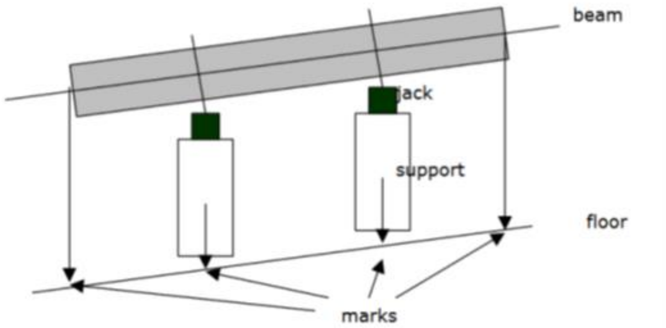



LHC underground geodetic network


Determination of the network

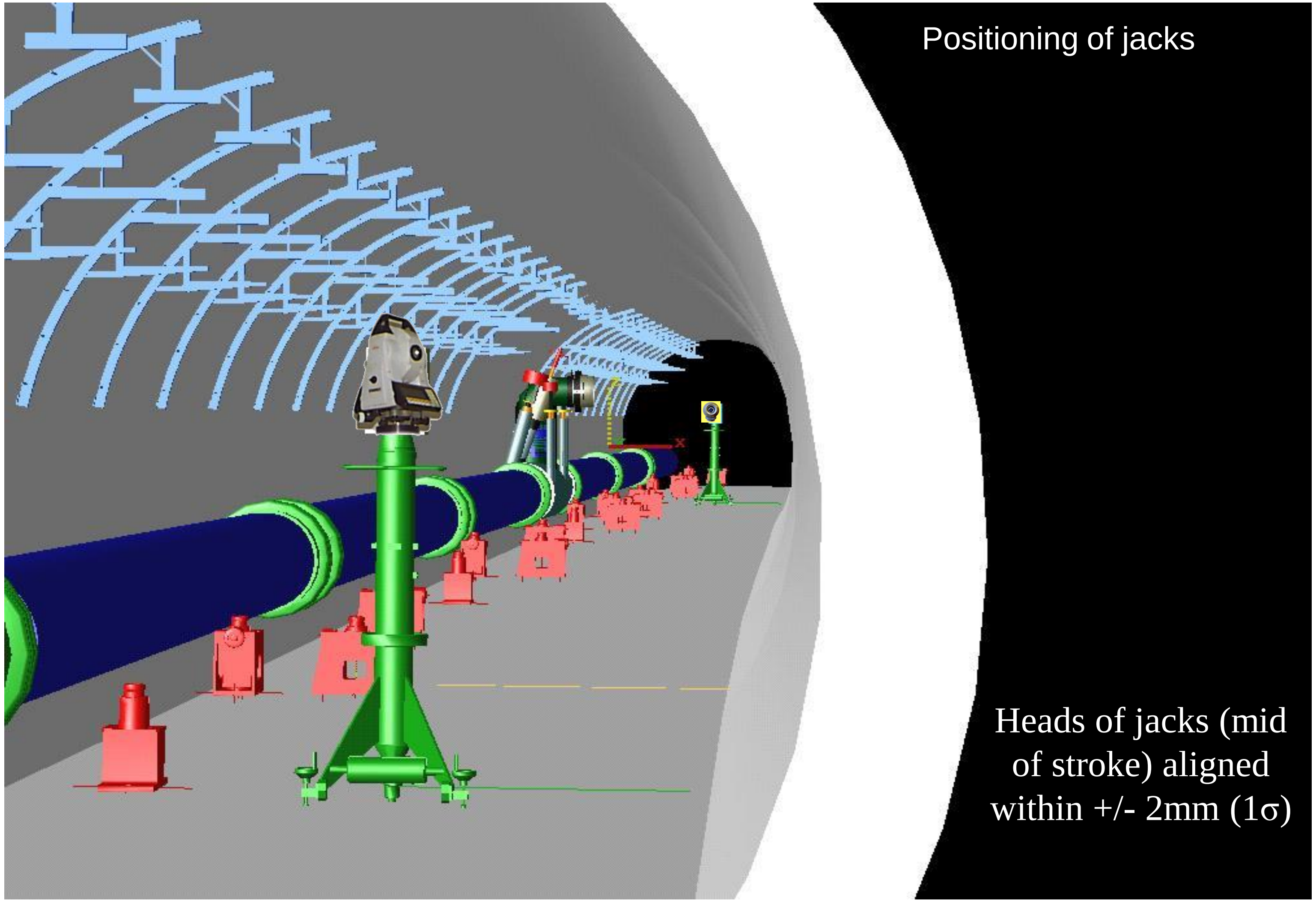
Marking on the floor

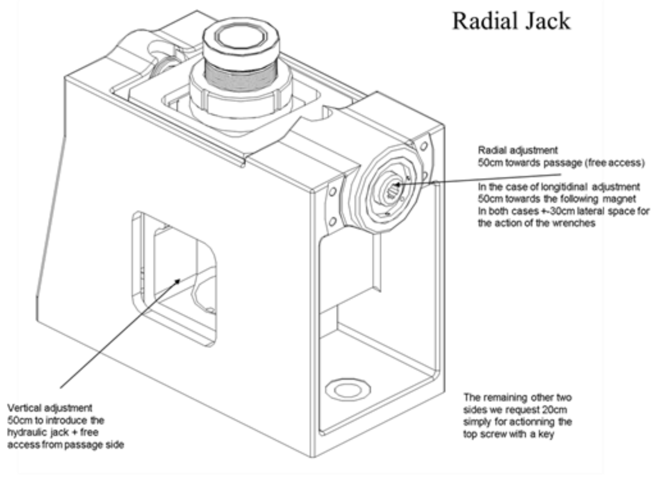




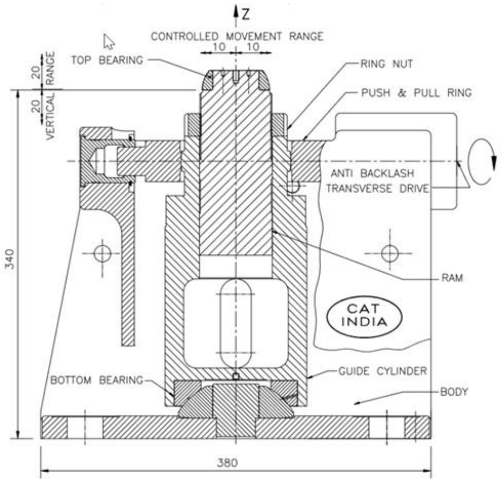
LHC Marking on the floor of the jack heads

