Surveying challenges and solutions in CERN's particle accelerators

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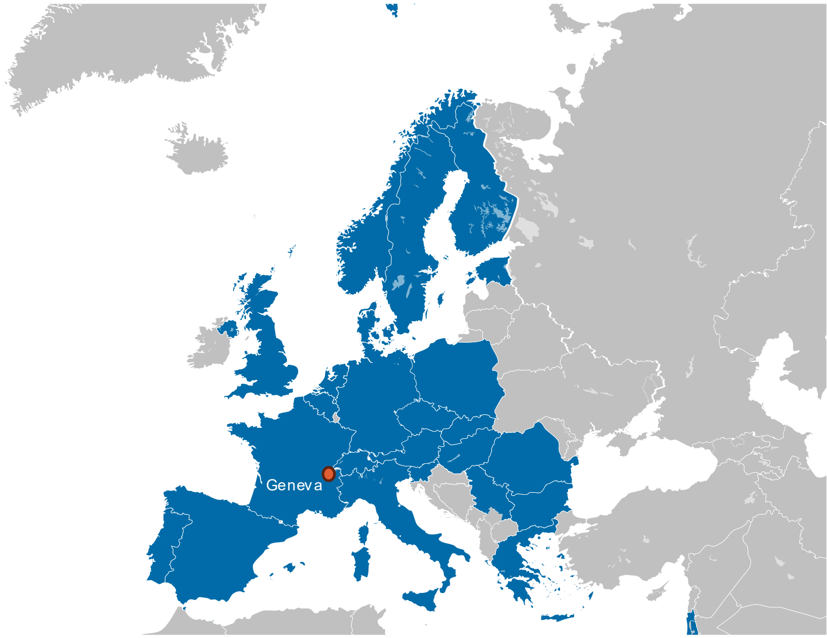
CERN

- **C**onseil **E**uropéen pour la **R**echerche **N**ucléaire was founded in 1954 with 12 European member states:
  - Nuclear / particle physics experiments getting too expensive for individual countries
  - Against the background of the Cold War; 'Science for Peace'
- Today (European Orgainsation for Nuclear Research): **exploring the fundamental structure of the universe by using powerful particle accelerators and detectors to study the basic building blocks of matter and the forces that govern them.**



Member States (25): Austria, Belgium, Bulgaria, Czech Republic, Denmark, Estonia, Finland, France, Germany, Greece, Hungary (1992), Israel, Italy, Netherlands, Norway, Poland, Portugal, Romania, Serbia, Slovakia, Slovenia, Spain, Sweden, Switzerland, United Kingdom

Associate Members: Brazil, Croatia, Cyprus, India, Ireland, Latvia, Lithuania, Pakistan, Turkey, Ukraine

Observers to Council: Japan, Russia (suspended), United States of America, JINR (suspended), European Commission, UNESCO

