The CERN Accelerator School

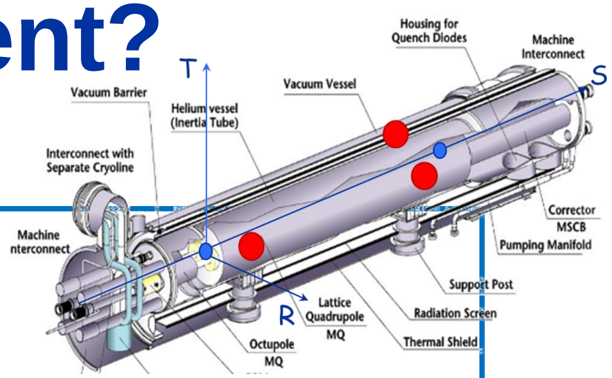
Mechanical & Materials Engineeri
for Particle Accelerators and Detecto

Alignment and Metrology for Particle Accelerators and Detectors

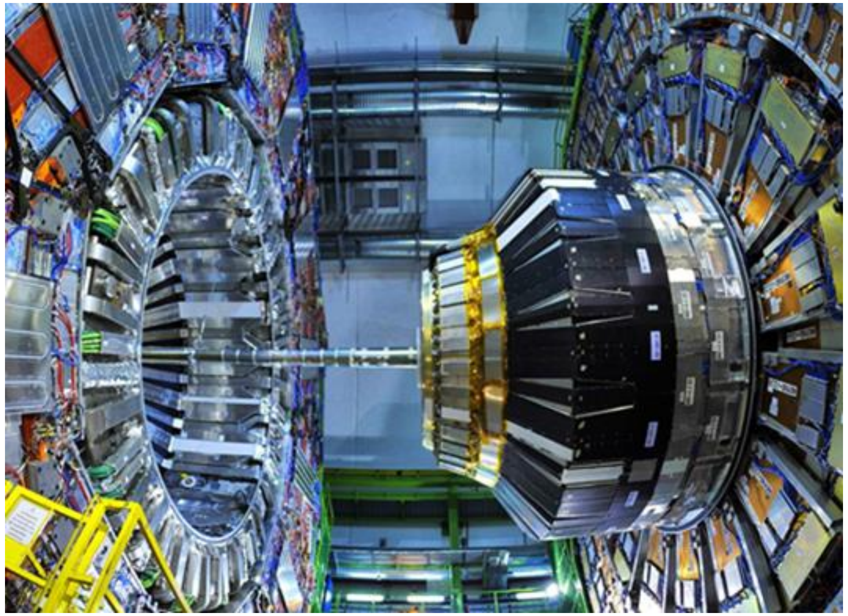
Hélène Mainaud Durand

14 June 2024

Why do we need high precision alignment?

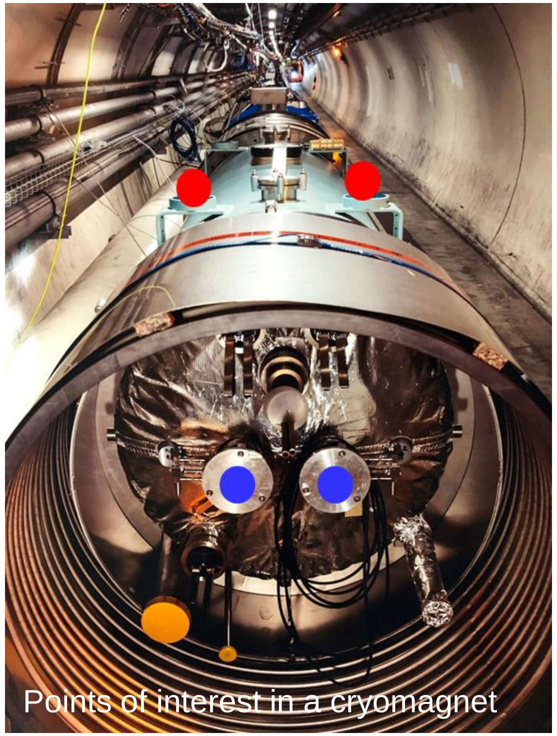


Control of the assemblies



CMS detector

Fiducialisation process



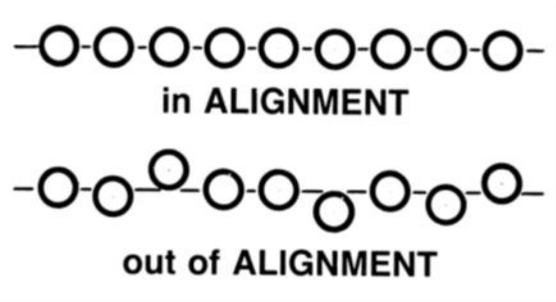
Points of interest in a cryomagnet

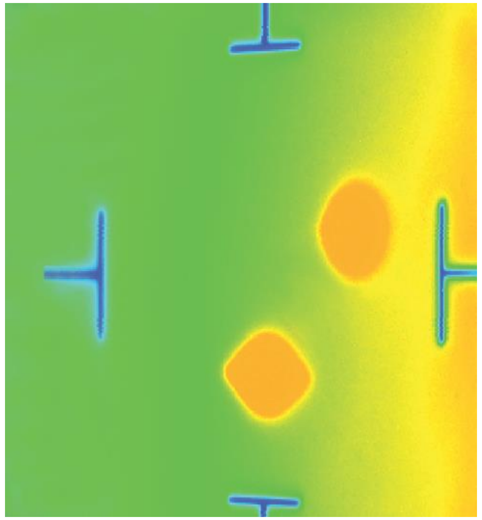
Fiducial

Jack

Why do we need high precision alignment?

To make the beam pass «through»: the components must be aligned in such a way that the beam is detected by beam position monitor, in order to launch «Beam based alignment»





10th September 2008:

2 yellow dots on a screen signaled the first time that protons had circulated CERN's LHC: bunch of subatomic particles making its way around a 27 km circumference tube.

The Earth is in constant motion:

- ✓ Frequency of realignment function of the alignment requirements and amplitude of ground motion
- ✓ Alignment tolerances: error of placement which, if exceeded, leads to a machine that is uncorrectable – with an unacceptable loss of luminosity

GM – Geodetic Metrology -- Our Mandate --

GM
Geodetic Metrology
GL: H. Mainaud Durand
DGL: J-C. Gayde

- **ASG** – Accelerator Survey & Geodetic measurements – SL: J-F. Fuchs
- **ESA** – Experimental Survey & Alignment – SL: J-C. Gayde
- **HPA** – High Precision Alignment Technol. – SL: M. Sosin
- **APC** – Acquisition Processing & Data Control Software – SL: F. Klumb

- ✓ ~60 persons
- ✓ 15 nationalities
- ✓ Multi-disciplinary

We provide metrology and alignment for components installed in the accelerators, their beam transfer lines and physics experiments throughout the CERN.

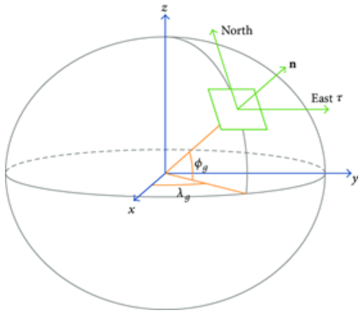
Nearly 60 km of beam lines!

~ 7500 accelerator components

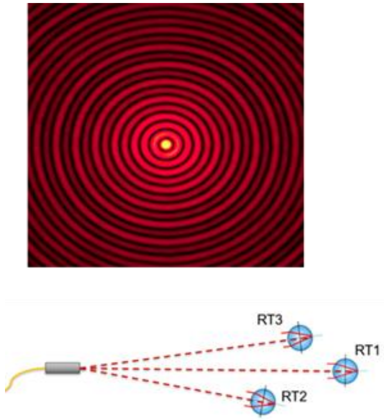
20 experiments

Thousands of sub-detectors!

Permanent monitoring



Geodetic aspects

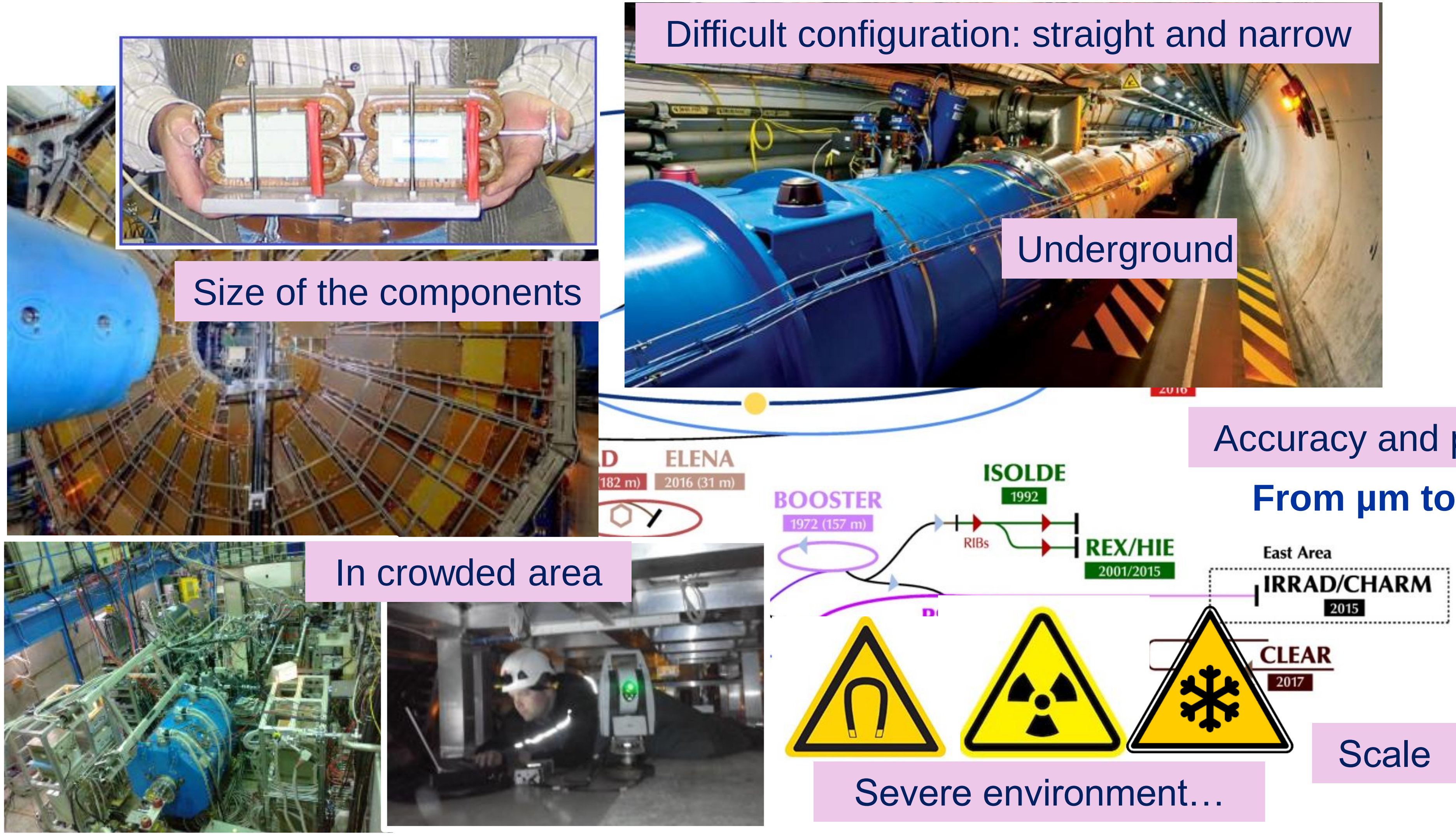


R&D

Georeferenced scans

Associated software

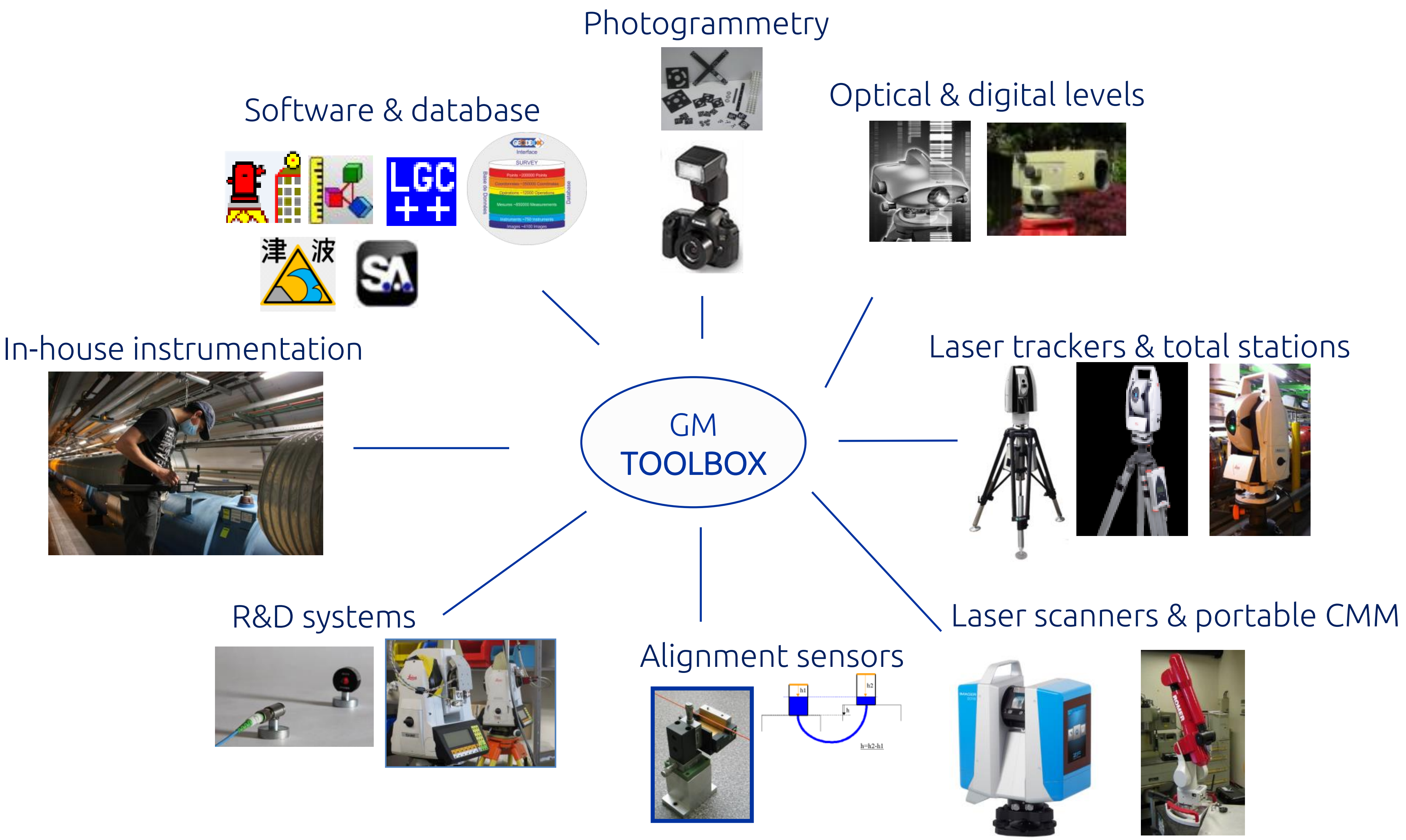
Some daily challenges



Accuracy and precision

From µm to mm

Our tool box


Photogrammetry
Optical & digital levels
Software & database
LGC ++
津 波
SA
In-house instrumentation
GM
TOOLBOX
Laser trackers & total stations
R&D systems
Alignment sensors
h=h2-h1
Laser scanners & portable CMM

Outline

Introduction

The different steps of the alignment of colliders, with LHC as case study

State of the art and current developments for HL-LHC

Towards the alignment of future colliders

Disclaimer: this presentation will be illustrated by a lot of examples coming from CERN, but can be generalized to all labs.