Positioning of jacks



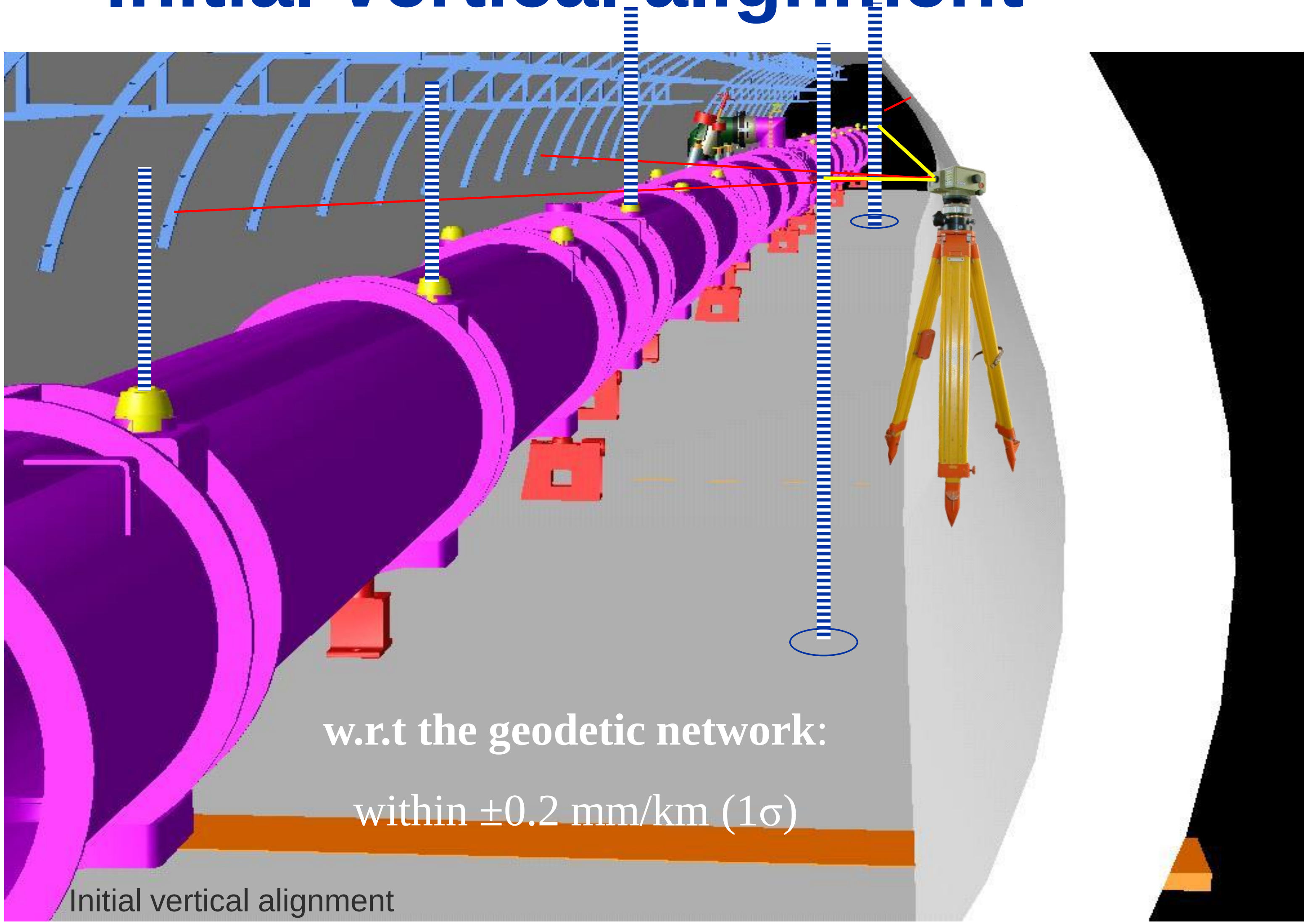


3D view of a LHC jack

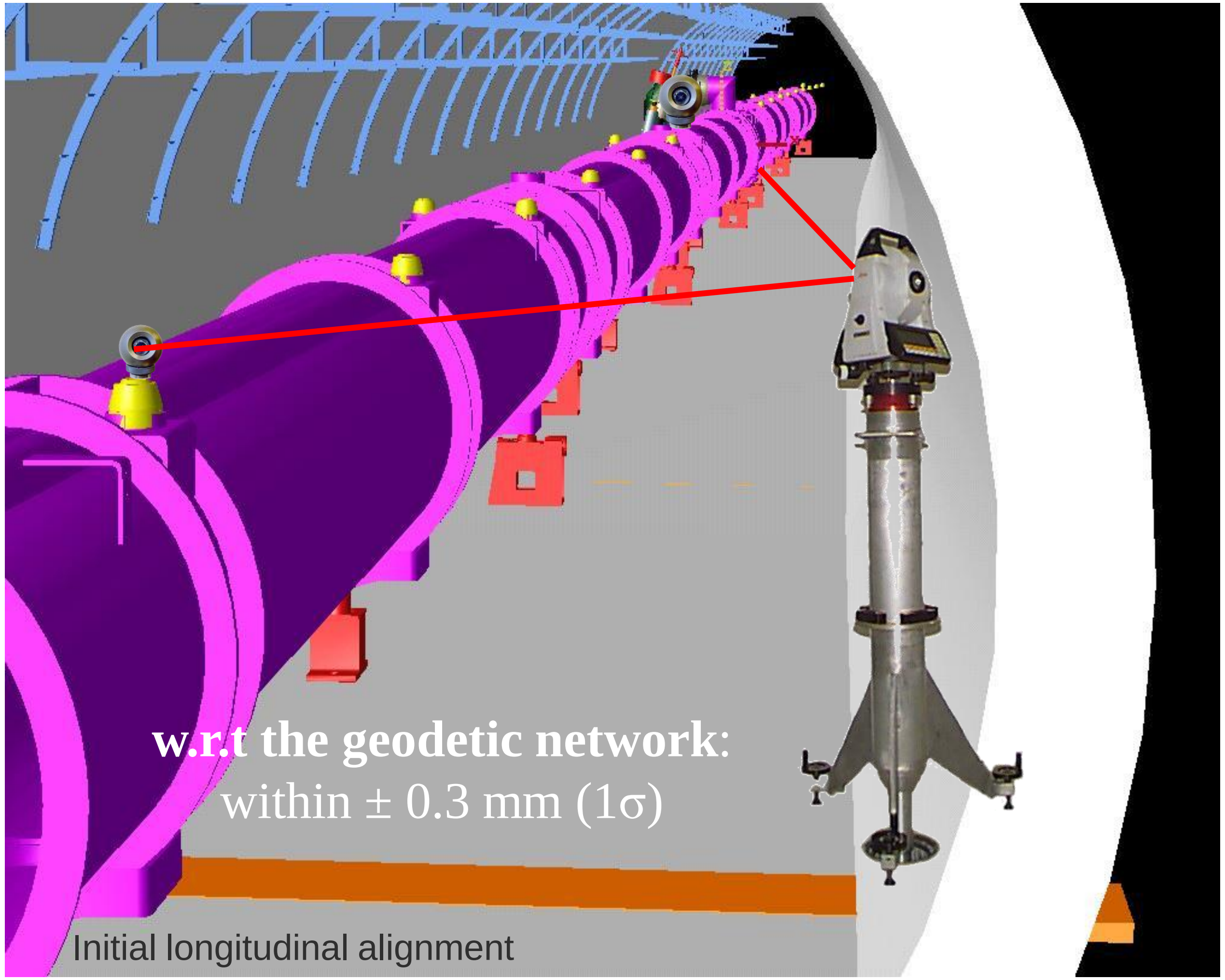


Cross section of a LHC jack

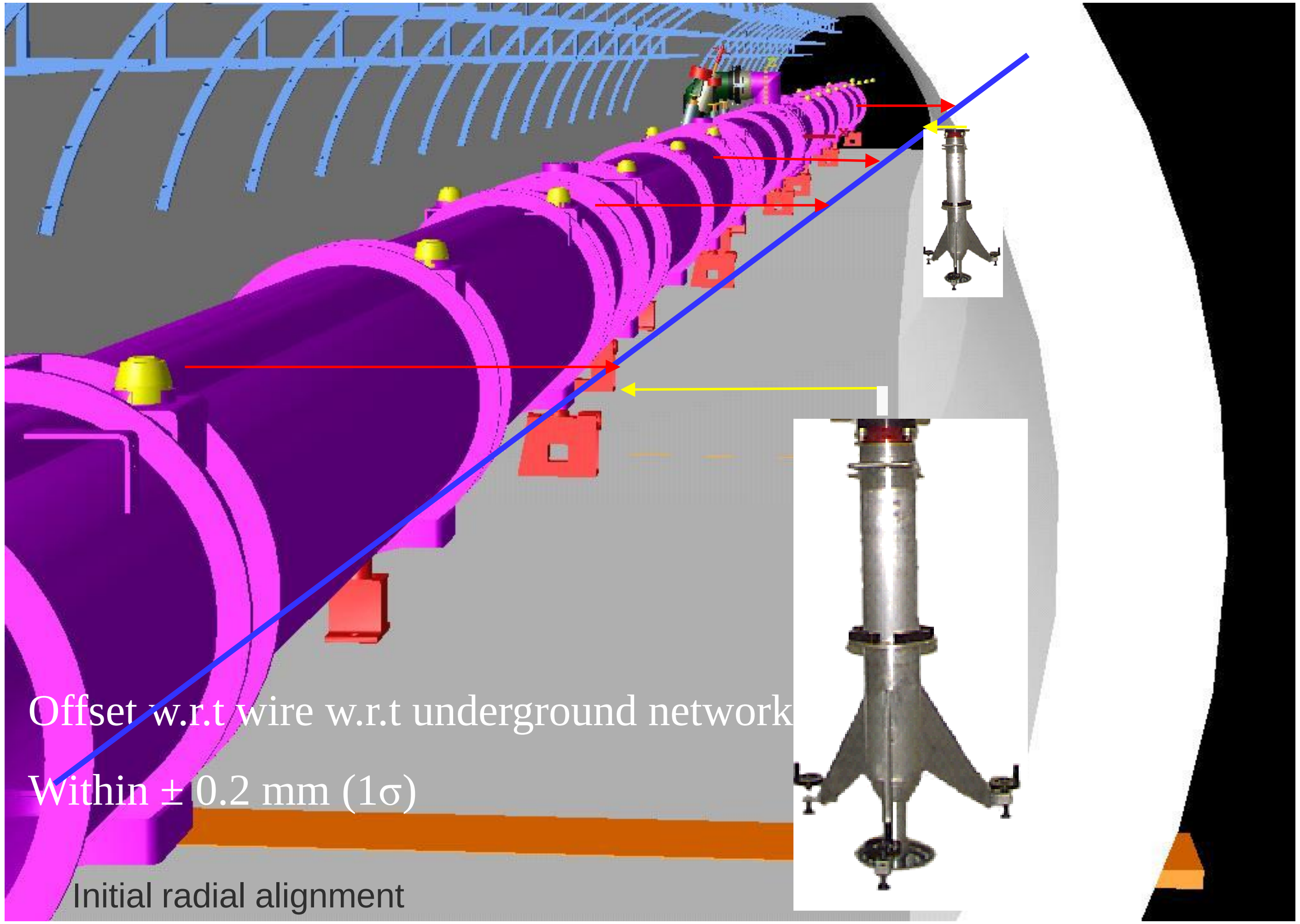
Initial vertical alignment

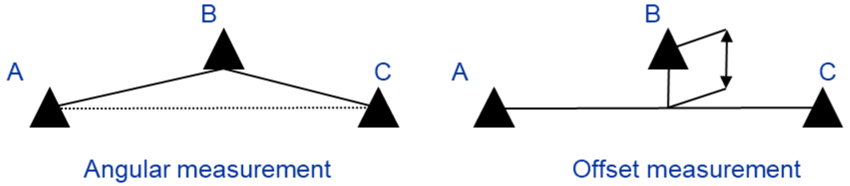