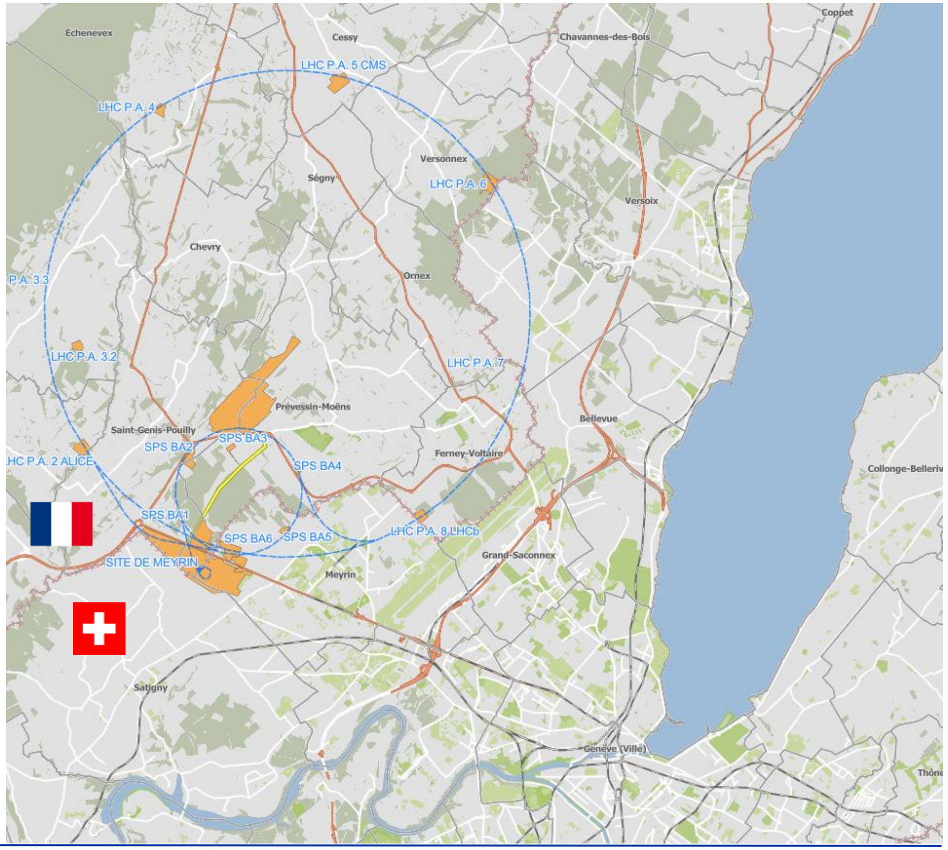
CERN

- **Revenue**

Member State contributions	85.6%
Associate Member State contributions	3.0%
Special contributions *(e.g.: to HL-LHC, specific experiments, from EU)*	3.7%
Other *(e.g.: knowledge transfer, donations,…)*	7.7%

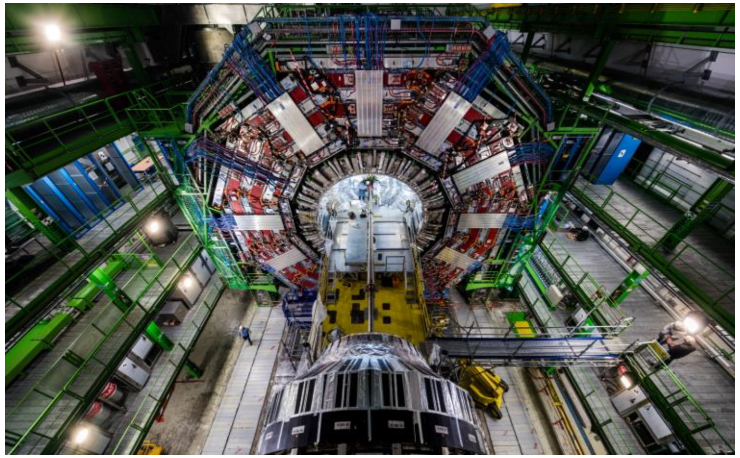
Principle: proportional to Gross National Income (equal effort for every country)

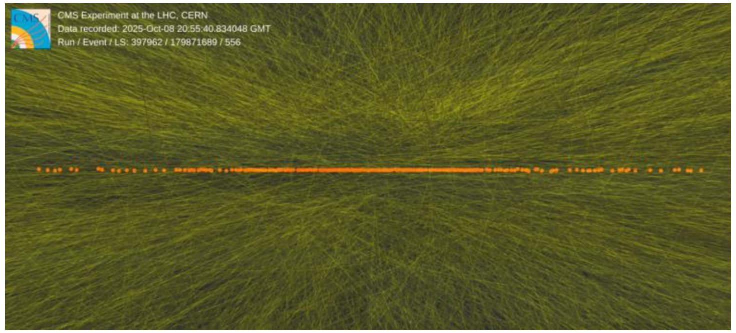
- Budget (2025): 1429 M CHF
- CERN employee (Staff+Grad/Fellow): 3560 (21 Hungarian)
- Users (external researchers and scientists): 11900 (92 Hungarian)
- Infrastructure:
  - Two main sites (Meyrin, Prévessin)
  - 625 ha (fenced: 220 ha)
  - 700+ buildings (500.000 m2)
  - 5 900 parking spots
  - 30 km roads



CERN mission

- Perform world-class research in fundamental physics.
- Provide a unique range of particle accelerator facilities that enable research at the forefront of human knowledge, in an environmentally responsible and sustainable way.
- Unite people from all over the world to push the frontiers of science and technology, for the benefit of all.
- Train new generations of physicists, engineers and technicians, and engage all citizens in research and in the values of science.





Some key dates

1973: Discovery of neutral currents in the Gargamelle bubble chamber.

1983: Discovery of the W and Z bosons in the UA1 and UA2 experiments.

1984: Carlo Rubbia and Simon van der Meer received the Nobel Prize in Physics for their decisive contributions to the discovery of the W and Z particles, carriers of the weak interaction.

1989: Identification of three families of light neutrinos at LEP.

1989: Sir Tim Berners-Lee wrote the first lines of code for the World Wide Web.

1992: Georges Charpak received the Nobel Prize in Physics for the invention and development of particle detectors: the multiwire proportional chamber.

1995: The first anti-hydrogen atoms were created at CERN.