Steps of alignment

On the surface

Definition of alignment tolerances

Definition of alignment strategy

Inside the tunnel

Time scale

Installation and determination of surface geodetic network

Transfer of reference in the tunnel

Installation and determination of an underground geodetic network

Control & assembly of components

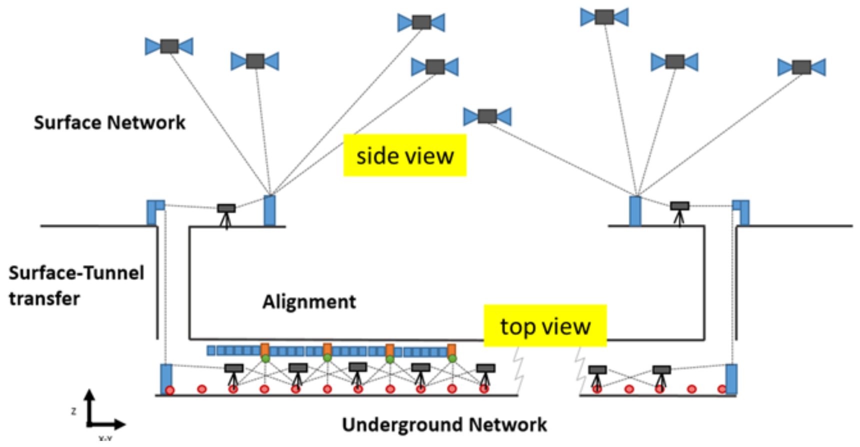
Fiducialisation of the components

Definition of their theoretical trajectory

Absolute alignment of the components

Relative alignment of the components

Maintenance of the alignment



Definition of alignment 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

Geodesy

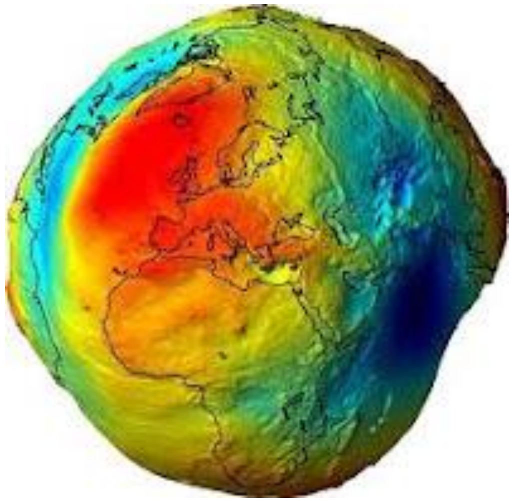
Geodesy is the science of accurately measuring and understanding 3 fundamental properties of the Earth :

- its geometrical shape;
- its orientation in space;
- its gravity field;

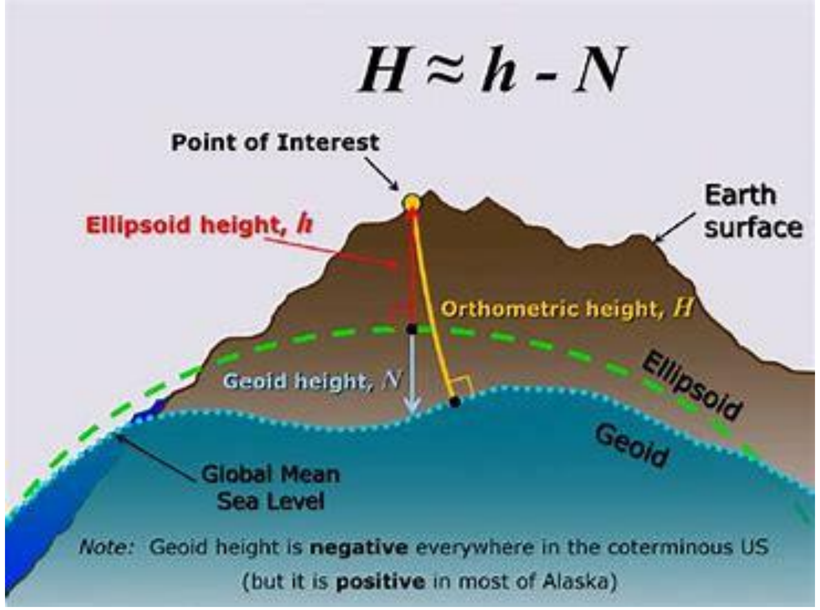
as well as the changes of these properties with time.

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
- A large part of instrumentation is set-up to perform measurements w.r.t to gravity
- We need to define the relative position of all area on surface and underground : sites, buildings, tunnels, accelerators, experiments



Geoid surface



Geoid surface vs ellipsoid

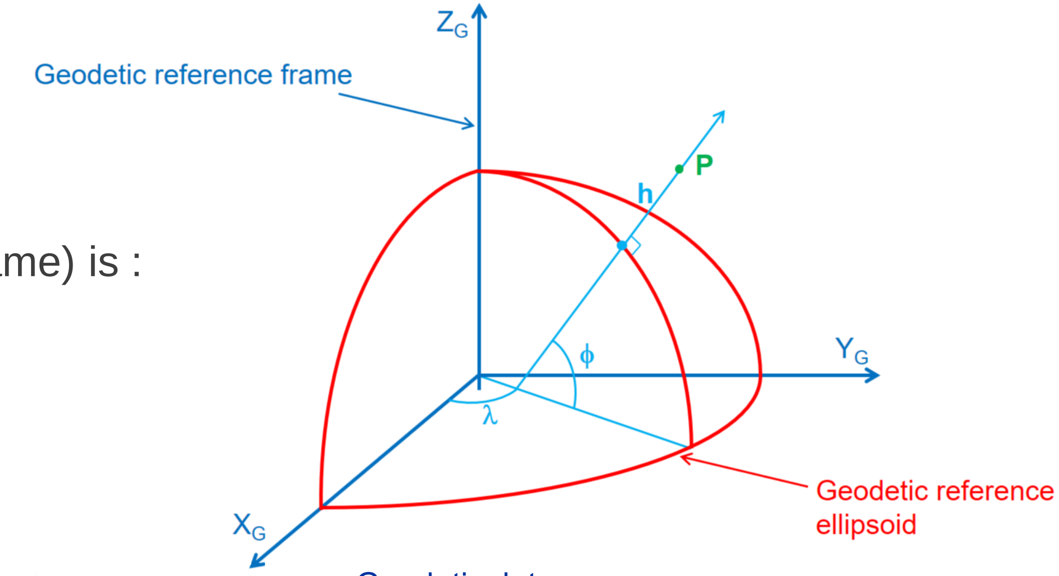
Geodesy

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

- A coordinate system
- A mathematical model
- A point of origin
- Sometimes a projection is also given

A geodetic 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.



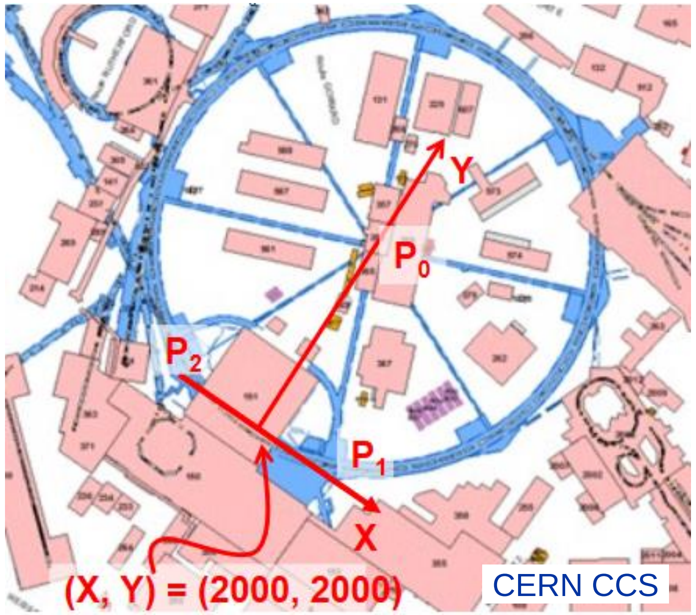
Geodetic datum

CCS : Cern Coordinates System

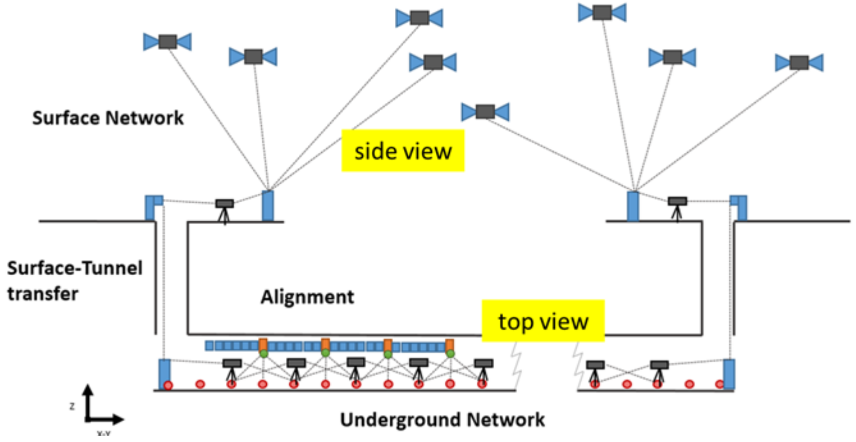
- The CCS is a right-handed 3D Cartesian coordinate system used to define the relative position of all the accelerators and experiments at CERN,
- The CCS is defined as follows :

- a right-handed Cartesian system;
- principal, or initial, point at P_0, the centre of the PS accelerator (the origin is by definition the centre of the line from P_2 to P_1);
- X-axis parallel to the vector from P_2 to P_1 of the PS, positive in the direction from P_2 to P_1;
- Y-axis perpendicular to the line, P_2P_1, passing through P_0, positive from the line, P_2P_1, towards P_0;
- Z-axis is collinear with the vertical at P_0;
- false coordinates at the P_0, in metres,

$$\begin{pmatrix} X_0 \\ Y_0 \\ Z_0 \end{pmatrix} = \begin{pmatrix} 2000.00000 \\ 2097.79265 \\ 2433.66000 \end{pmatrix}$$



Geodetic network and its transfer



Physical realization of points in an underlying reference system.

Absolute reference for all subsequent geodetic and survey work

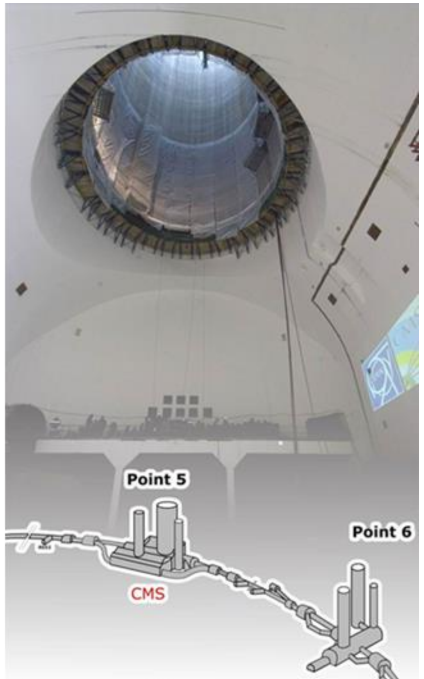
- Civil engineering
- Infrastructure
- Alignment

Networks with different orders of precision.

Mixture of permanent GNSS stations and geodetic pillars


GNSS station


Geodetic pillar



Transfer through shaft

Underground geodetic network

The underground network consists of a **backbone of monuments** preferably in the floor or on the walls.

Unfortunately, the **configuration of a tunnel network is quite bad** (linear, long and narrow) with refraction issue

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 (1σ) 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.

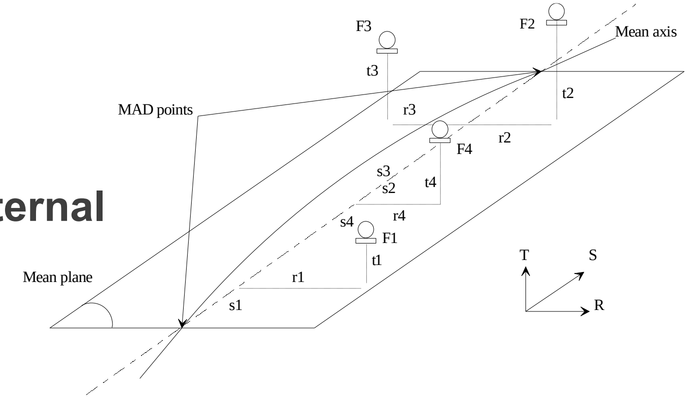
GGPSO, LHC underground geodetic network

Highly accurate determination of the North direction (Azimuth)

GGPSO

Forced centering system on a GGPSO

Fiducialisation



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

- Magnetic measurements combined with laser tracker (warm magnets)
- CMM measurements, for smaller components and requirements of the order of micrometers.
- Laser tracker measurements when the requirements are of the order of 0.1 mm rms

Magnetic measurement bench

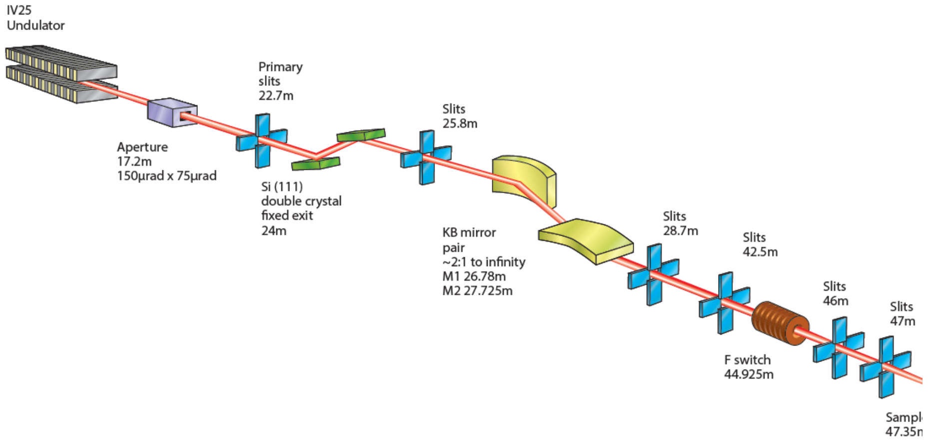
CMM (Metrology Lab')

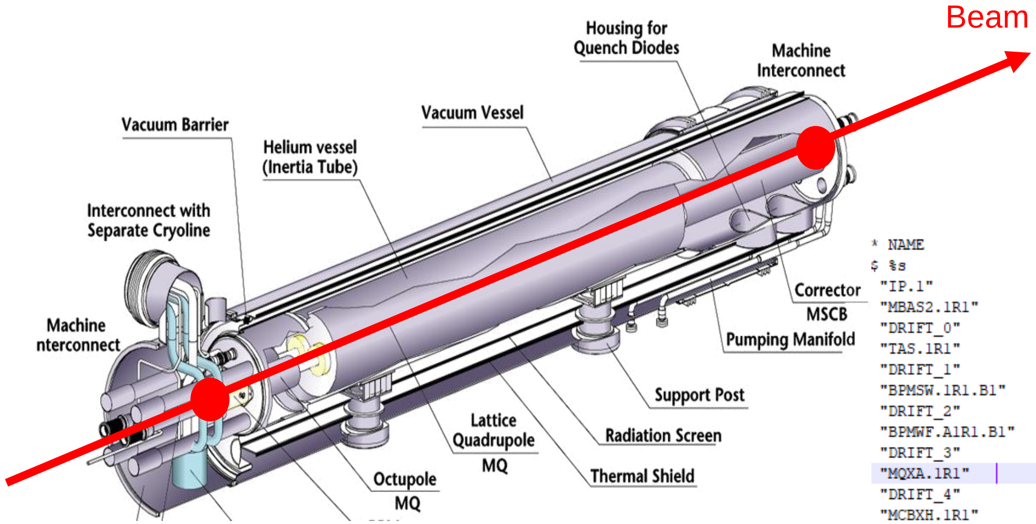
Laser Tracker

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
- Each component position is defined by a **start / end points** and **orientations**





Beam Points

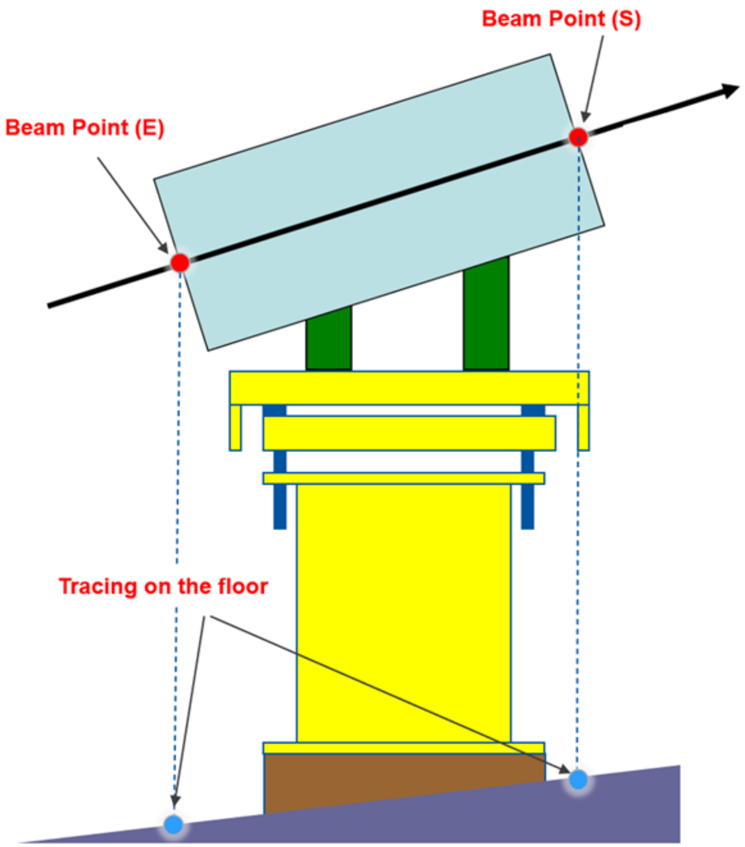
* NAME	S	L	ANGLE	X	Y	Z	THETA	PHI	PSI	GLOBALTILT
$ %s	%le	%le	%le	%le	%le	%le	%le	%le	%le	%le
"IP.1"	0.000000000	0.000000000	0.000000000	-2202.210270000	2359.006560000	2710.638820000	-4.315508007	0.012427956	-0.006530924	-0.006530924
"MBAS2.1R1"	3.000000000	3.000000000	0.000000000	-2199.443670316	2359.043842909	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	-2182.982402196	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