Initial longitudinal alignment



Initial radial alignment

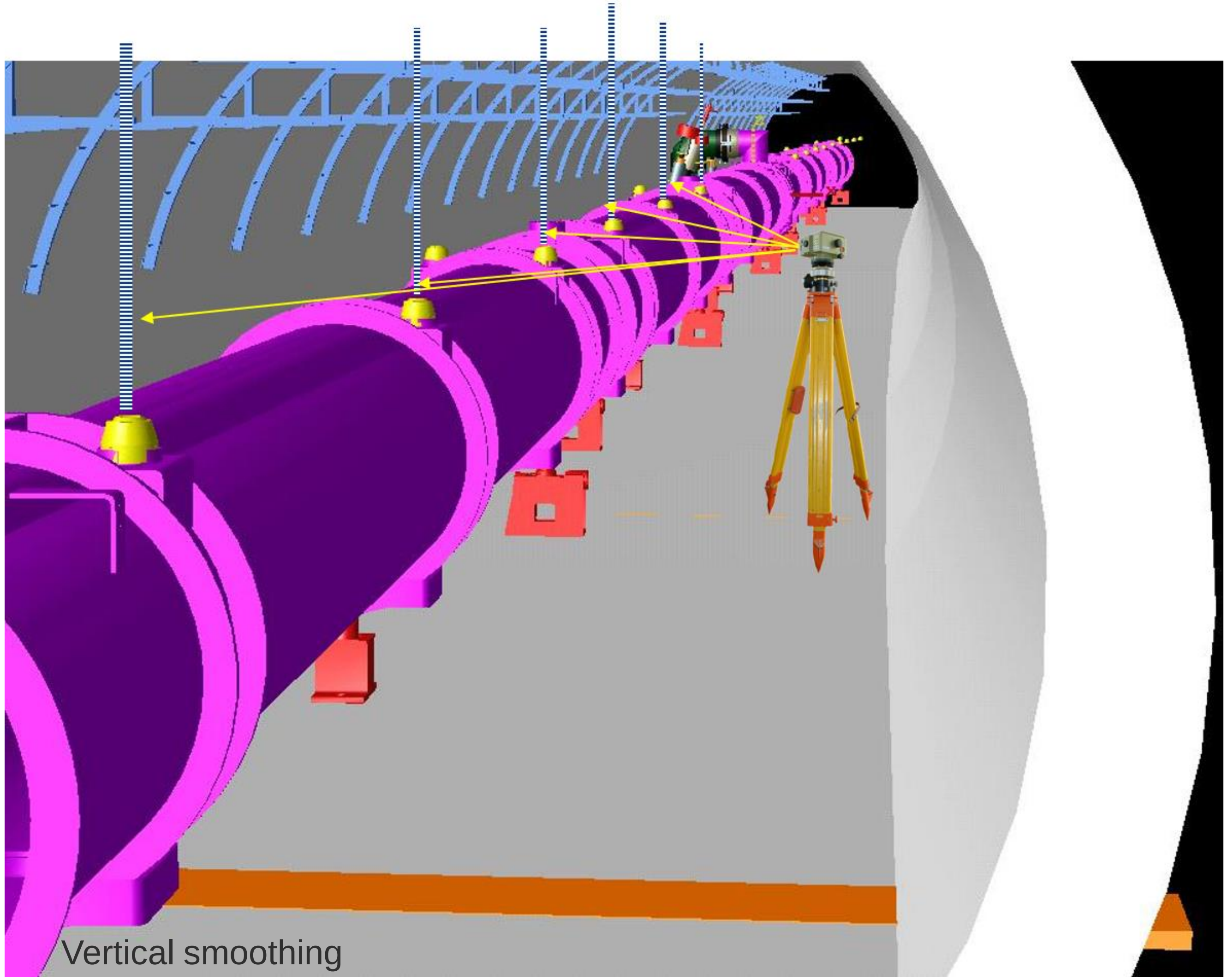


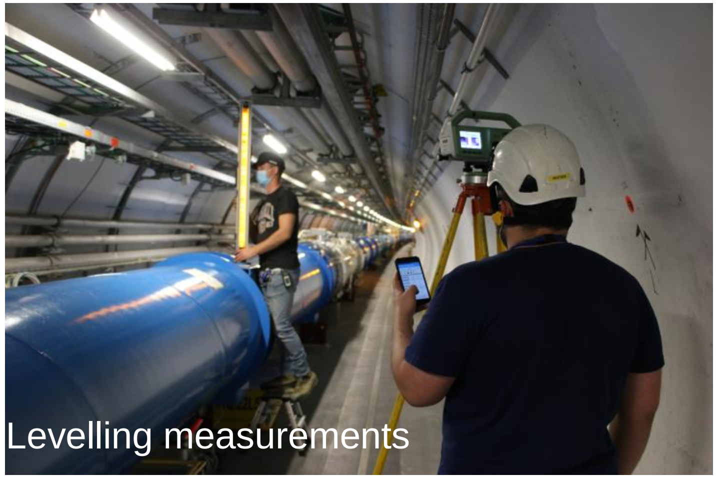


Replacing angular measurement by offset measurement

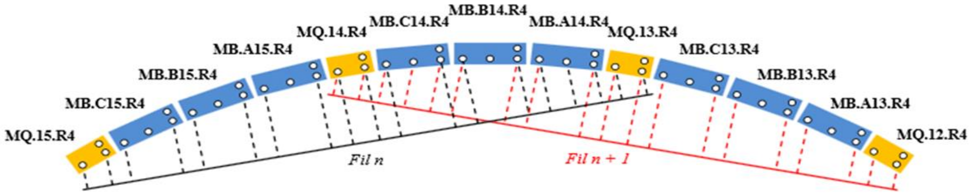
Wire offset measurement = alternative to angle measurements