Absolute alignment of components

The absolute alignment consists of 3 steps:

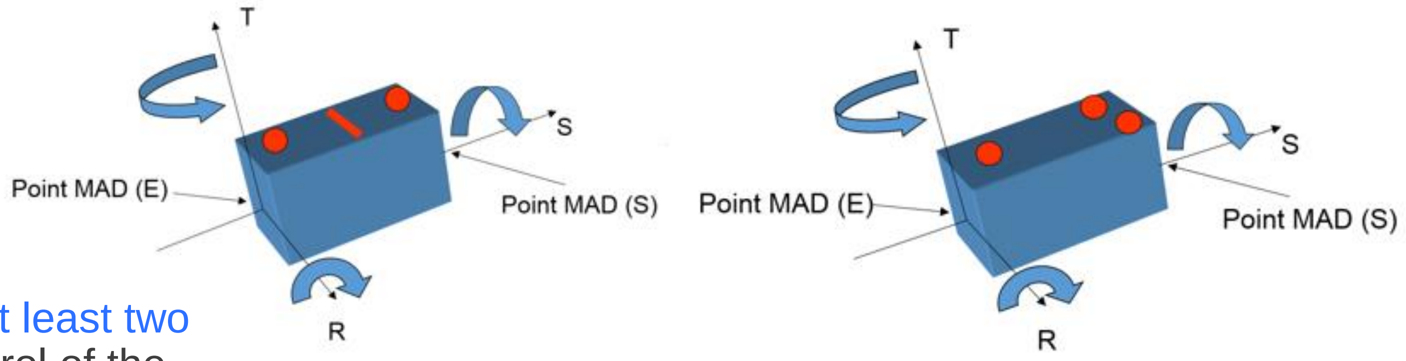
- **Marking on the floor:** vertical projection of the geometrical mean of the beam line, using the installation drawings.
- **Positioning of the jacks** (or adjustment platform): the stroke of jacks compensates the errors of the floor, the errors in their positioning, cryostat construction errors and ground motion during the life of the accelerator. Jacks 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

LHC jacks' installation



From the component to the tunnel floor

Adjustment systems



The beam points are not visible in the tunnel

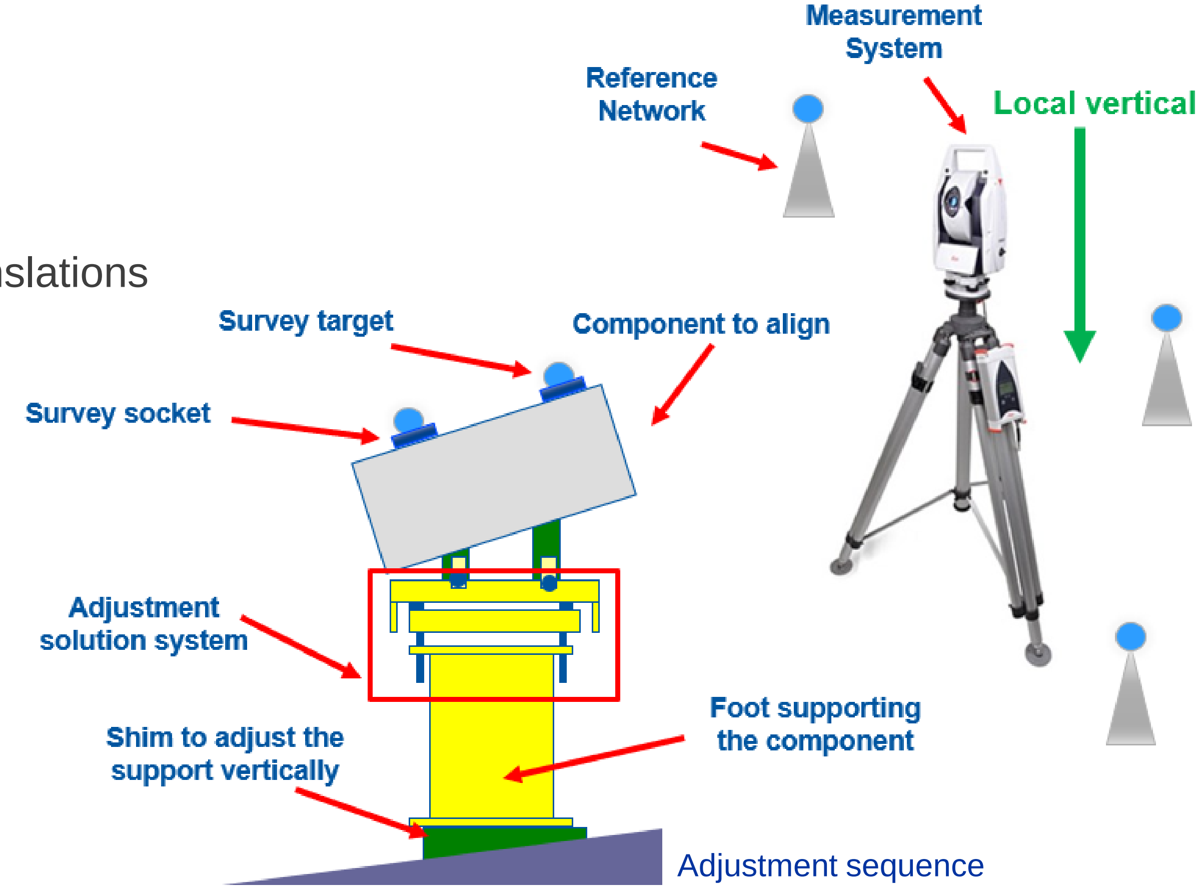
Each component/object to be aligned is equipped with at least two reference alignment targets and a reference for the control of the roll angle. These reference targets are called **fiducials**.

- 2 fiducials + 1 roll surface
- 3 fiducials

Adjustment solution : 6 degrees of freedom: 3 angles and 3 translations

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

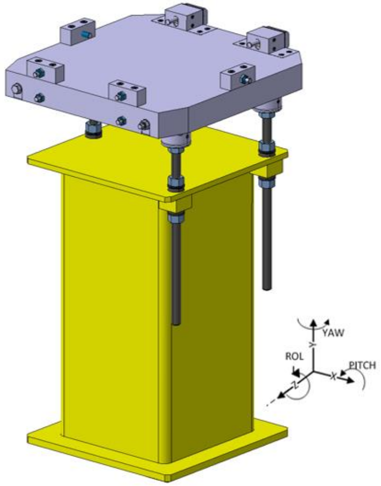
- To adjust the roll angle
- To adjust the vertical position : E / S
- To adjust the radial position : E / S
- To adjust longitudinal position : E / S



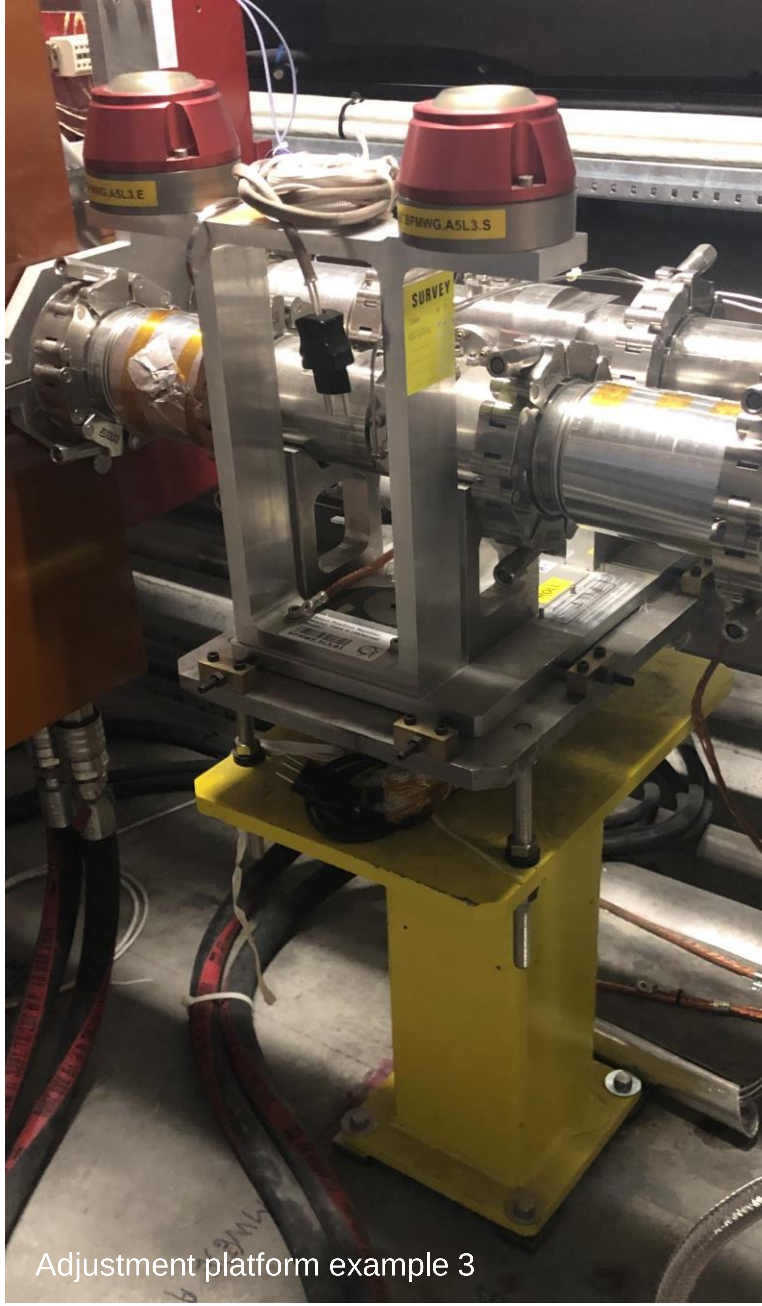
Adjustment sequence

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

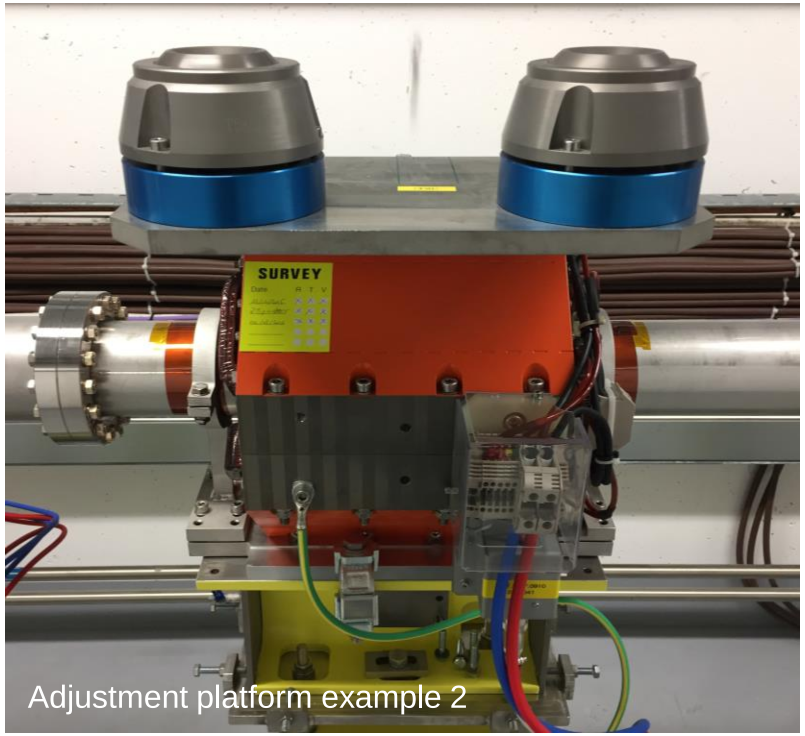


Alignment plate + support



Adjustment platform example 3

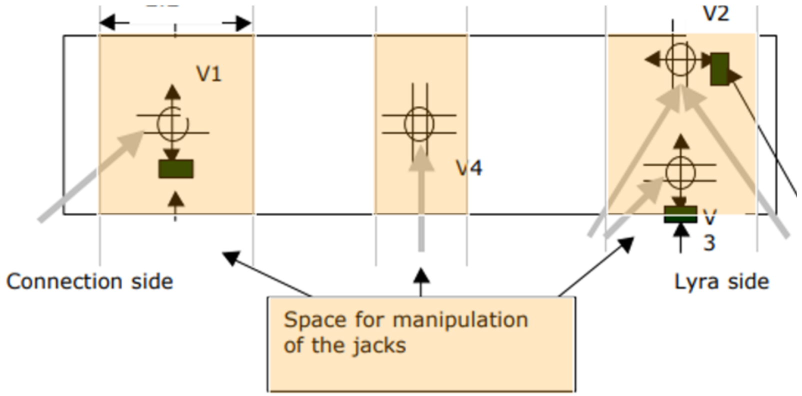
Adjustment platform example 1



Adjustment platform example 2

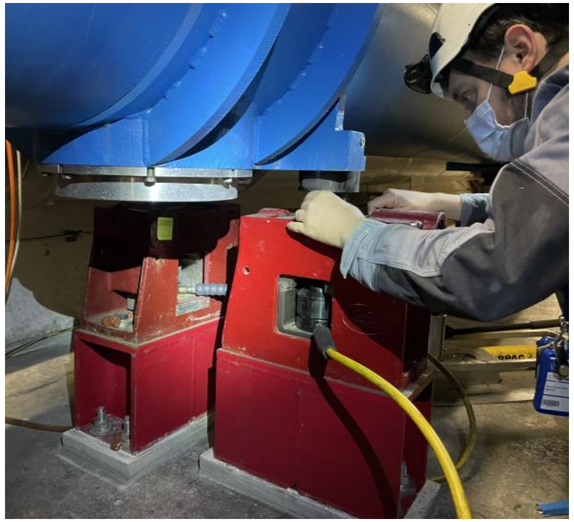
Jacks (LHC)