Vertical smoothing



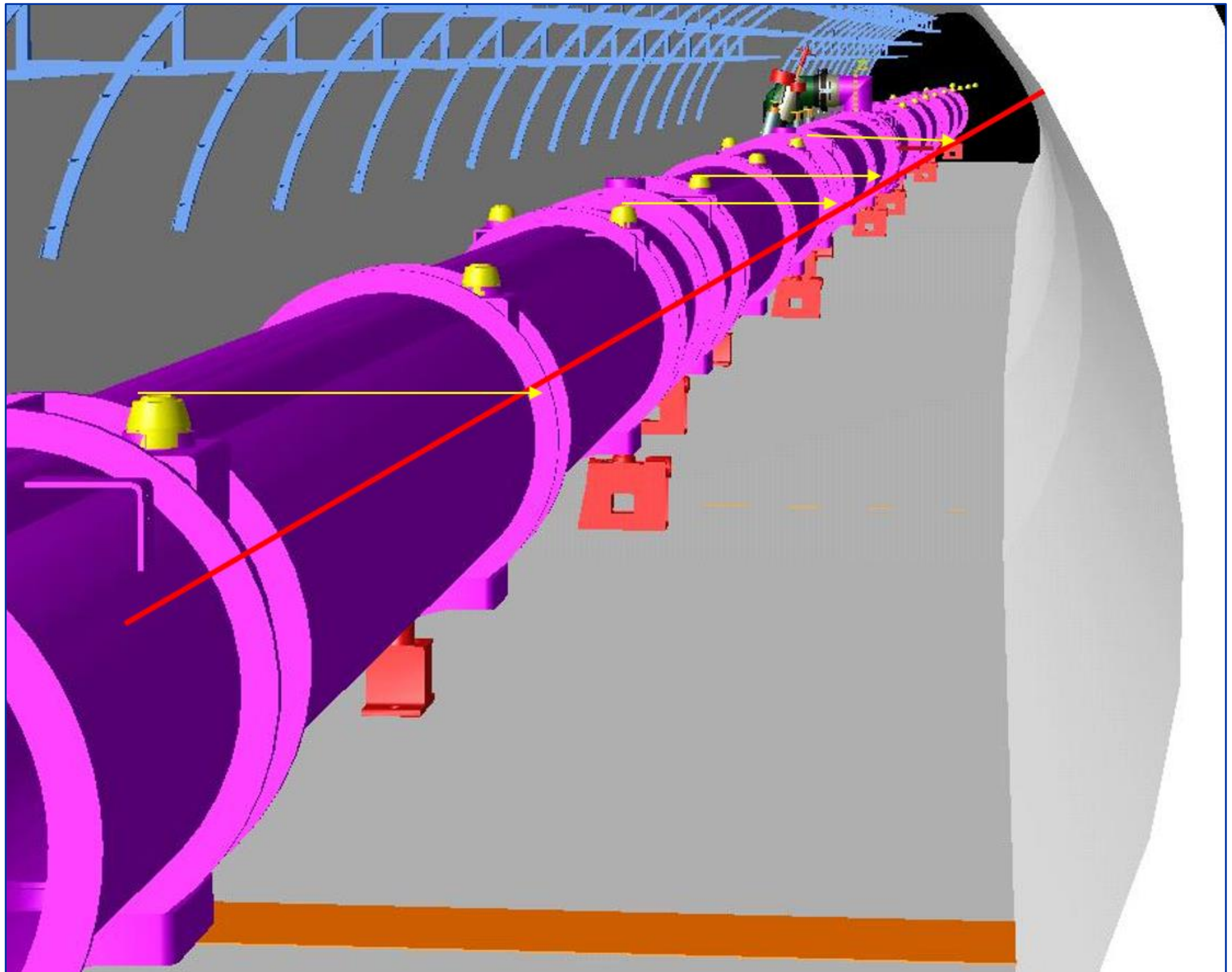


Radial smoothing

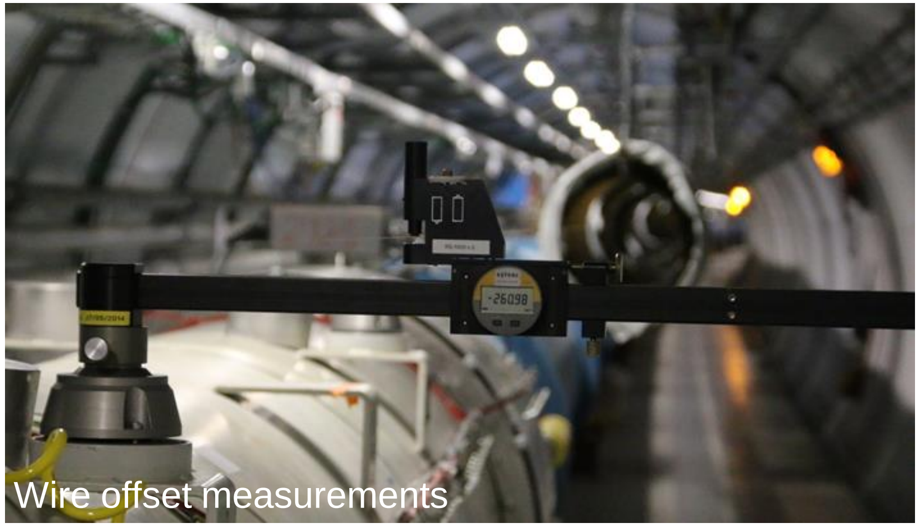


How to use a stretched wire in circular portions

- 120 m wire, redundancy of 2-3 components
- ~ 400 - 500 m/day / team

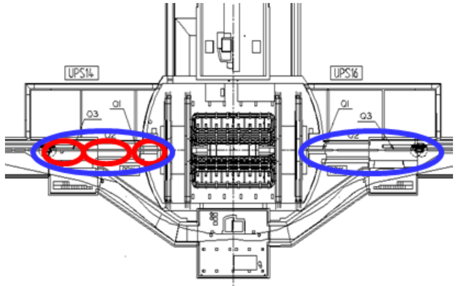


Radial smoothing w.r.t. a stretched wire

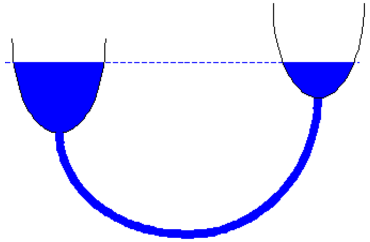


Wire offset measurements

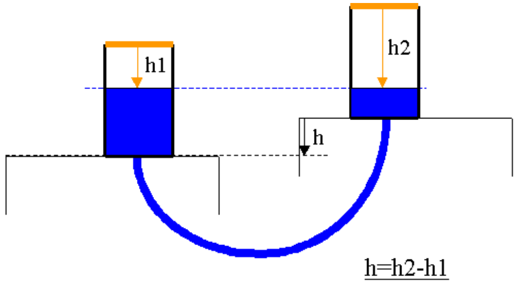
Specific case of LHC low beta triplets



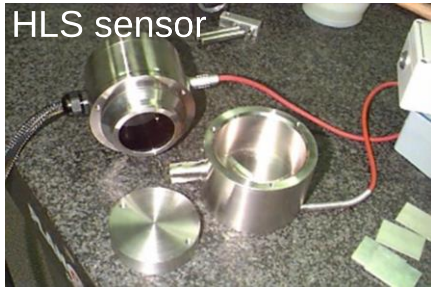
Hydrostatic Levelling Sensors (HLS):



Communicating vessels



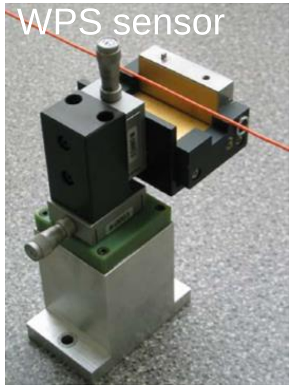
Difference of height measurement

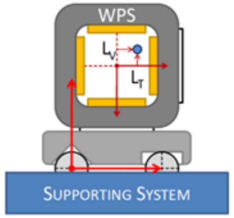


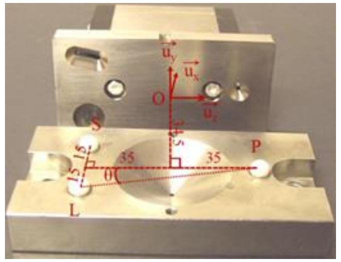
$$C = \frac{\varepsilon_o \varepsilon_r S}{d}$$

- Reference surface = water
- Vertical measurements
- Continuous measurements (1 Hz)
- Repeatability : ± 1 µm
- Accuracy: 5 µm (1σ)
- Range: 5 mm

Wire Positioning Sensors (WPS):

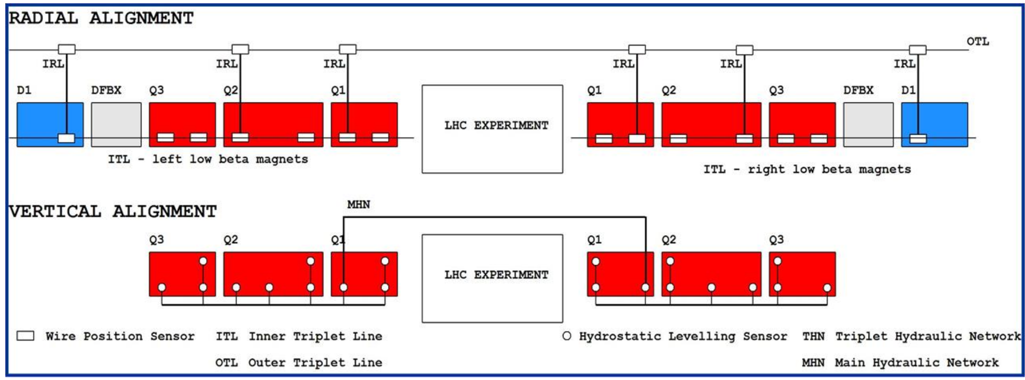




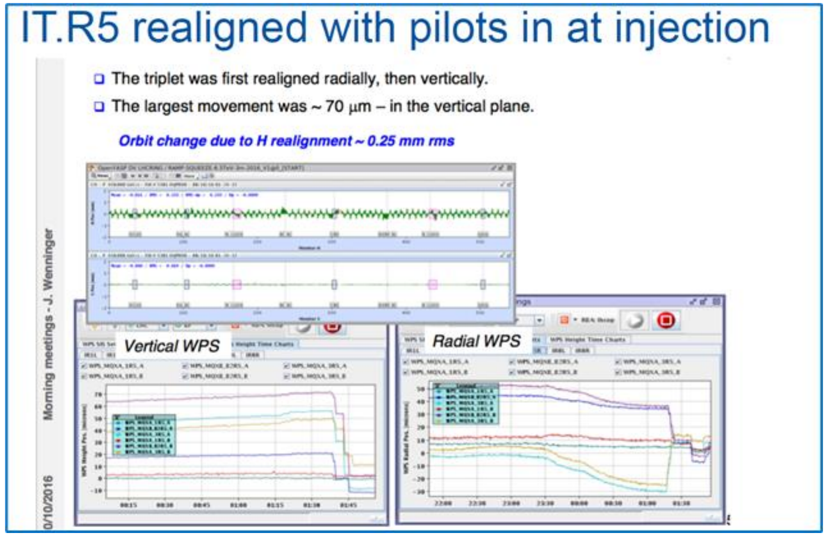


- Reference surface = stretched wire
- Vertical + radial measurements
- Continuous measurements (up to 100 Hz)
- Repeatability : ± 1 µm
- Accuracy: 5 µm (1σ)
- Range: ± 5 mm

Specific case of LHC low beta triplets



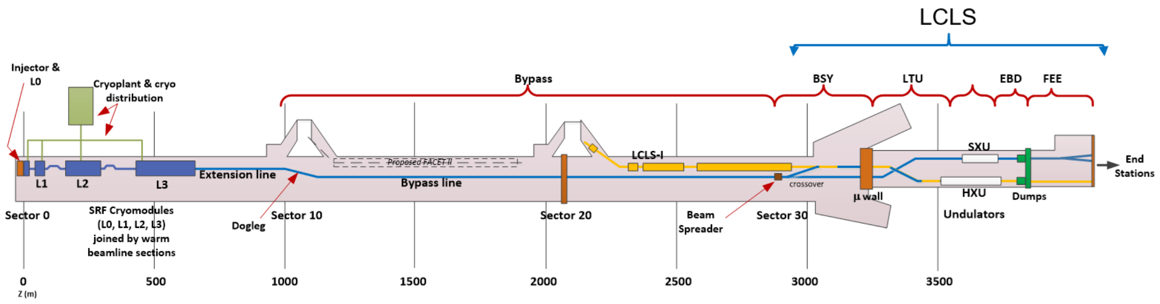
Low beta quadrupoles: alignment sensors configuration



State of the art

In other laboratories : SLAC – alignment tolerances reached at LCLS-I (Georg Gassner)

Step	Alignment tolerances
Fiducialisation (over 4 m)	Within 50 µm
Field alignment: local alignment w.r.t. the network	100 µm
Network: mid range (200m)	0.3 mm
Network: long range (1 km)	2 – 3 mm



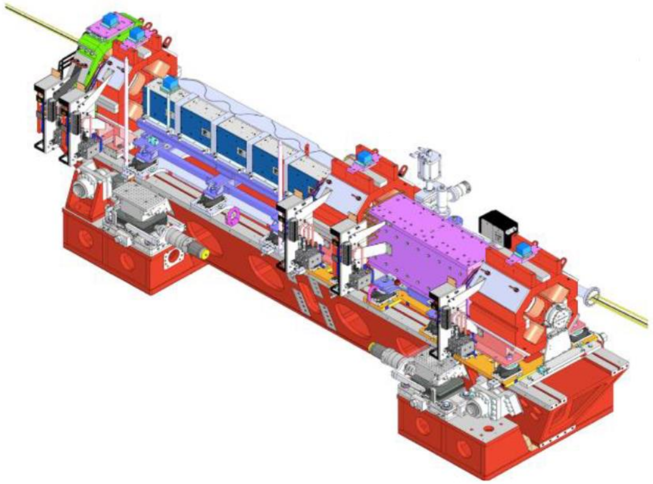
Similar alignment tolerances

State of the art

In synchrotrons – ESRF EBS

A few uncertainties reached (Input from David Martin):

Step	Long. (µm)	Radial (µm)	Vertical (µm)
Fiducialisation		19	34
Alignment	126	30	31
Transport impact		~ 10 µm	
Magnet residuals center w.r.t. a smooth curve		52	30



EBS Girder

Very tight uncertainties achieved for ESRF EBS! Very special care put on ~ **130 girders** during the preparation, installation and alignment of the components.

Outlook

Introduction: a few definitions

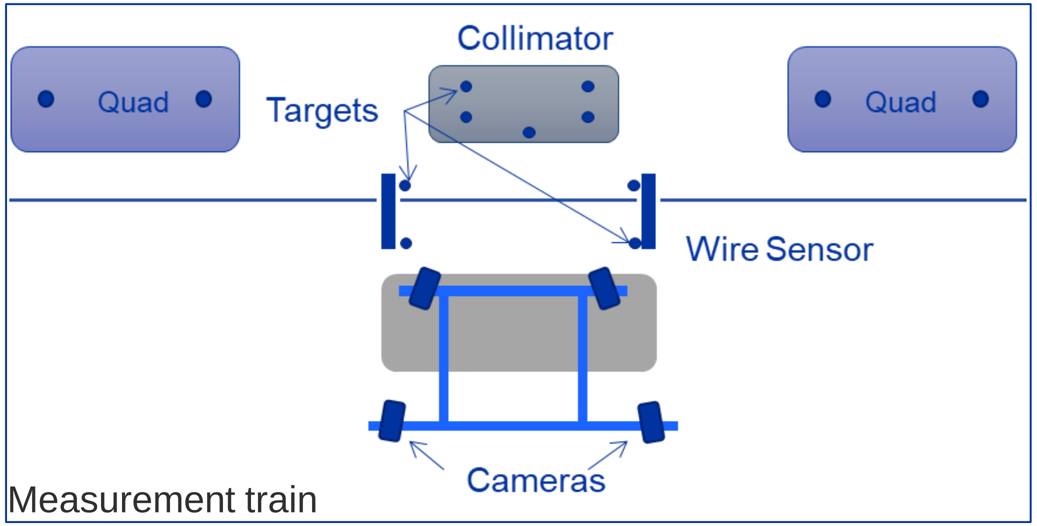
The different steps of the alignment of colliders

State of the art

Towards the alignment of future colliders:

- **Upgrade of measurements in the LHC using a “Survey” Wagon**
- **An intermediate step: HL-LHC**
- **Case of CLIC studies**
- **Proposed directions of R&D for the FCC-ee**

Towards the automated determination of the position of components in the LHC



Motivations:

- **Limit the doses** taken by personnel when components are located in high radioactive area
- **Gain time**; perform measurements when the tunnel is not accessible by personnel, or in the shadow of test activities

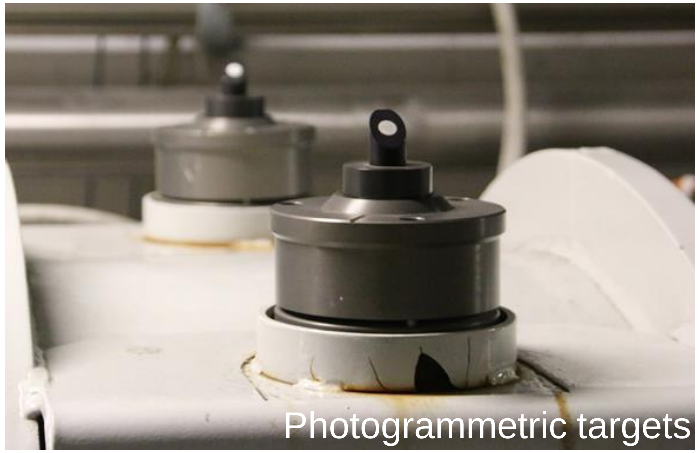
Objectives:

- Control of the component (collimator) position in vertical and horizontal plane, w.r.t. to neighboring components
- Within ± 0.2 mm (1σ)
- Remote operated with non-contact measurements

Solution:

- Stretched wire measurements to limit the propagation of measurement error
- Close range digital photogrammetry
- Suppression of wire sensor by photogrammetry

Towards the automated determination of the position of components in the LHC



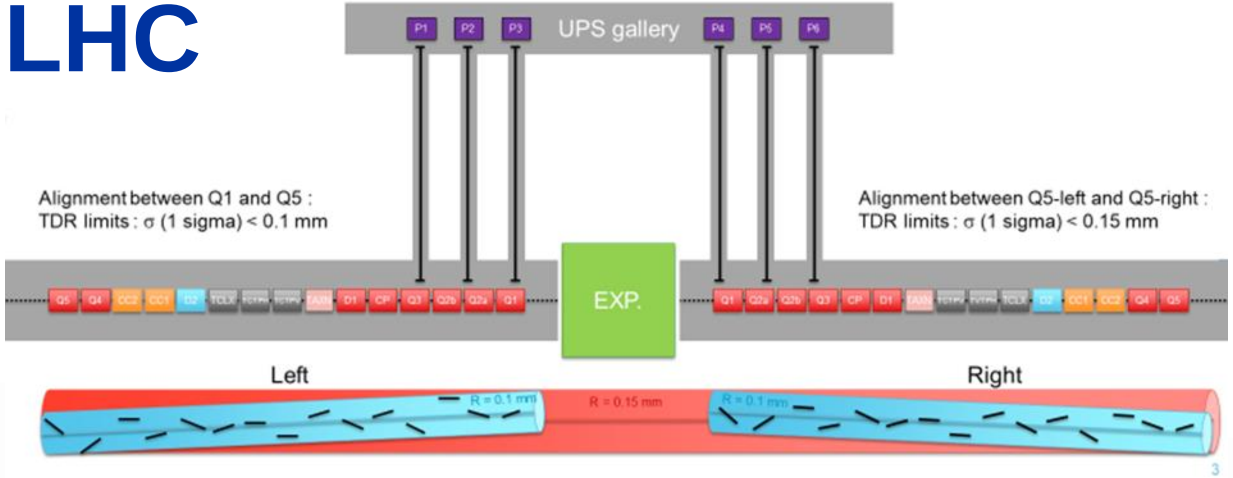
Next steps for the LHC:

- Adapt the solution to the LSS1 and LSS5 of the LHC
- Develop the vertical determination
- Integrate automatic target recognition
- Adapt the solution to the arcs of the LHC

For future colliders:

- Develop measurements methods adaptable on other supports than a Survey Wagon → robots or drones for example
- Develop permanent references in the tunnel, auto-determined, w.r.t. which a relative alignment could be performed
- Replace the stretched wire by another reference of alignment

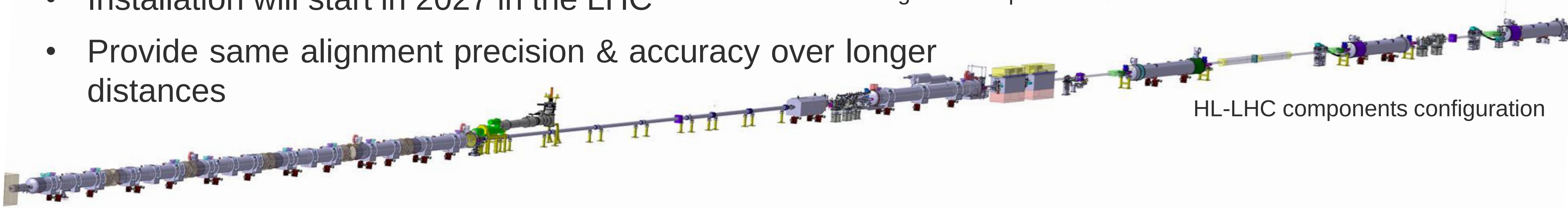
An intermediary step : HL-LHC



HL-LHC alignment requirements

High Luminosity LHC (HL-LHC)

- Major upgrade program for LHC
- 1.2 km of beamline will be exchanged
- Installation will start in 2027 in the LHC
- Provide same alignment precision & accuracy over longer distances

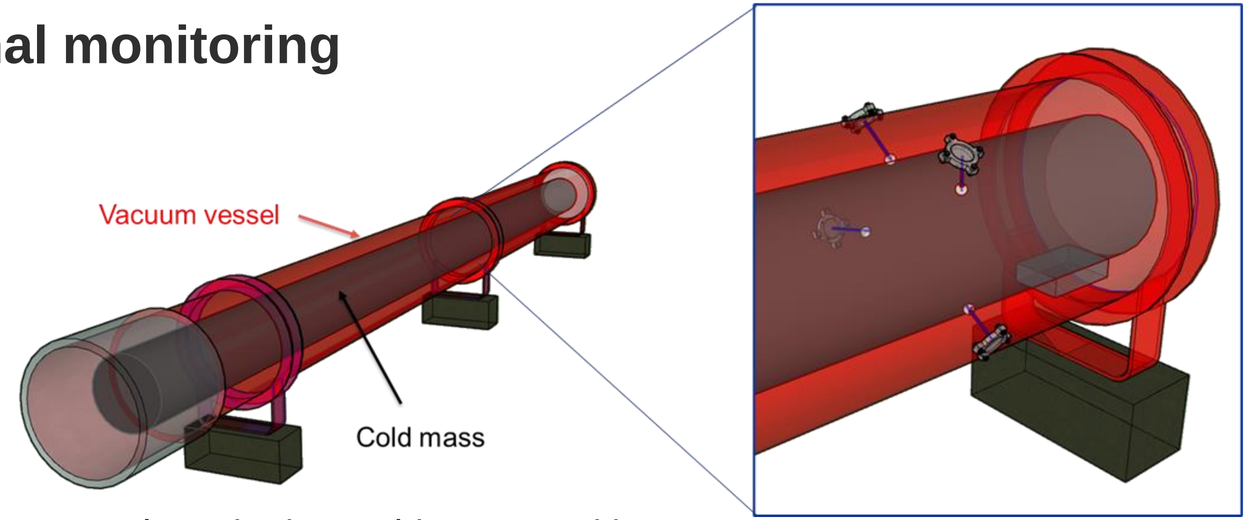

HL-LHC components configuration

Full Remote Alignment System (FRAS):

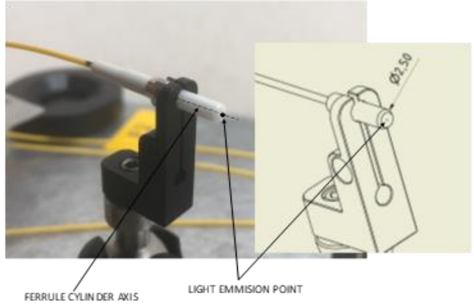
- All components equipped with alignment sensors and supported by motorized adjustment solutions (jacks vs platform) or FRAS compatible
- Remote alignment of ±2.5 mm, to reposition the machine w.r.t. the IP, to correct ground motion.
- Internal monitoring of components inside their cryostat