R & L adjustment

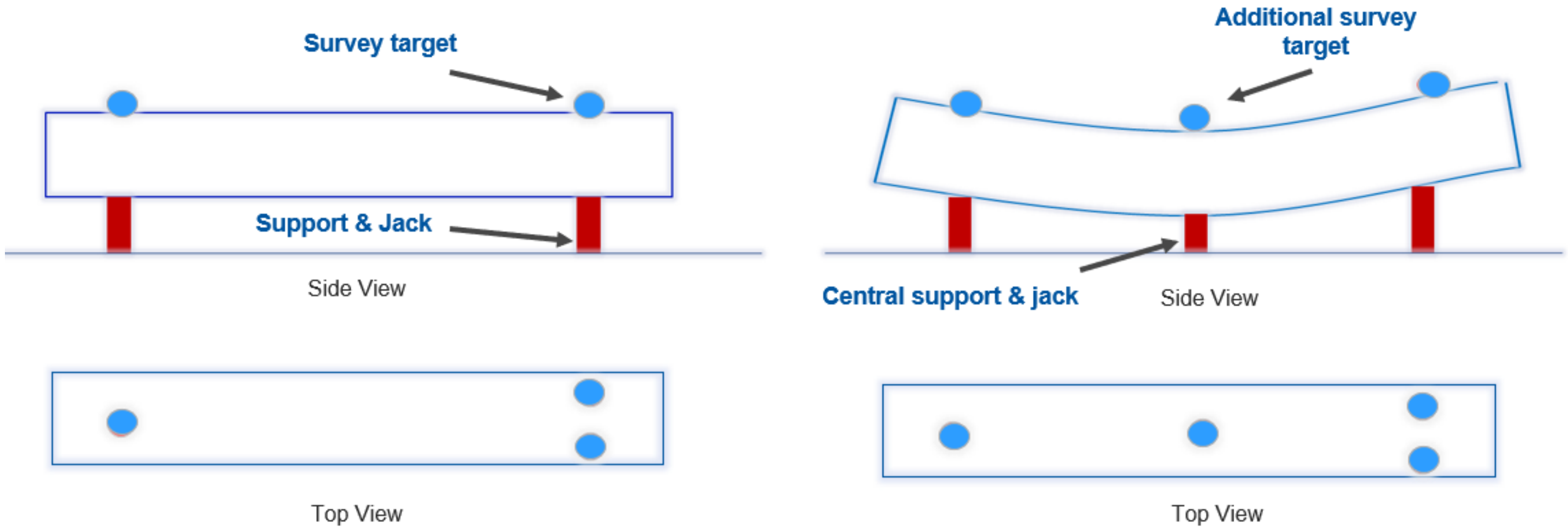


LHC jack

R & L adjustment

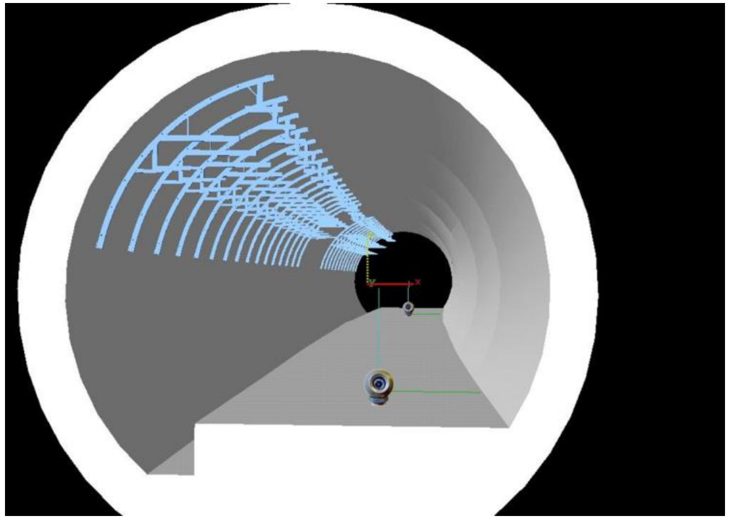


Vertical adjustment

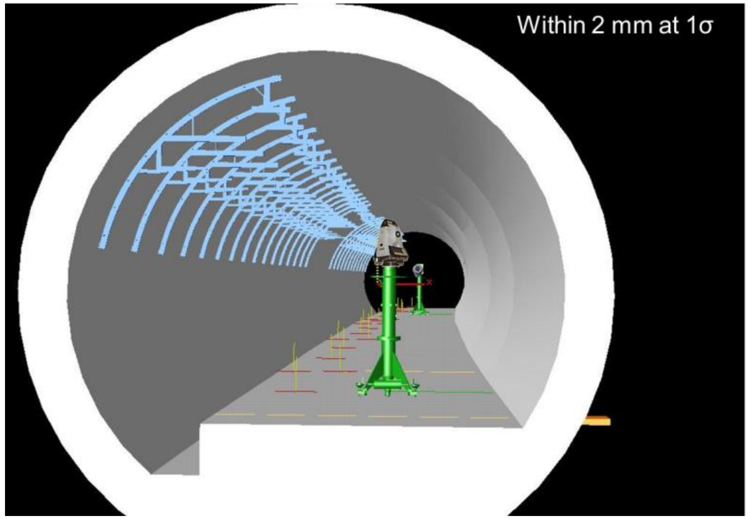


Jack configuration

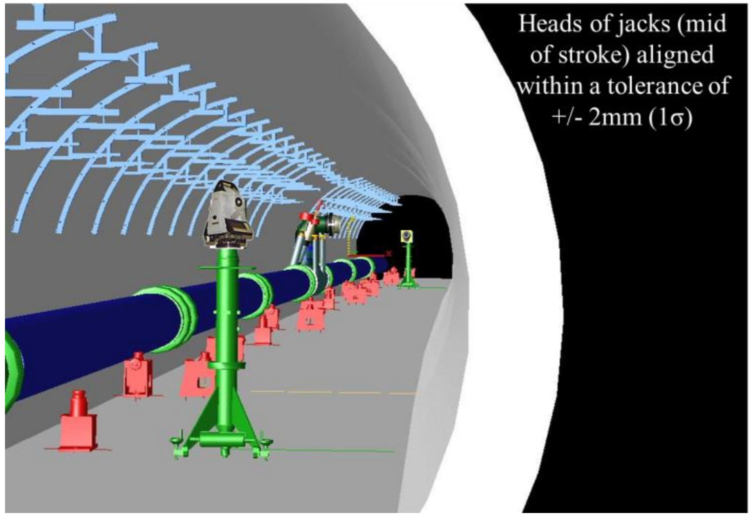
Towards the initial absolute alignment



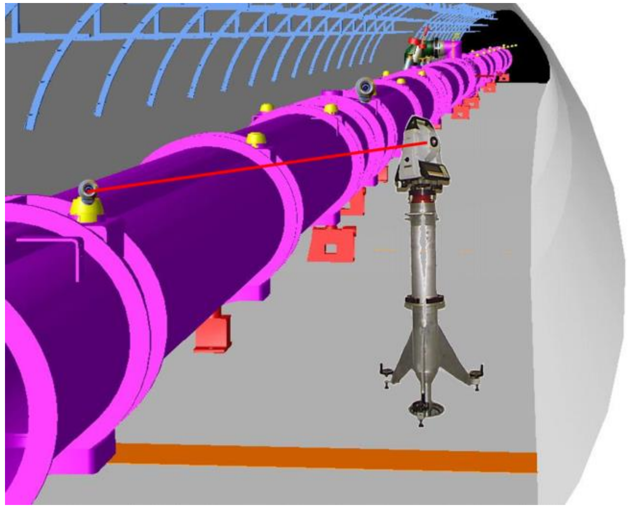
Underground geodetic network



Marking on the tunnel floor

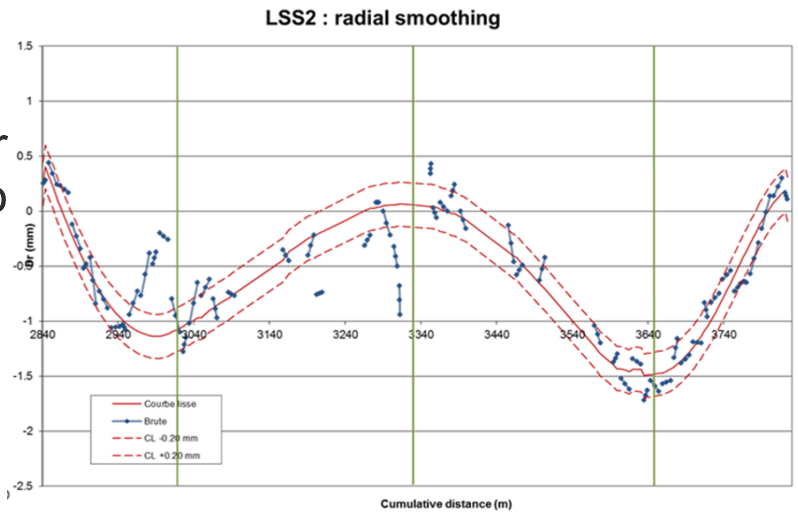


Jacks for the components' adjustment

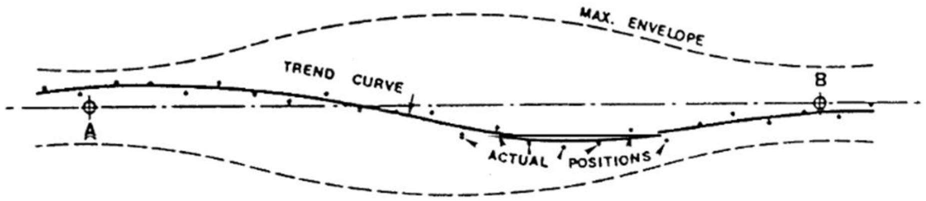


Initial absolute alignment

Relative alignment of components



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.



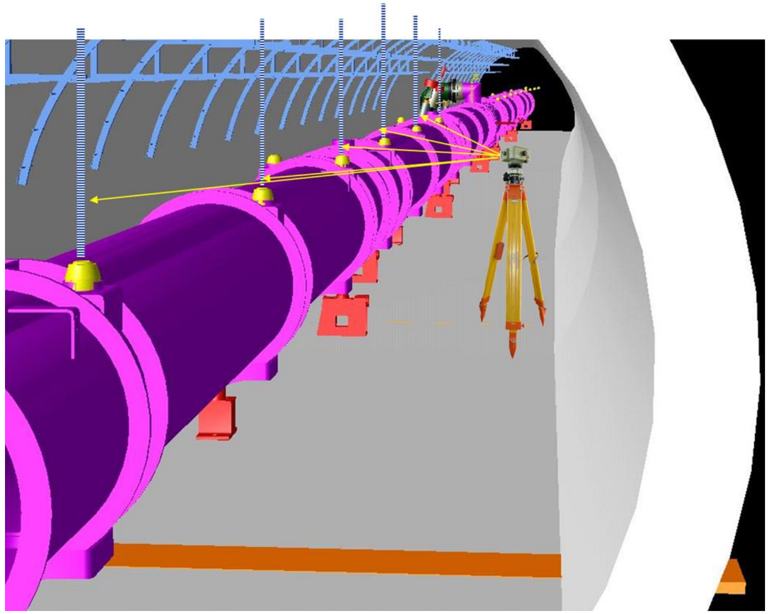
Position of magnets with respect to theoretical orbit

Collider	Epoch	Circumference	Vertical (mm) (1σ)	Transv. (mm) (1σ)
PS (p)	50's	650 m	0.3	0.6
SPS (p)	60's	6 km	0.2	0.2
LEP (e+e-)	80's	27 km	0.2 - 0.3	0.2 - 0.3
LHC (pp)	2000	27 km	0.20	0.20
CLIC (e+e-)	?	2 x 25 km	0.014 - 0.017 *	0.014 - 0.017*
FCC (ee)	?	80-100 km	0.1 *	0.1*

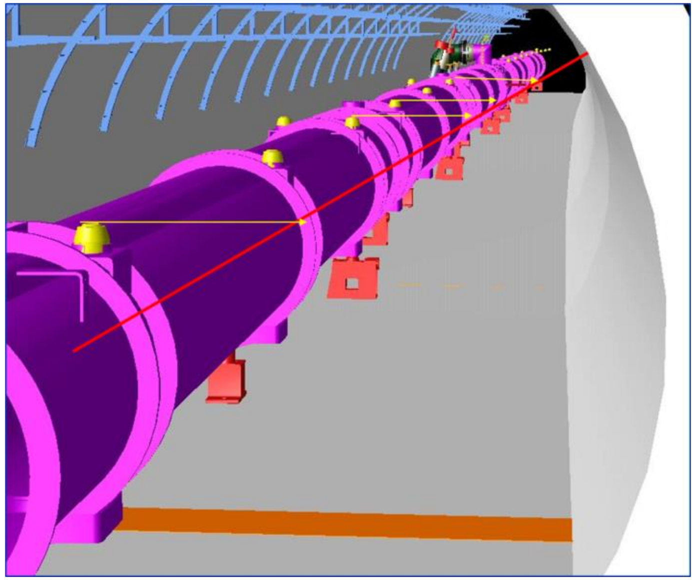
Over a sliding window of 200m

* All errors included

The LHC alignment



Vertical smoothing performed by levelling



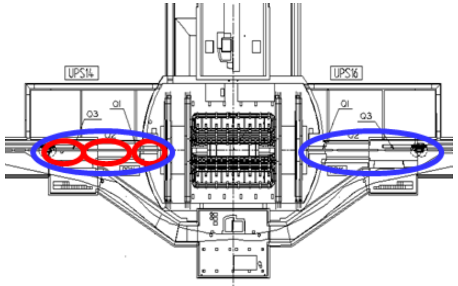
Radial smoothing performed by wire offset measurements

Levelling

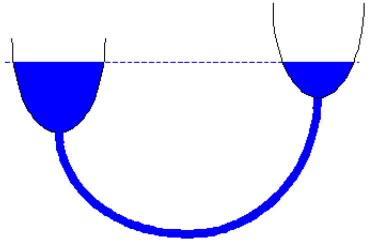
Wire offset measurements

See Paper «Long Shutdown 2 LHC smoothing status and data analysis», Fuchs J-F and al., LINK

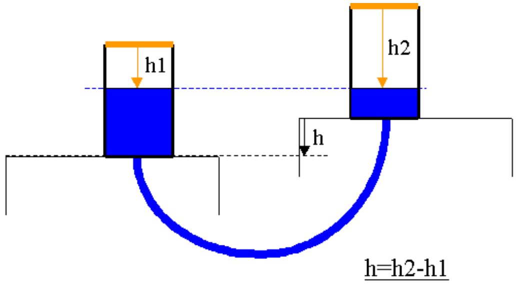
Specific case of LHC low beta triplets



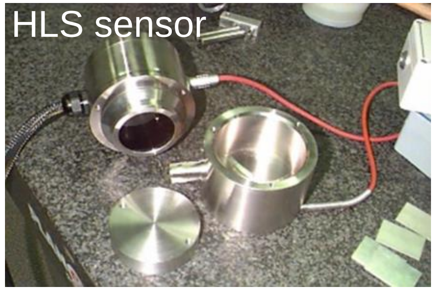
Hydrostatic Levelling Sensors (HLS):



Communicating vessels



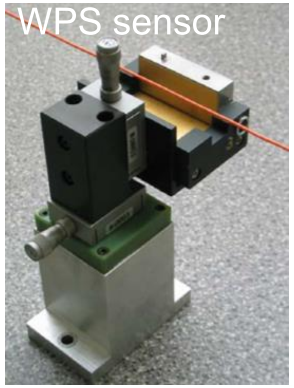
Difference of height measurement

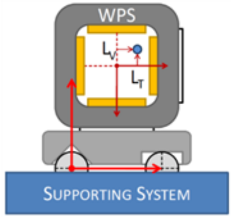


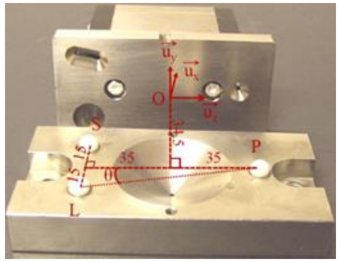
$$C = \frac{\varepsilon_o \varepsilon_r S}{d}$$

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

Wire Positioning Sensors (WPS):



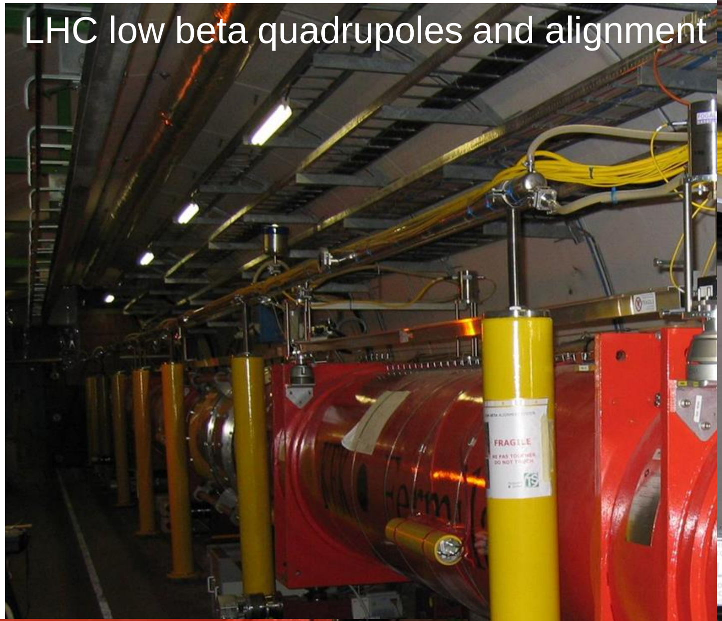




- Reference surface = stretched wire
- Vertical + radial measurements
- Continuous measurements (up to 100 Hz)
- Repeatability : ± 1 µm
- Accuracy: 5 µm (1σ)
- Range: ± 5 mm

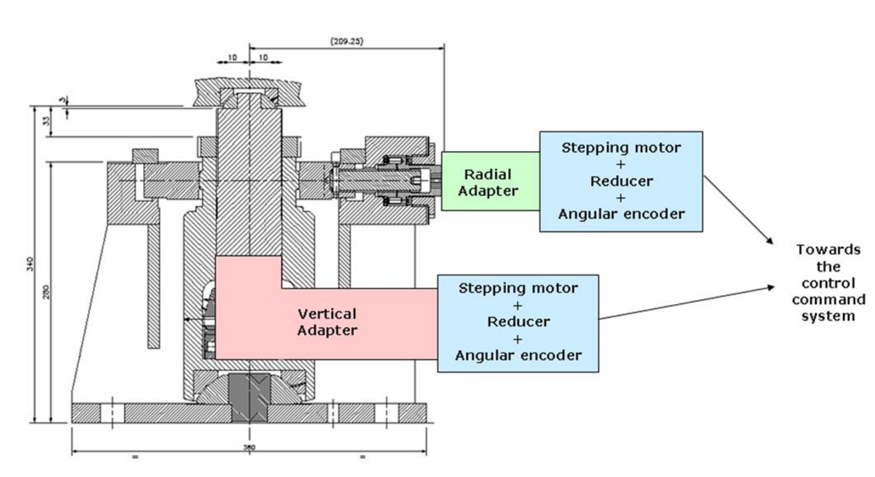
See Paper «3D calculation for the alignment of LHC low beta quadrupoles», Rude V. et al., CERN-Be-2023-003,LINK

Specific case of LHC low beta triplets

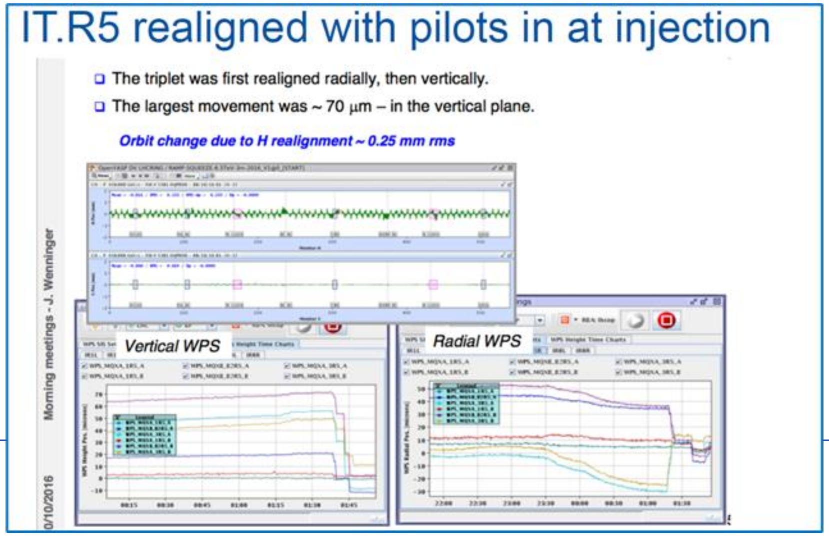

LHC low beta quadrupoles and alignment


HLS and WPS sensors


Motorized jacks



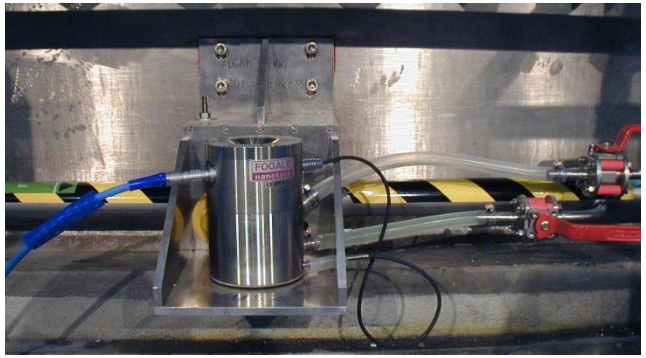
Motorized jacks for LHC low beta triplets

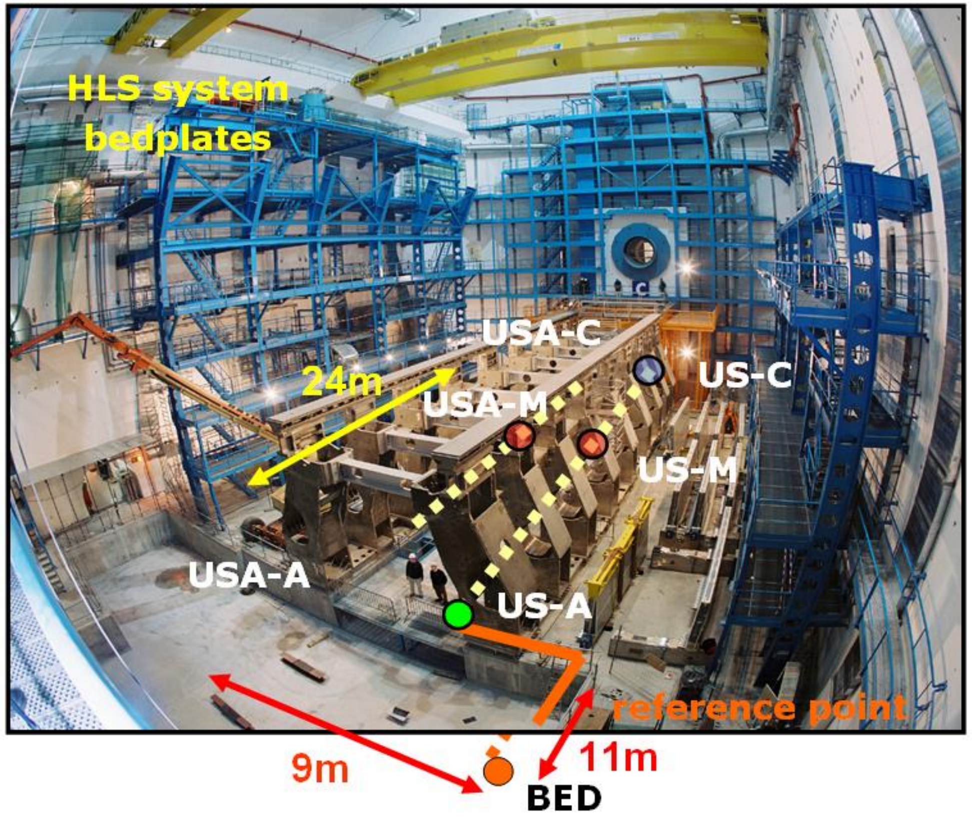


HLS Sensors

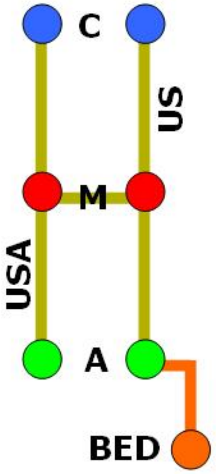
Hydrostatic Levelling System (HLS)

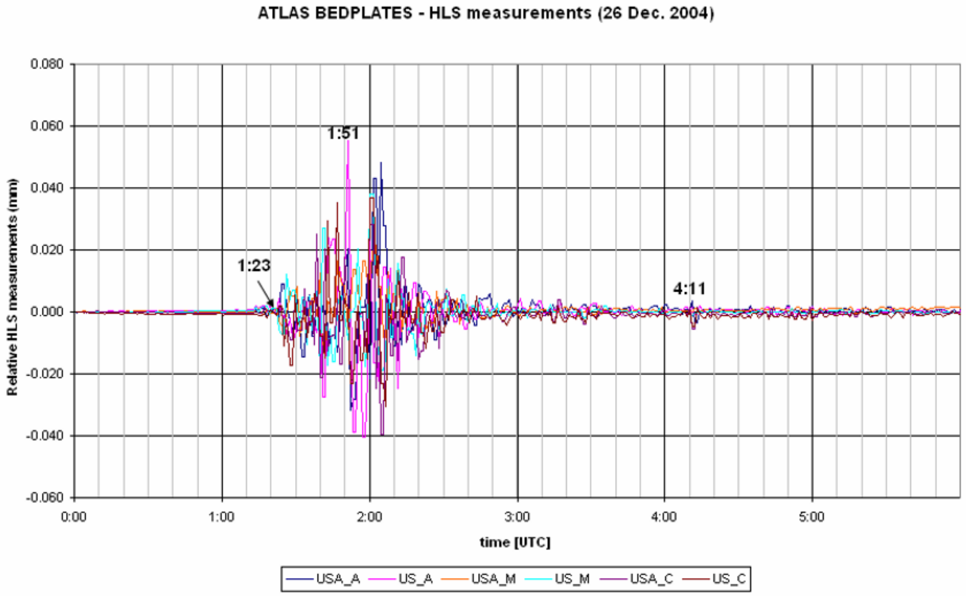
- HLS applications : ATLAS bedplates





ATLAS bedplates in 2003



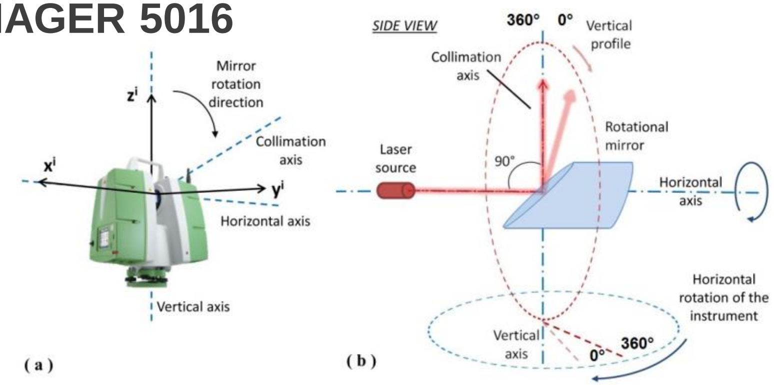


M 9.1 - 2004 Sumatra - Andaman Islands Earthquake

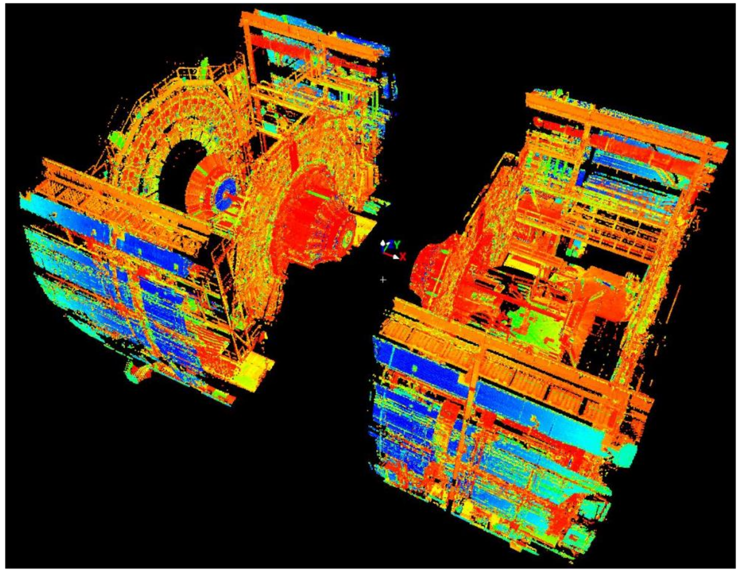
2004-12-26 00:58:53 (UTC) | 3.295°N 95.982°E | 30.0 km depth