An Intermediary step: HL-LHC

Internal monitoring



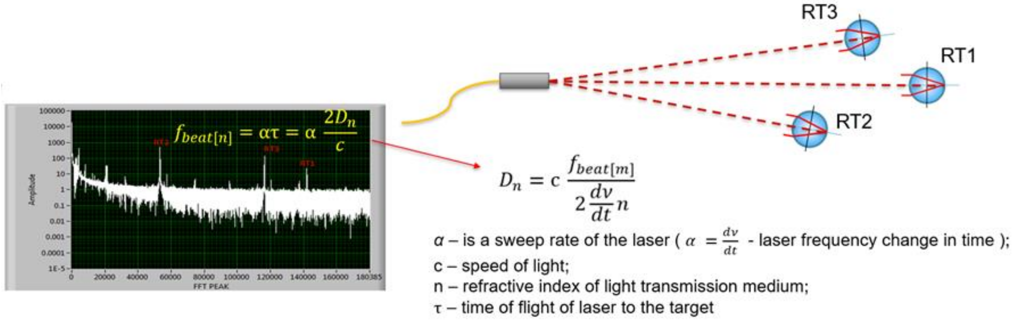
Internal monitoring: cold mass position vs cryostat



Absolute distance measurement between ferrule and glass spheres

Environment :

- Temperature : 1.9 K (Cryogenics conditions)
- Vacuum : 10^{-6} mBar
- Radiation : 1 MGy



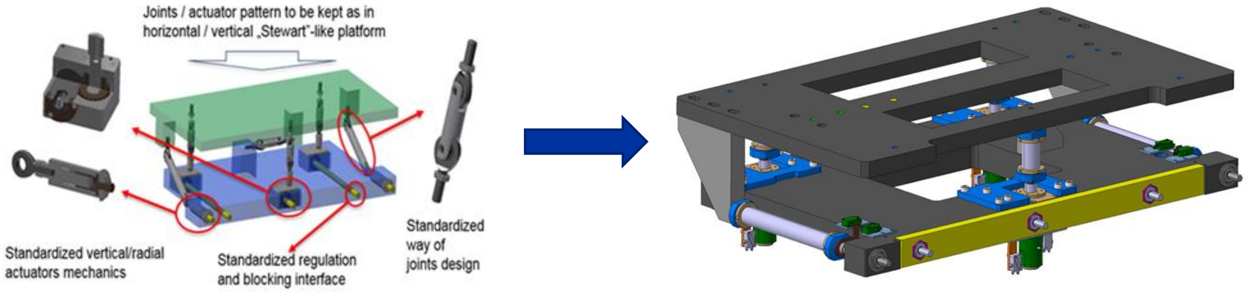
Frequency Sweeping Interferometry principle.

Continuous monitoring of the cold mass position w.r.t. vacuum vessel within an accuracy of 0.1 mm

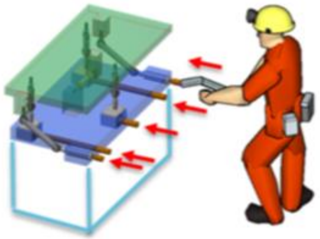
An intermediary step: HL-LHC

Development & qualification of robust adjustment solutions

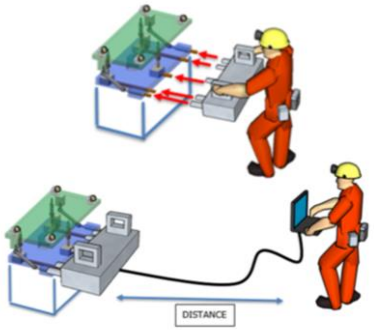
For light components (< 2 tons)



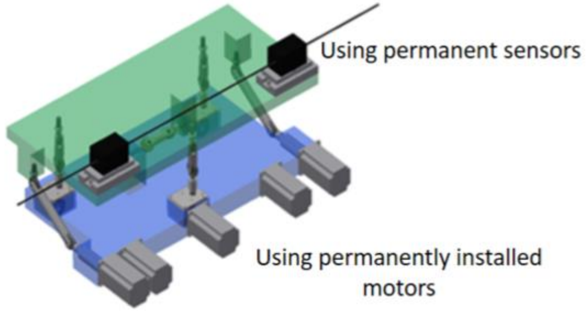
Development of a Universal Alignment Platform



Manual adjustment

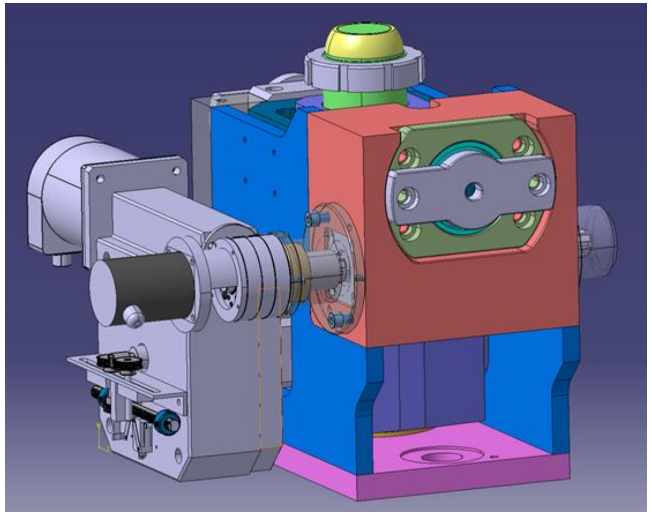


Manual adjustment with plug-in motors



Motorized adjustment

For heavy components (> 2 tons)



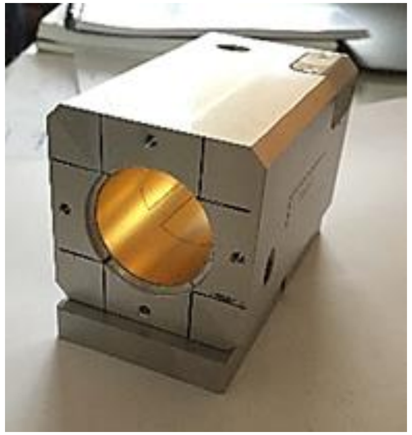
3D view of a HL-LHC motorized jack

An intermediary step: HL-LHC

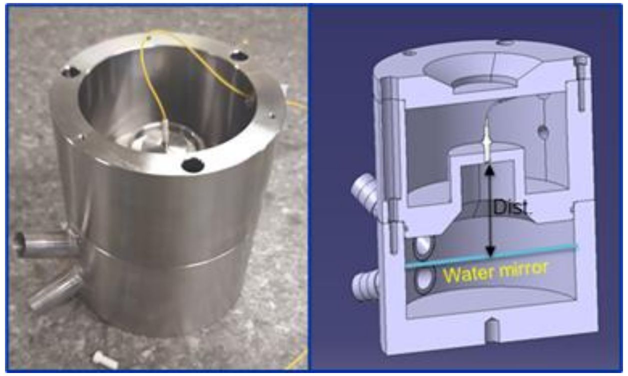
Development & qualification of robust alignment solutions : ALIGNMENT SENSORS:

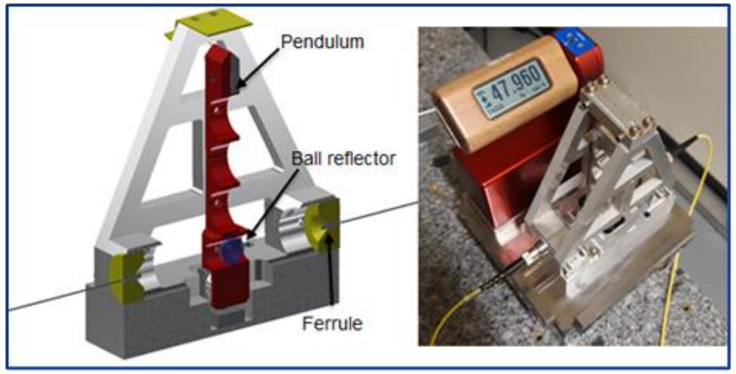
- In-house development (to master the choice of the electronics components)
- To optimize the cost
- To improve the performance (increased length between the sensor and its remote electronics)
- To increase the robustness and radiation hardness

Capacitive based WPS



FSI based HLS and inclinometers sensors





See Mateusz Sosin's lecture tomorrow morning

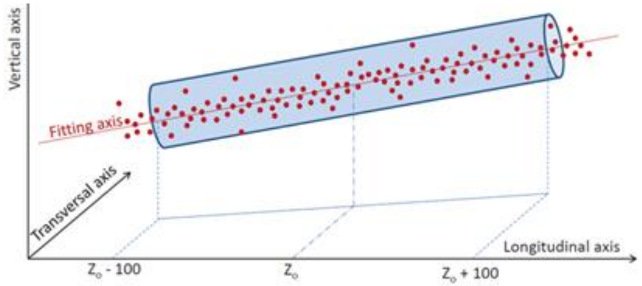
Towards the alignment of future colliders…

A few requirements…

- Up to 20 000 modules (2m length)
- Implementation plan submitted in 2018, with a full strategy of alignment, including PACMAN type fiducialisation.