3D scanning

Z+F IMAGER 5016



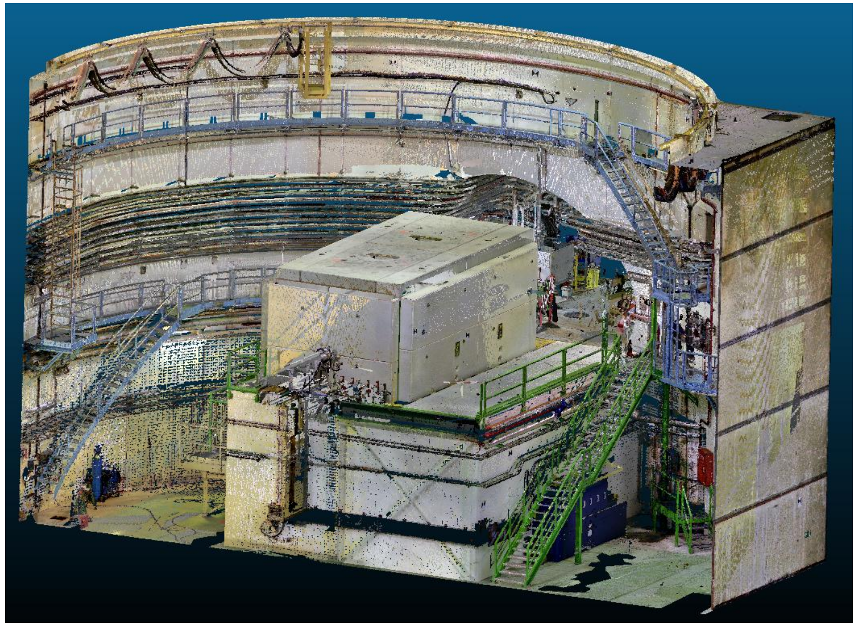
East Area Experimental lines



CMS

Transfer lines

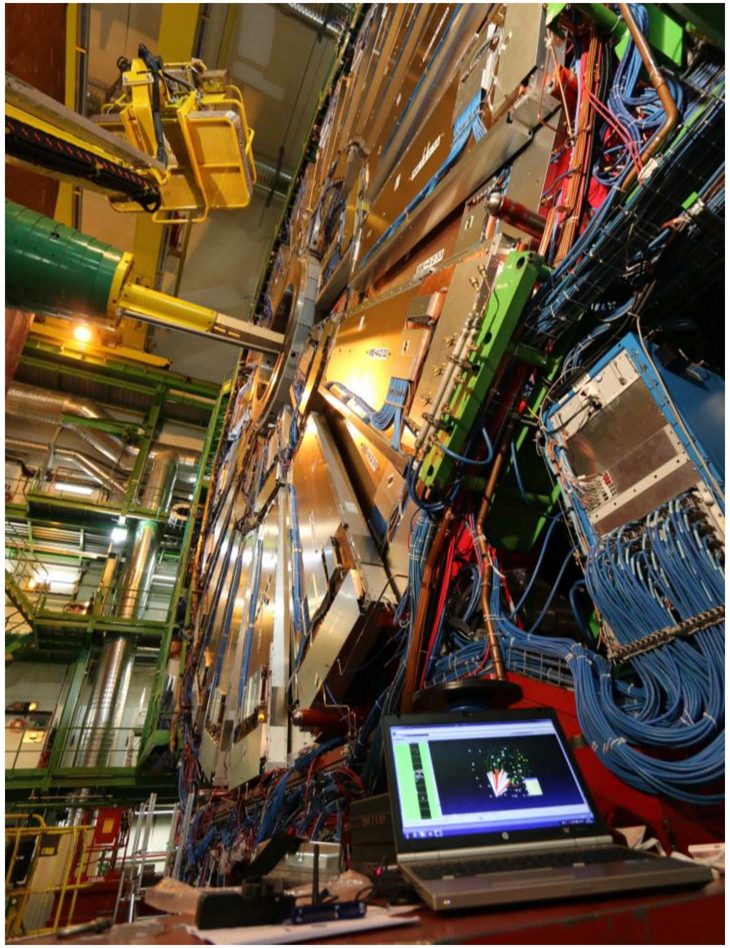
HL-LHC New galleries

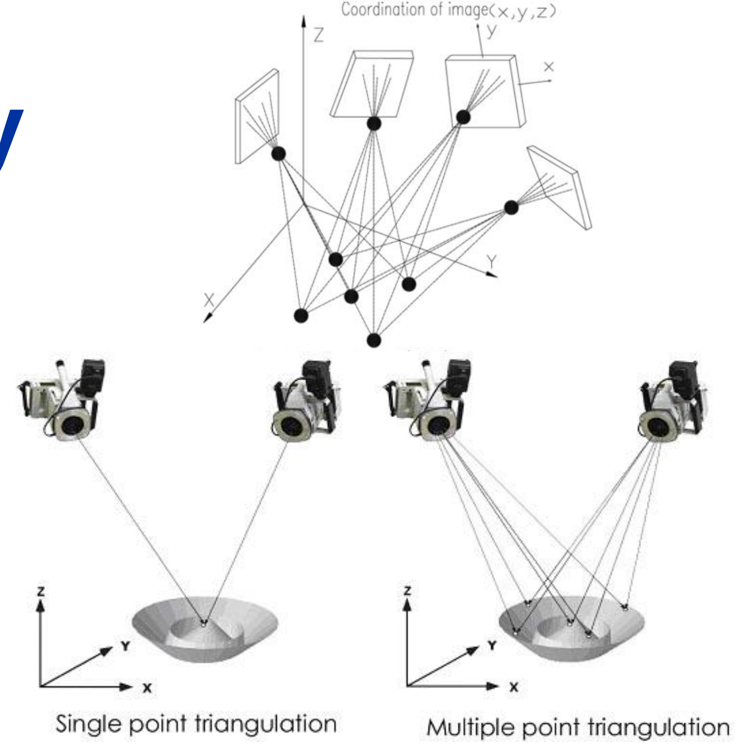


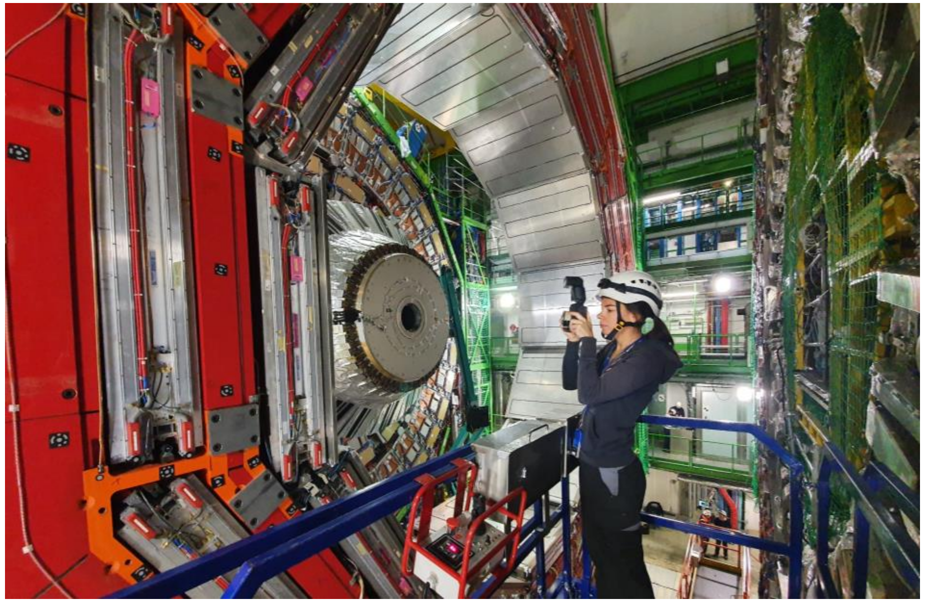
SPS, BA5

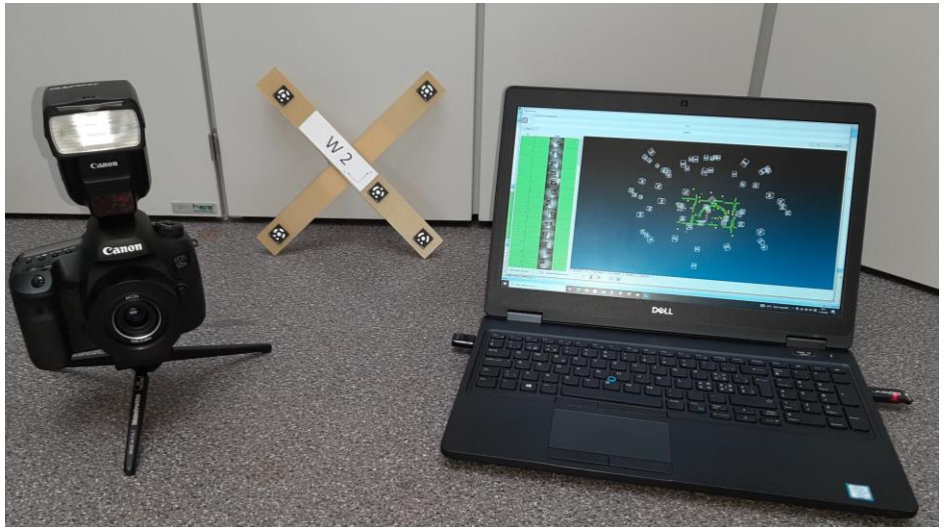
Photogrammetry

Aicon & Canon 5Ds

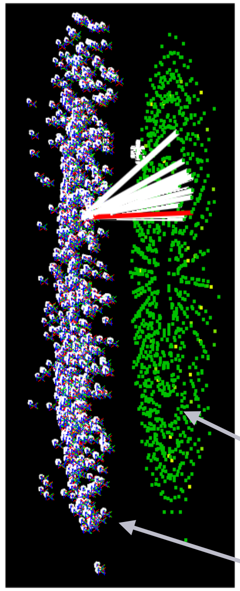








ATLAS TGC3-C Big Wheel measurement



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

Outlook

Introduction

The different steps of the alignment (LHC as case study)

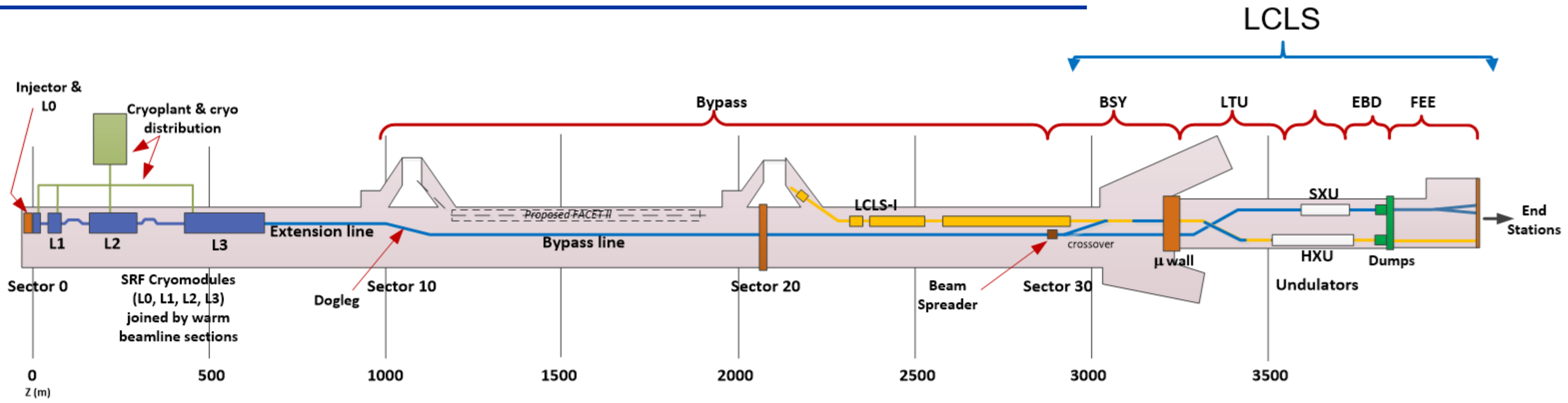
State of the art and current developments for HL-LHC

Towards the alignment of future colliders

State of the art

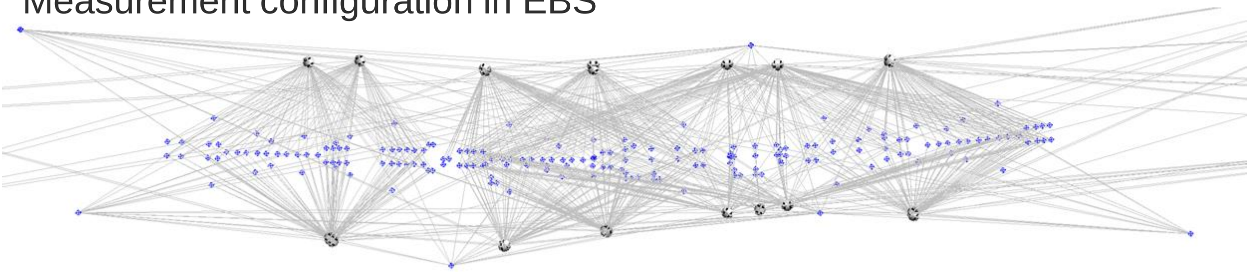
In other laboratories : SLAC – alignment tolerances reached at LCLS-I (Georg Gassner)

Step	Error budget
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



State of the art

Measurement configuration in EBS

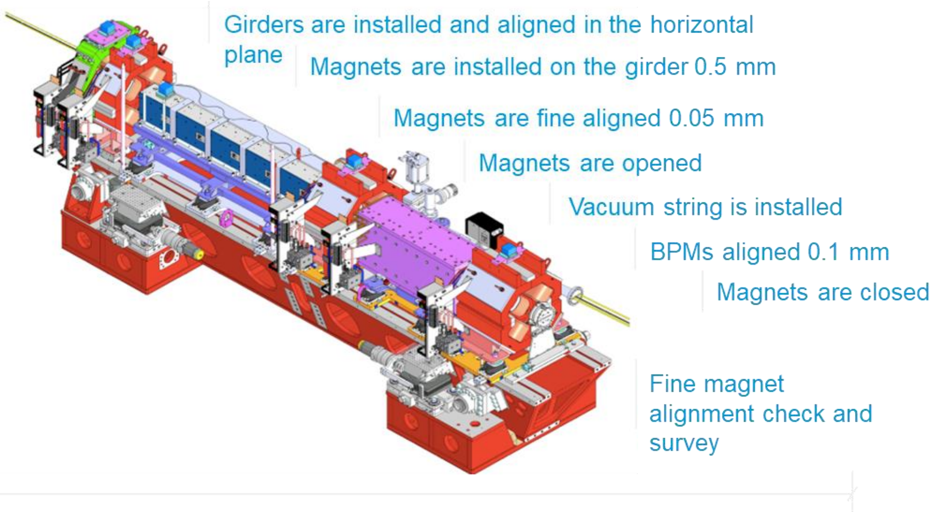


In synchrotrons – ESRF Extremely Brilliant Source (EBS)

(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

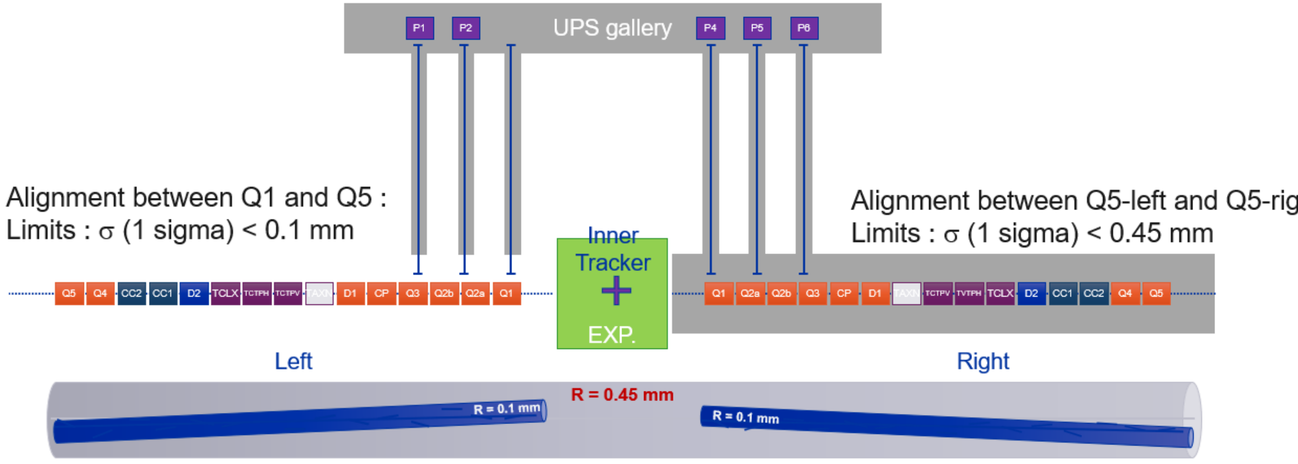
EBS Girder



Assembly was made at ESRF01 – a dedicated building

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

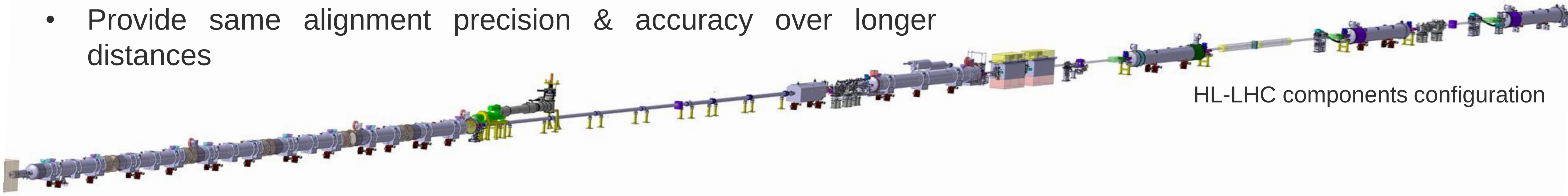
Specific case: HL-LHC



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

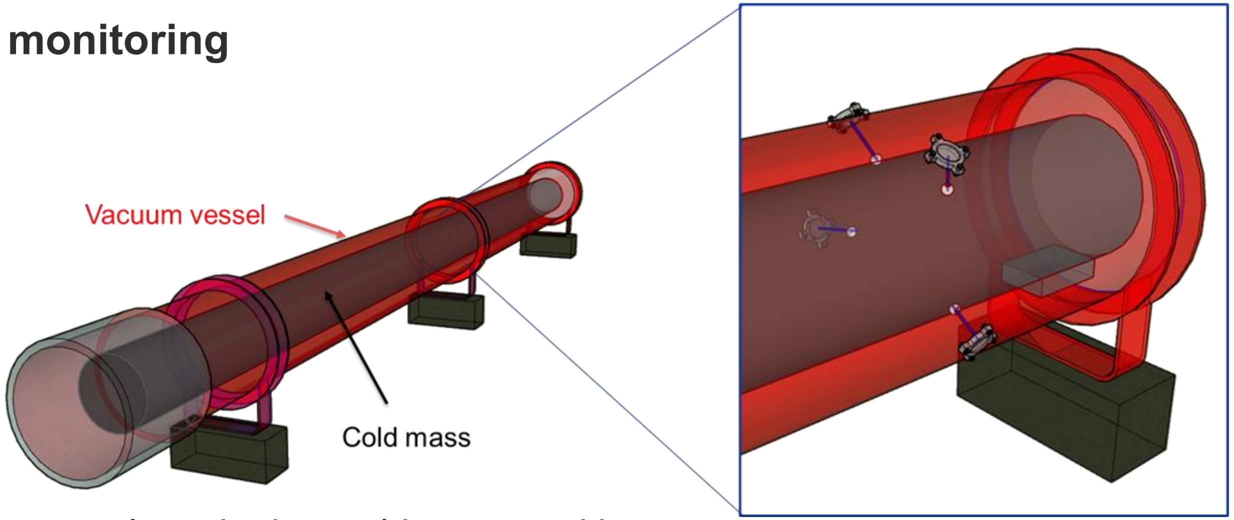
Full Remote Alignment System (FRAS):

- 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

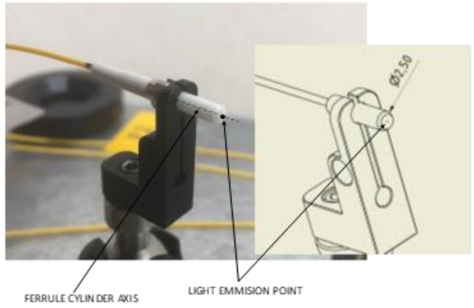
An Intermediary step: HL-LHC

See Paper «Frequency sweeping interferometry for robust and reliable distance measurements in harsh environment», Sosin M. et al., LINK

Internal monitoring



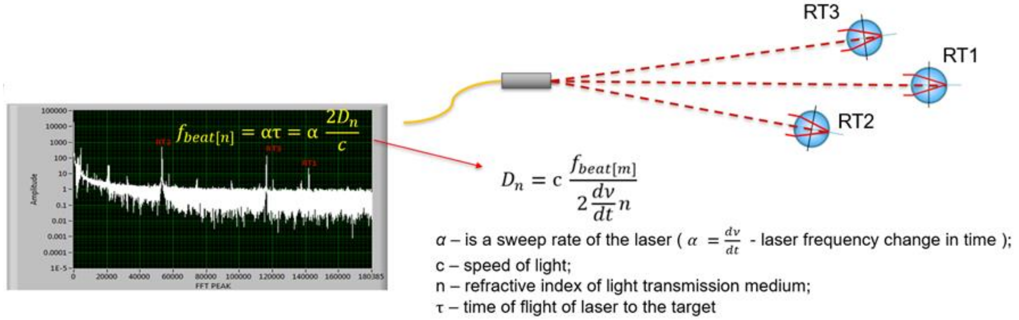
Internal monitoring: cold mass position vs cryostat



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.

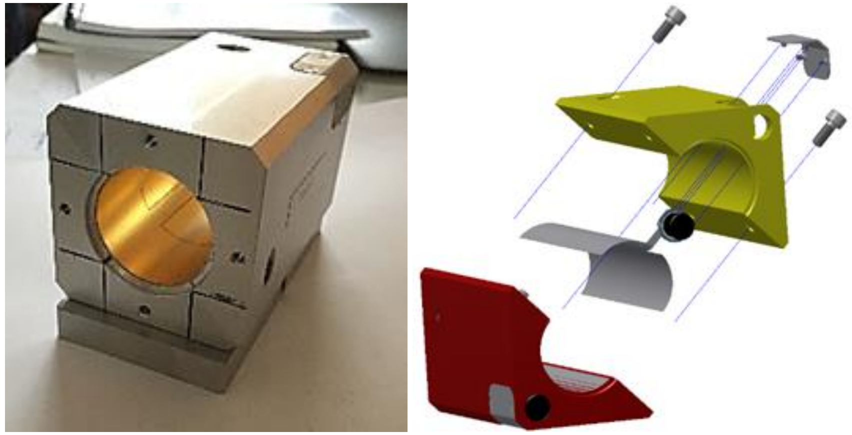
Continuous monitoring of the cold mass position w.r.t. vacuum vessel within an accuracy of 0.1 mm

An intermediary step: HL-LHC

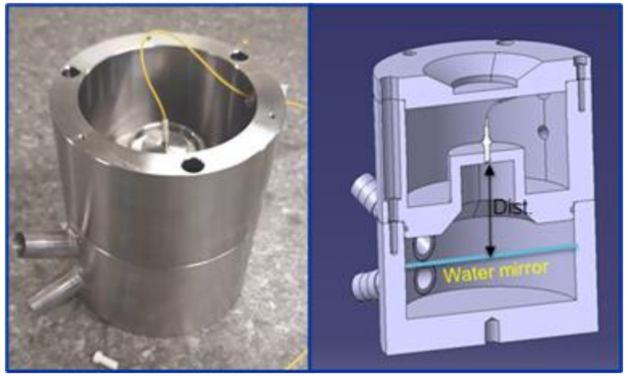
Development & qualification of robust alignment solutions : ALIGNMENT SENSORS:

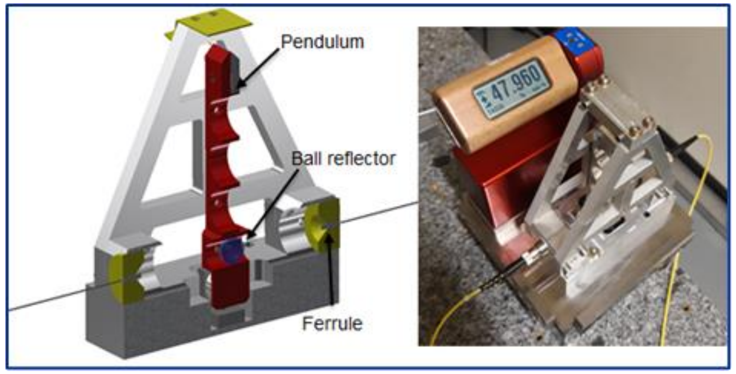
- In-house development (to master the choice of the electronics components)
- To optimize the cost
- To improve the performance (increased length between the sensor and its remote electronics)
- To increase the robustness and radiation hardness

Capacitive based WPS



FSI based HLS and inclinometers sensors





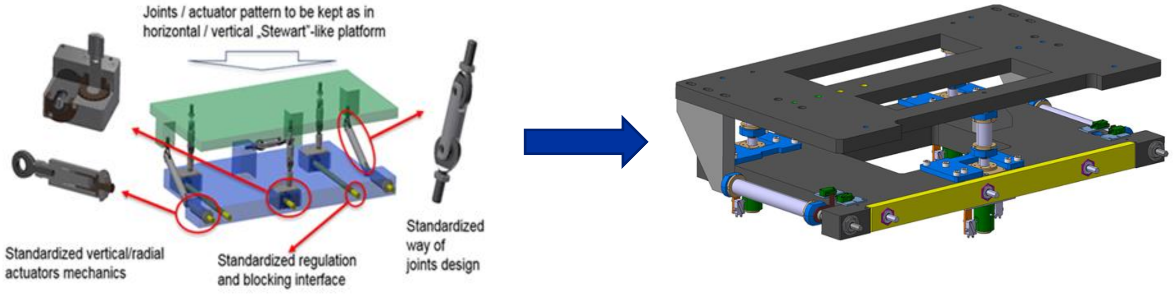
See Paper «Full Remote Alignment System for the High-Luminosity Large Hadron collider HL-LHC», Mainaud Durand H. et al., LINK

An intermediary step: HL-LHC

See Paper «Design and study of a 6 degree-of-freedom universal adjustment platform», Sosin M., LINK

Development & qualification of robust adjustment solutions

For light components (< 2 tons)

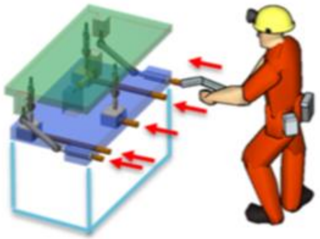


Development of a Universal Alignment Platform

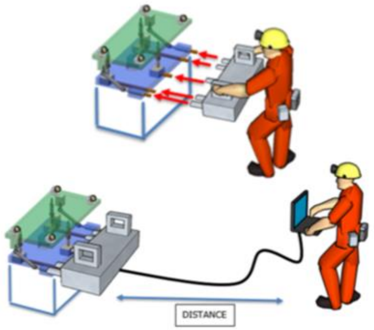
Two sizes of UAP designed and tested:

- **SMALL UAP** – for components with weight < 300 kg
- **BIG UAP** - for components, with weight < 2 t

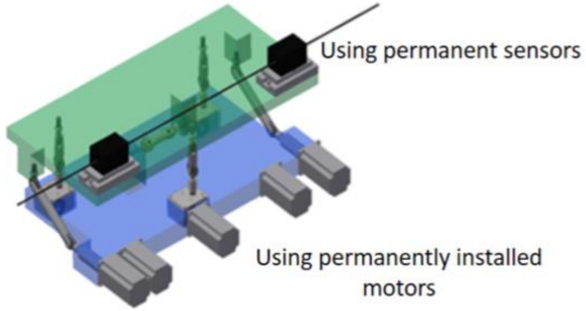
- SMALL and BIG UAP design methodology is the same
- Each platform has different family of joints/adjustment jigs
- Micrometric adjustment resolution
- Long term stability < 50 µm



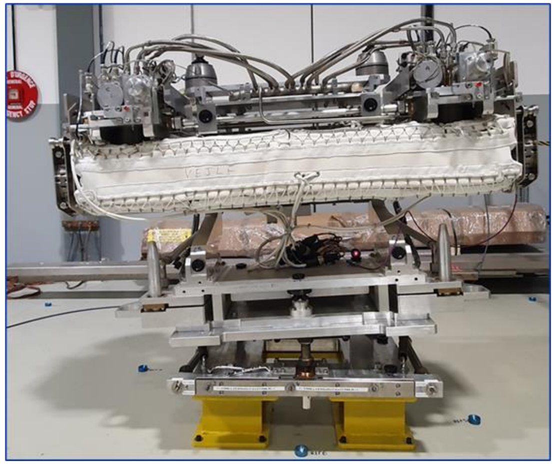
Manual adjustment



Manual adjustment with plug-in motors



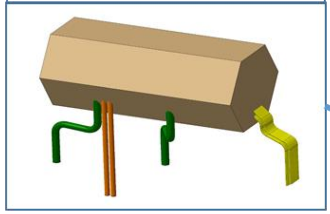
Motorized adjustment



Universal Platform

UAP is NOT a single PLATFORM
UAP is a design FRAMEWORK

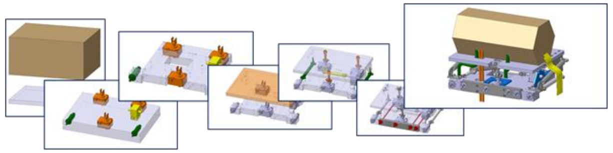
COMPONENT TO BE ALIGNED



STANDARDIZED JIGS AND JOINTS

LHCGUPS_0001
LHCGUPS_0007

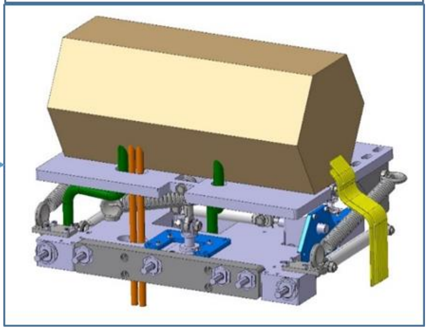
DESIGN PROCESS



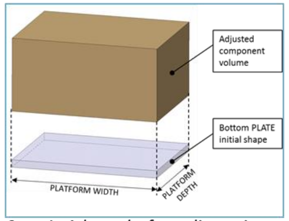
EDMS 2145045

DESIGN GUIDELINES FOR SMALL UAP

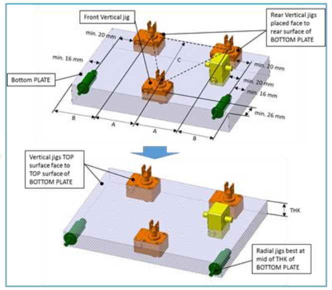
DEDICATED ADJUSTMENT PLATFORM



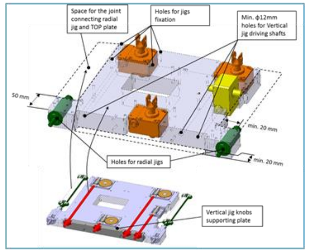
Please contact Mateusz Sosin and Michel Noir for further info.



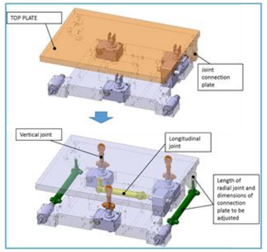
Step 1: *Adapt platform dimensions to supported component dimensions*



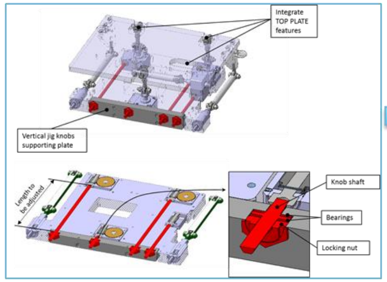
Step 2: *Arrange jigs pattern within Bottom plate volume (top)*; Step 3: *Adjust thickness of the plate and position of radial jigs (bottom)*



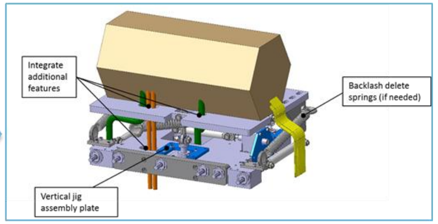
Step 4: *Prepare the space for the UAP functional sub-components*



Step 5: *Prepare the Top plate initial model and adjust the joints length*



Step 6: *Prepare the Top plate initial model and adjust the joints length*



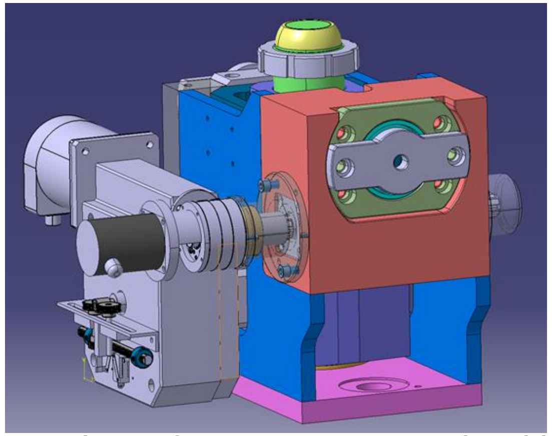
Step 7: *Integrate all user specific features and vertical jig assembly plates*

<u>Engineers implements their own UAPs according to specific requirements, considering design guidelines and using standardized components („LEGO" blocks approah)</u>

An intermediary step: HL-LHC

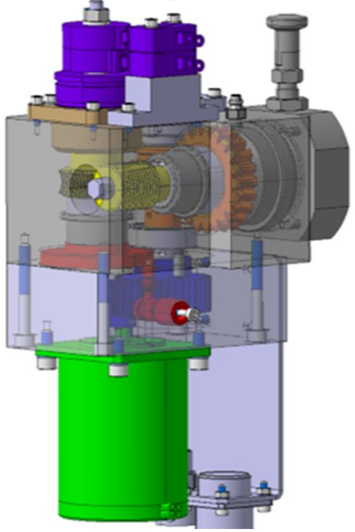
Development & qualification of robust adjustment solutions

For heavy components (> 2 tons)

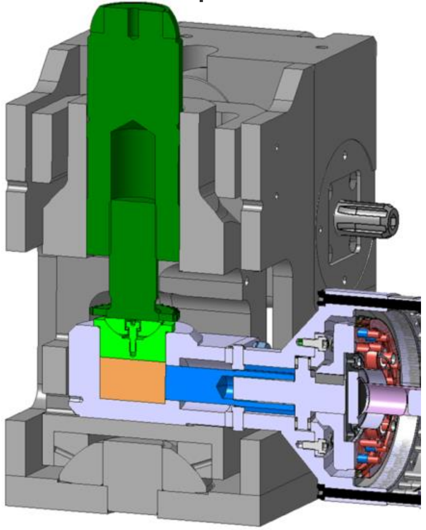


3D view of a HL-LHC motorized jack

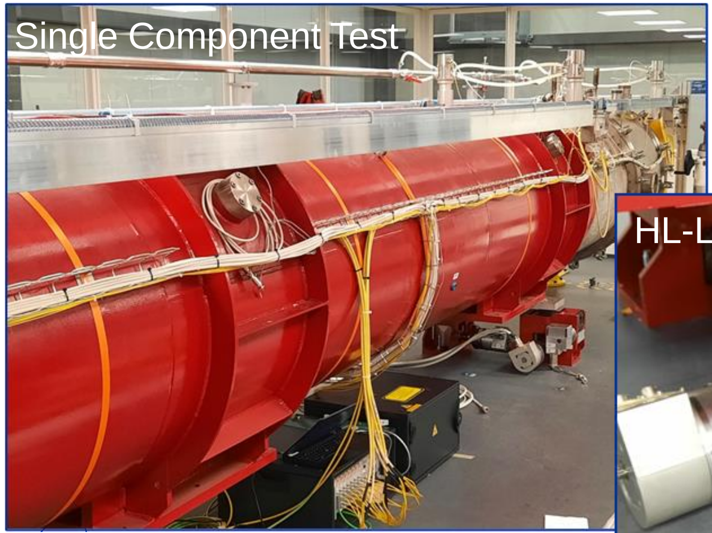
Radial adapter



Vertical adapter



- Safe Working Load of 17.5t
- Quasi-hydraulic solution using polyurethane pastille
  - Angular transmission
  - Anti-backlash thanks to pastille stress
- Irreversibility integrated in the pushing finger thread



- High gear ratio incorporated in the Jack itself → Worm Gear
- Driving output for the radial adapter → Rotation
- Use of an anti-backlash system → Fine resolution

Outlook

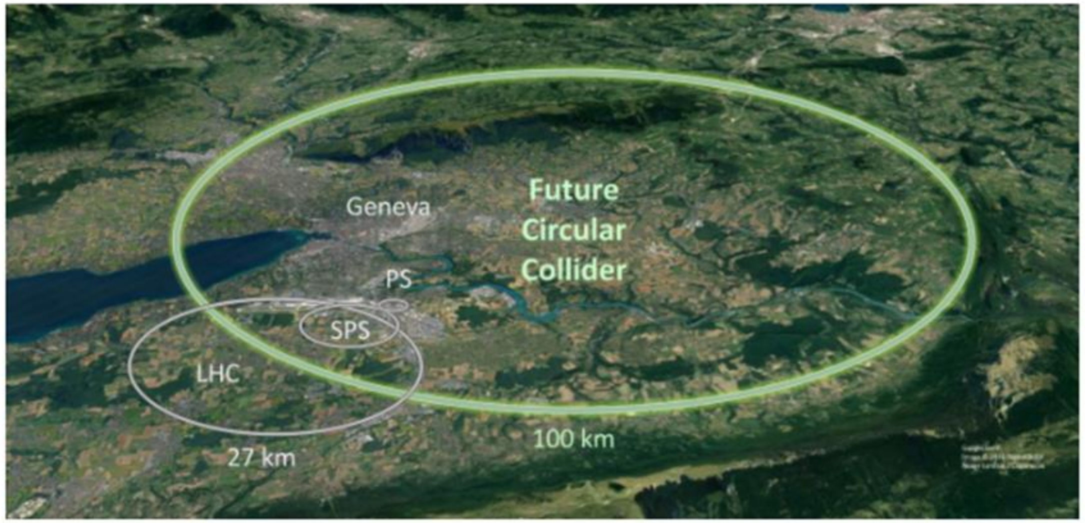
Introduction

The different steps of the alignment of colliders

State of the art and current development for HL-LHC

Towards the alignment of future colliders

Challenges for future colliders



A schematic map showing a possible location for the Future Circular Collider (Image: CERN)

A few challenges:

- Geodetic aspects for such a collider
- Alignment:
  - **Thousands** of components to fiducialise, pre-align on girders and later in the tunnel, within tight alignment tolerances (smaller than the LHC) in a non-stable tunnel:
    - Propose **sustainable and affordable solutions** (from cost point of view), robust and efficient.
    - Develop **automated solutions** of alignment for all these steps of alignment.