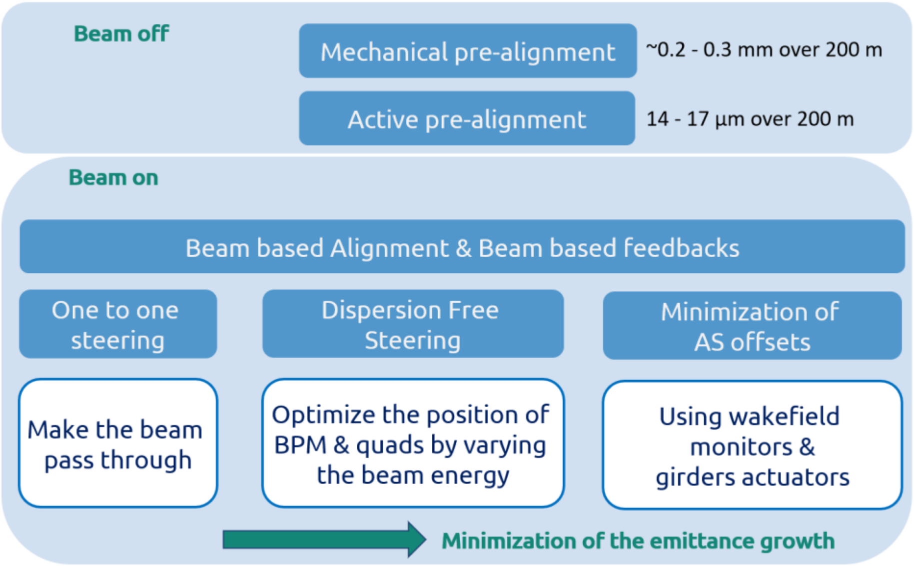
Along Main Linac: over sliding windows of 200 m:

Component type	AS	BPM	MB Quad	DB quad
Radius (µm)	14	14	17	20
	~ 140000	~ 4000	~ 4000	~ 40000



CLIC active pre-alignment tolerance

At the level of the reference axis (including fiducialisation)



CLIC alignment strategy

CLIC: status of R&D studies

- Very tight tolerances requiring an active pre-alignment of the CLIC components

- Active pre-alignment means continuous determination of the position of components using alignment sensors, and their remote adjustment (when outside the tolerances) using actuators.

- A **complete strategy** has been proposed and qualified on dedicated mock-ups:
  - To implement all along the tunnel a **permanent long range geodetic network** made of overlapping stretched wires and WPS sensors to limit the error propagation and provide a straight alignment reference between pits.
  - Simplify the challenge of active alignment by **pre-aligning several components on a girder** and aligning the girder.
  - **Alignment sensors and actuators associated with each girder** to perform their remote alignment in the tunnel with respect to the straight alignment reference.

Automated fiducialisation «PACMAN type»

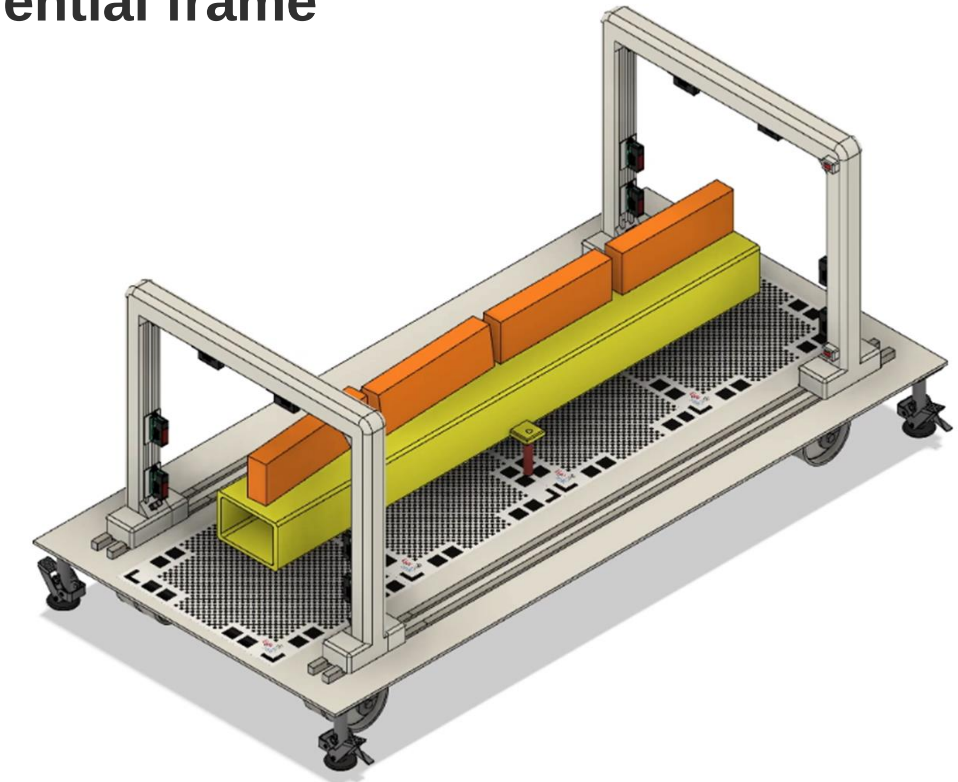
Concept

- New solution to perform a **more flexible and accurate fiducialisation** («**PACMAN**»)

- To relax mechanical tolerances
- To keep the possibility to re-align the components after transport in the tunnel
- More info: PACMAN

Automated fiducialisation «PACMAN type»

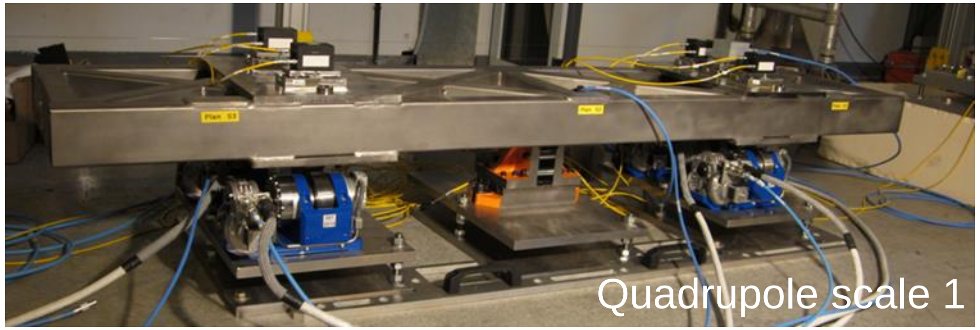
Automated alignment of components in the girder referential frame



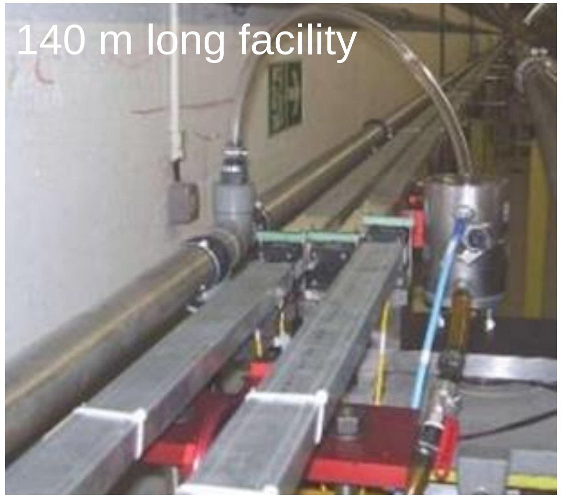
Proposal from students (euspen challenge)

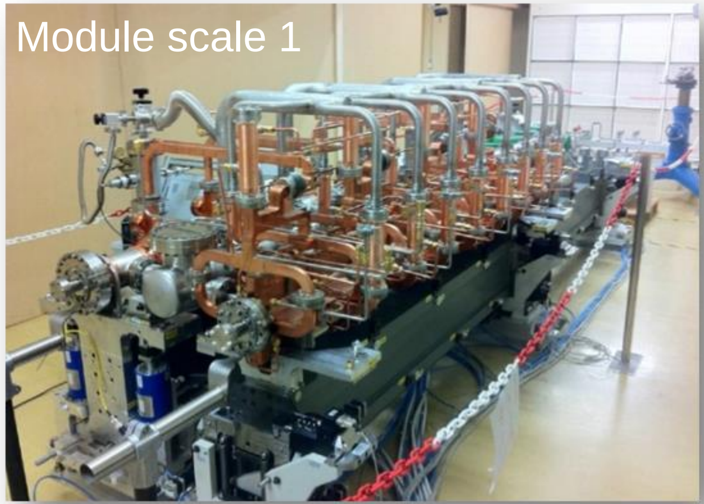
- Will be needed for all future colliders
- Different fiducialisation solutions to develop for components (sextupoles, BPM, quadrupoles)
- Process to be fully automated at 20°C
- To be studied: impact of temperature, transport, etc.
- Integrate 3D reconstruction and digital twin for each girder, historic data documentation
- Develop methods to perform in-situ controls in the tunnel

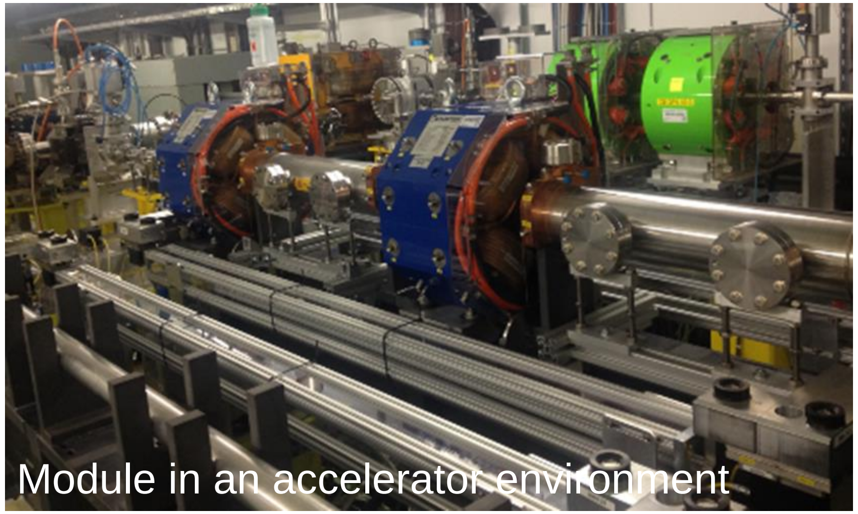
CLIC: status of R&D studies



Strategy validated on different mock-ups:







Simulations on the long range/short range solution **confirmed experimentally** at a micrometric level

Quadrupole positioned within 1 µm (radial/vertical and 5 µrad (roll)