Automated fiducialisation «PACMAN type»

Concept

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

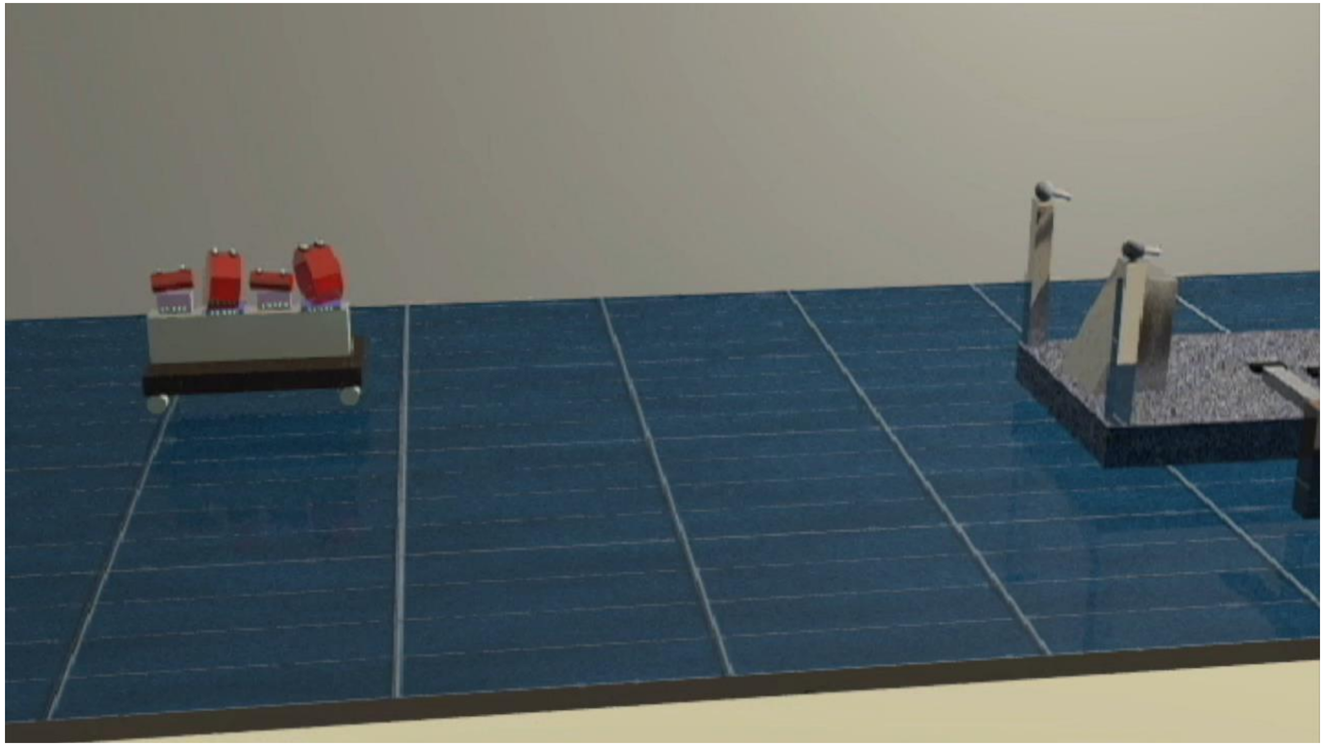
- To relax mechanical tolerances
- To keep the possibility to re-align the components after transport in the tunnel
- More info: PACMAN

See Paper «The new CLIC main linac installation and alignment strategy», Mainaud Durand et al., IPAC2018, WEPAF066

Automated fiducialisation «PACMAN type»

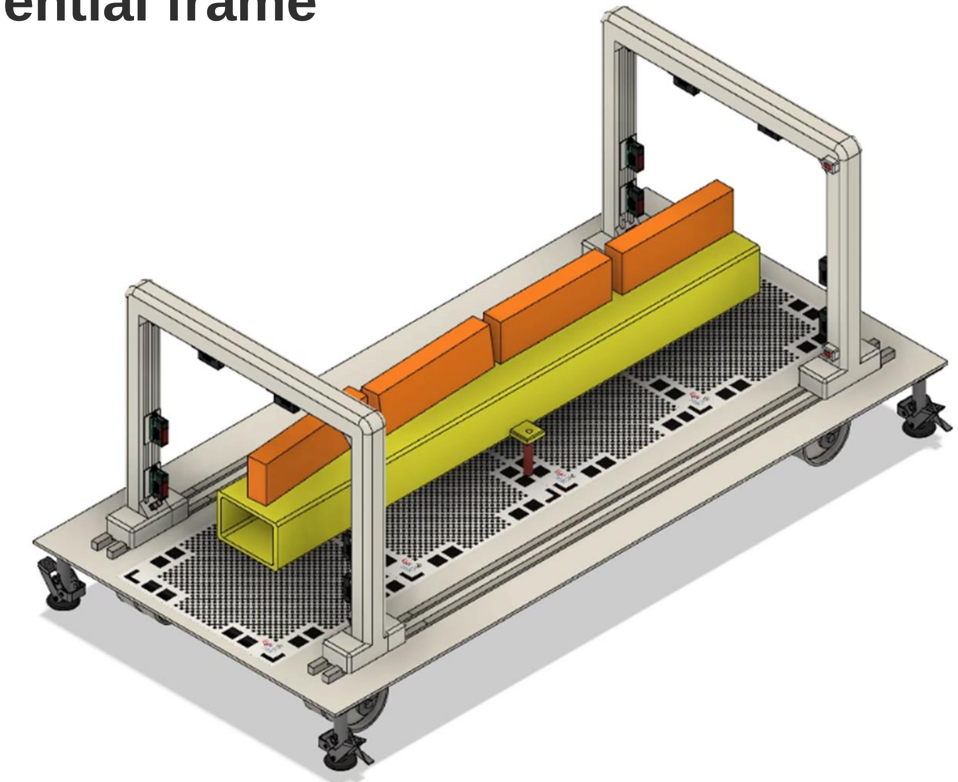
Concept

- Another scenario, to perform at the same time fiducialisation and alignment of components on the girder



Automated fiducialisation «PACMAN type»

Automated alignment of components in the girder referential frame

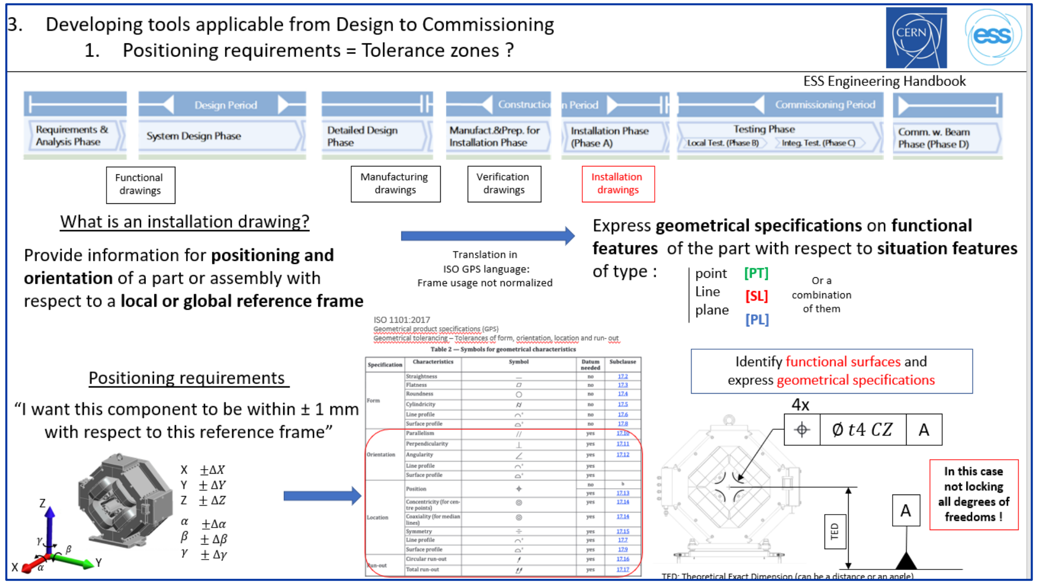


Proposal from students (euspen challenge)

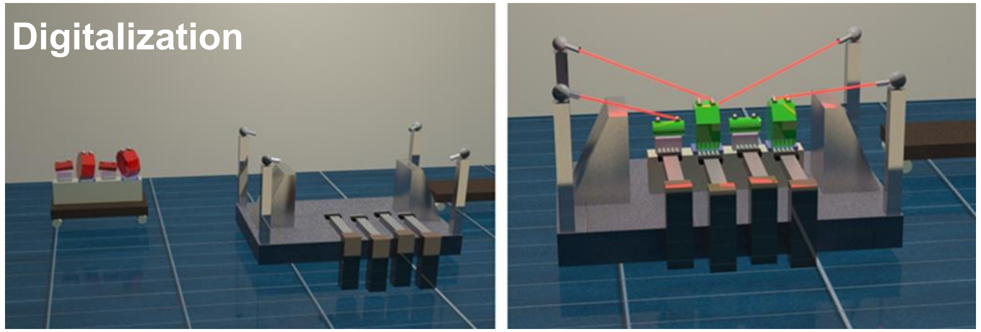
- Will be needed for all future colliders
- Different fiducialisation solutions to develop for components (sextupoles, BPM, quadrupoles)
- Process to be fully automated at 20°C
- To be studied: impact of temperature, transport, etc.
- Integrate 3D reconstruction and digital twin for each girder, historic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

Some perspectives for survey & alignment

Engineering to Alignment (E2A)



AI, machine learning, augmented reality, digitalization applied to Surveying



Possibility to have Data2Cloud (from 3D scans) for the remote visualization of the girder assemblies with a historic data documentation

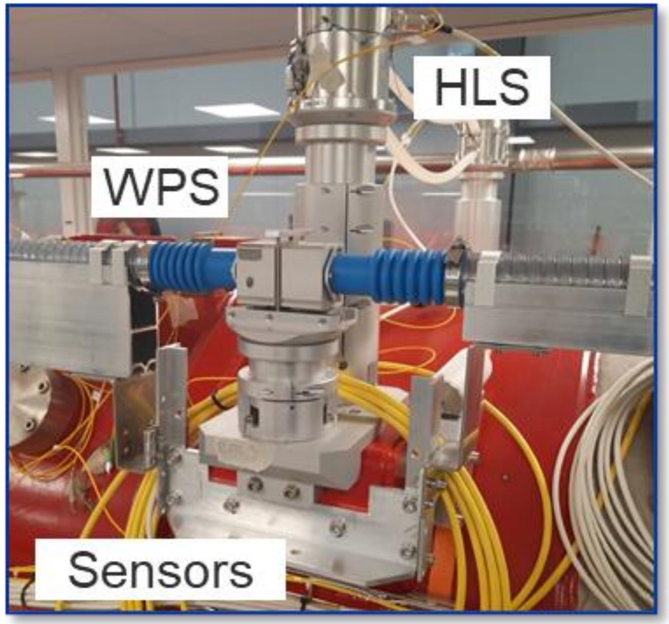
Digital twin for the online anomaly detection and simulation (impact of temperature, humidity, etc.)

Automation

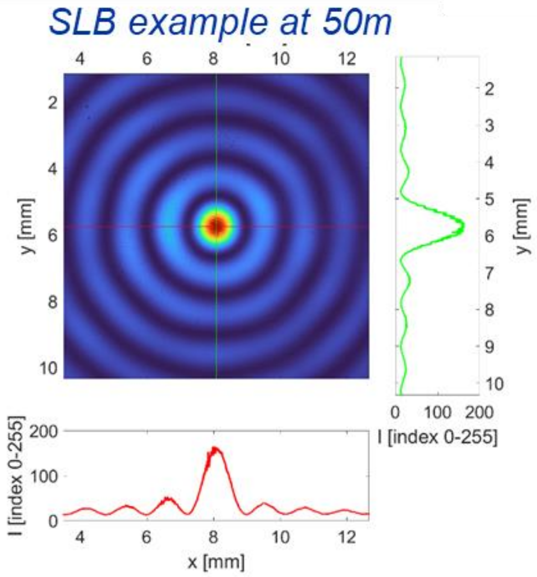
Future trends

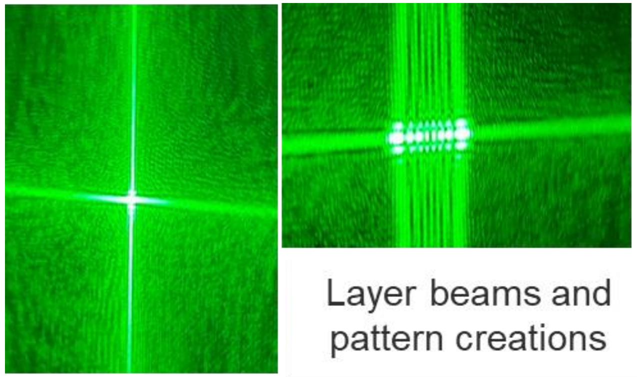
Towards a new generation of sensors

- ✓ Radiation hard
- ✓ Low cost
- ✓ Limited amount of cables
- ✓ No black box (CERN design & industrialized)
- ✓ Open hardware
- ✓ Sustainable



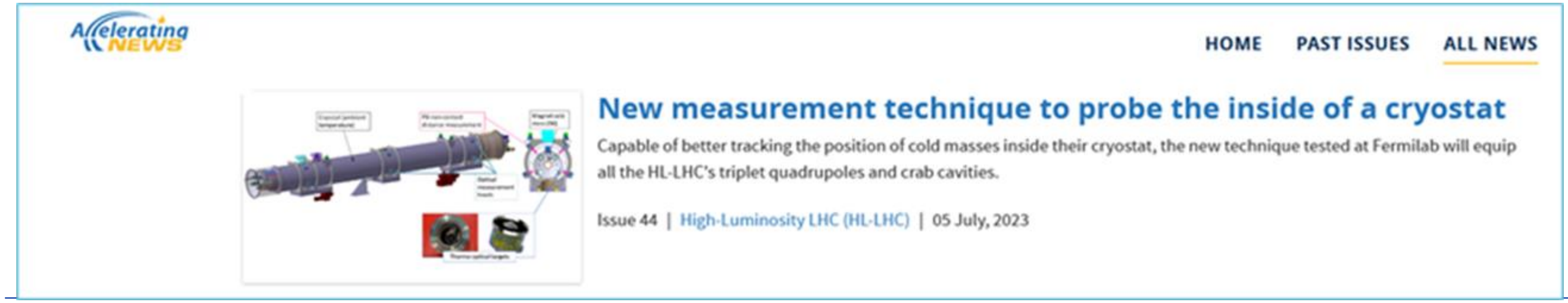
Sensors for Full Remote Alignment System (FRAS)





Layer beams and pattern creations

Structured Laser Beam


Accelerating NEWS

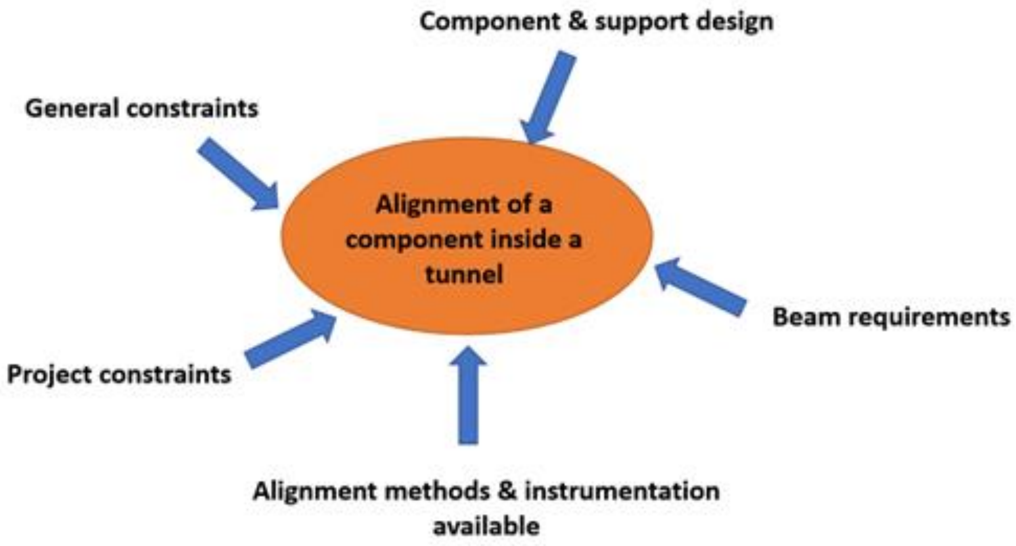
HOME PAST ISSUES ALL NEWS

New measurement technique to probe the inside of a cryostat

Capable of better tracking the position of cold masses inside their cryostat, the new technique tested at Fermilab will equip all the HL-LHC's triplet quadrupoles and crab cavities.

Issue 44 | High-Luminosity LHC (HL-LHC) | 05 July, 2023

Take away messages



Do not forget Survey & alignment in your project, you will gain:
- Time
- Accuracy
- Efficiency

We have to find win-win solutions, as standardization is key for us.

A full workflow is being put in place in the frame of the Engineering to Alignment (E2A) project at CERN, including the generation of installation drawings. Survey guidelines are also there to help with available solutions (different types of fiducials, supports, jacks, sequences of alignment, etc.).

Please integrate us ASAP in your project: we can help you simplifying and decreasing the cost of supporting / adjustment solutions, we can provide assembly solutions, and offer different solutions for high accuracy 3D measurements and adjustment.

Thank you very much! Any questions?

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