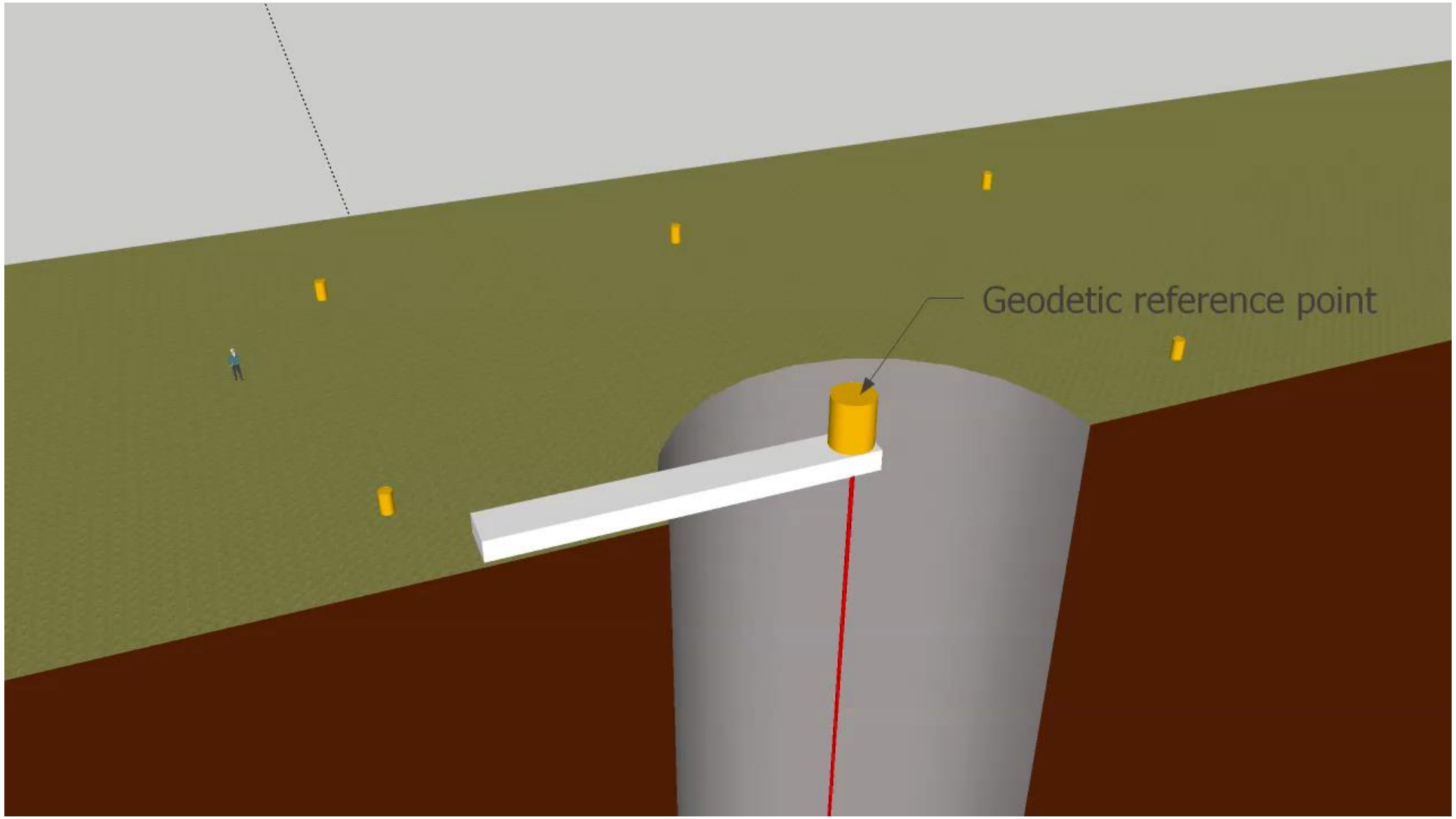
Solutions **qualified in a real accelerator environment** (CLEX)

But only at 20°C

Cost optimization needed!

A lot of lessons learnt ; the developed solutions are now applied for the alignment of HL-LHC

CLIC: status of R&D studies



Towards the alignment of future colliders…

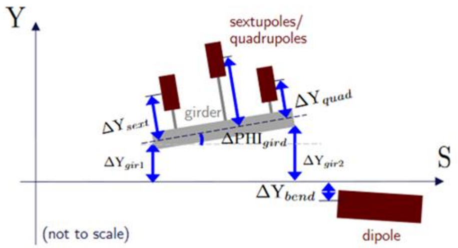
FCC

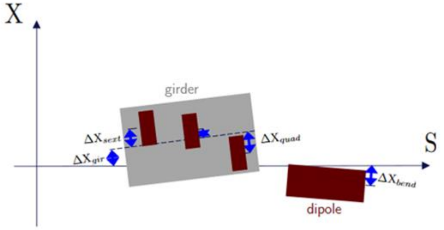
A few requirements (from Tessa Charles)

Type	ΔX (μm)	ΔY (μm)	ΔPSI (μrad)	ΔS (μm)	ΔTHETA (μrad)	ΔPHI (μrad)	Field Errors
Arc quadrupole*	50	50	300	150	100	100	$\Delta k/k = 2 \times 10^{-4}$
Arc sextupoles*	50	50	300	150	100	100	$\Delta k/k = 2 \times 10^{-4}$
Dipoles	1000	1000	300	1000	-	-	$\Delta B/B = 1 \times 10^{-4}$
Girders	150	150	-	1000	-	-	
IR quadrupole	100	100	250	50	100	100	$\Delta k/k = 2 \times 10^{-4}$
IR sextupoles	100	100	250	50	100	100	$\Delta k/k = 2 \times 10^{-4}$
BPM**	-	-	100	-	-	-	-

* misalignment relative to girder placement
** misalignment relative to quadrupole placement

Misalignments are randomly distributed via a Gaussian distribution, truncated at 2.5 sigma.





A few comments:

- **Standard methods** from the LHC **too long and fastidious** as there will be a far higher number of components, in a brand-new tunnel, with an unknown ground motion
- **Temperature gradients** might have a great impact on the alignment
- The methods developed for CLIC (linear) can't be applied integrated for the FCC (circular)

Towards the alignment of future colliders

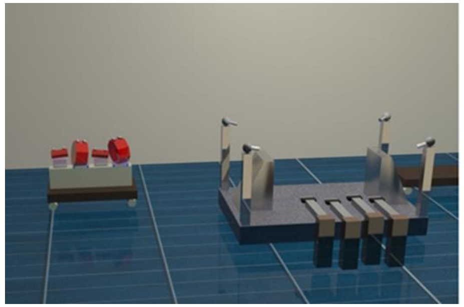
Same trends of requirements:

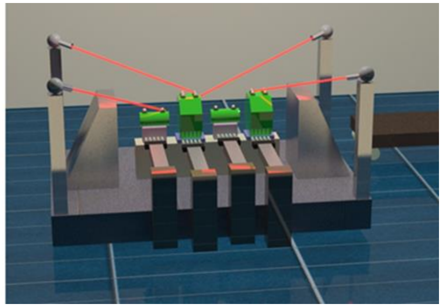
- More accurate
- Less costly
- Robust, low (even no) maintenance, radiation hard
- Simplification by aligning several components on a girder
- **Automation of all steps of alignment needed**: marking on the floor, jacks positioning, initial alignment
- **To gain time in the maintenance**, **to limit the doses taken by the personnel**: Full remote alignment using alignment sensors and actuators // automation of the alignment

Focus on fiducialisation and smoothing steps in the tunnel, as geodetic networks covered yesterday.

HL-LHC will demonstrate the Full Remote Alignment System (FRAS), which will have to be extrapolated to a low cost version for circular colliders.

Towards fiducialisation solutions





Fiducialisation process:

- Key step: **tolerances of synchrotrons, but not for the same number of components!**
- Will consist of the **fiducialisation** of all components + **pre-alignment on a common girder**.
- **Different strategies to be studied**:
  - «Mechanically focused»
  - PACMAN: with mechanical tolerances relaxed
- The process will have to be **fully automated, at 20°C**.
- To be studied: **impact of transport**, **impact of temperature** on components alignment, etc.
- We need a **digitalization strategy** (from 3D scans) integrating:
  - **Data2Cloud** for the remote visualization of the girder assemblies with a historic data documentation
  - **Digital twin** for the online anomaly detection and simulation (impact of temperature, etc.)

Towards smoothing /relative alignment solutions

Two directions of study for the smoothing process:

- **Develop and automate new measurement methods to decrease the duration of interventions, installed on specific wagon or robots**
  - Performing local measurements w.r.t. alignment references to limit the propagation error.
  - The alignment references could be permanently installed or displaced with a train or robot (reproducing the smoothing conditions)
  - Develop low-cost universal targets detectable and measurable by different types of measurements

- **Develop specific alignment sensors (rad-hard, with limited cables (preferably using optical fibers), low-cost and robust, less invasive as possible from the integration point of view)**
  - FSI-based alignment sensors: «chained configuration» - 1 optical fibers for several sensors, compatible with a high level of radiations
  - Structure Laser Beam: use its specific properties for alignment.

Summary

The alignment of current colliders is performed using a combination of **high-accuracy instrumentation** and **specifically developed methods and instrumentation** (radial offset measurement w.r.t. a stretched wire, alignment sensors & motorized jacks for very specific area).

Thanks to the R&D studies carried out on the **CLIC studies**, **new solutions** have been **proposed and validated** for the initial alignment of components on girders and their fiducialisation, and their micrometric alignment in the tunnel.

The developed alignment sensors and adjustment solutions proposed are now being adapted to the Full Remote Alignment System (FRAS) implemented for the alignment of HL-LHC components in LSS1 and LSS5.

Future colliders (and even the LHC) will require **automated methods of alignment**, **combined with the development of low-cost sensors and adjustment solutions**. New solutions will have to be studied, developed and qualified for circular colliders.

The next lecture, given by J-C. Gayde and M. Sosin will introduce two promising technologies (and their applications) based on **Frequency Sweeping Interferometry** and **Structured Laser Beam**.

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