2008: Start-up of the LHC (Large Hadron Collider).

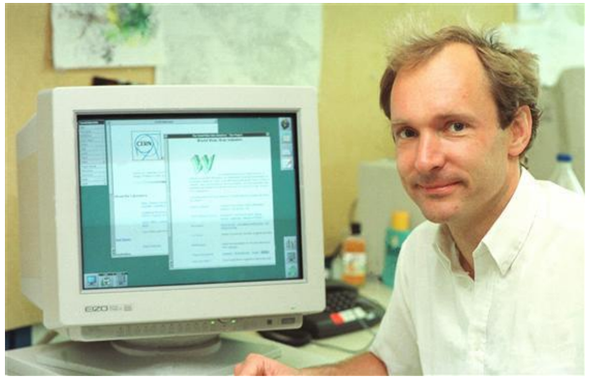
2012: Discovery of the Higgs boson!

2013: On October 8, 2013, the Nobel Prize in Physics was jointly awarded to François Englert and Peter Higgs for the theoretical discovery of the mechanism that contributes to our understanding of the origin of mass of subatomic particles, confirmed by the discovery made by the ATLAS and CMS experiments at CERN's LHC.

Working at CERN when Nobel prize
- 1984: Carlo Rubbia and Simon van der Meer
- 1988: Jack Steinberger
- 1992: Georges Charpak

Working at CERN after Nobel prize
- 1952: Felix Bloch
- 1976: Sam Ting

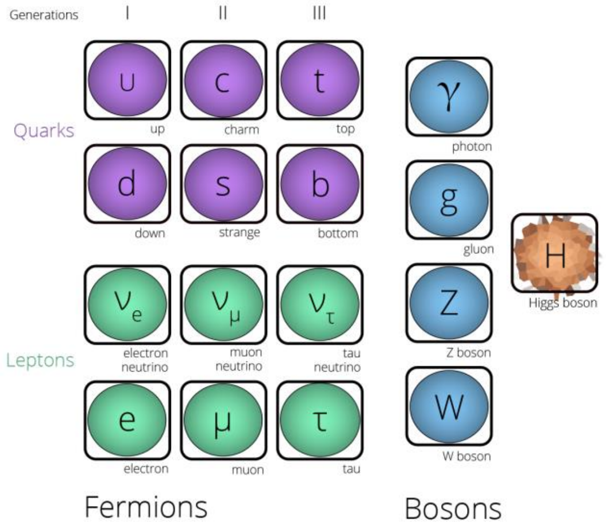
Nobel prize thanks to discoveries at CERN:
- 2013: Peter Higgs and Francois Englert



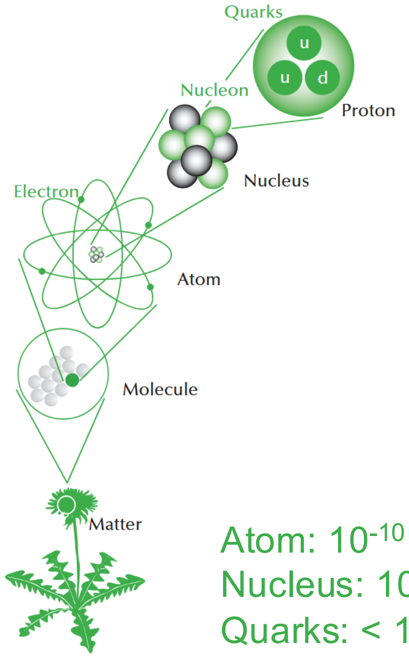
Particle physics

- According to the **Standard Model**, all matter around us is made of **elementary particles**, the building blocks of matter. These particles occur in two basic types called quarks and leptons. Each group consists of six particles, which are related in pairs, or “generations”.

- There are four **fundamental forces** at work in the universe. The strong force, the weak force, the electromagnetic force, and the gravitational force. Three of the fundamental forces result from the exchange of force-carrier particles, which belong to a broader group called “bosons”. Particles of matter transfer discrete amounts of energy by exchanging bosons with each other. Each fundamental force has its own corresponding boson:
  - Electromagnetic force (photons)
  - Weak force (bosons)
  - Strong nuclear force (gluons)
  - Gravitation (*gravitons?*)



+ antimatter partners



Atom: 10^{-10} m
Nucleus: 10^{-14} m
Quarks: $< 10^{-19}$ m

What is still missing?

The **Standard Model** explains a lot, but not everything.

- Dark matter

Proposed to explain gravitational effects in the universe that ordinary matter alone can't account for. Could involve new, undiscovered particles, but what are they?

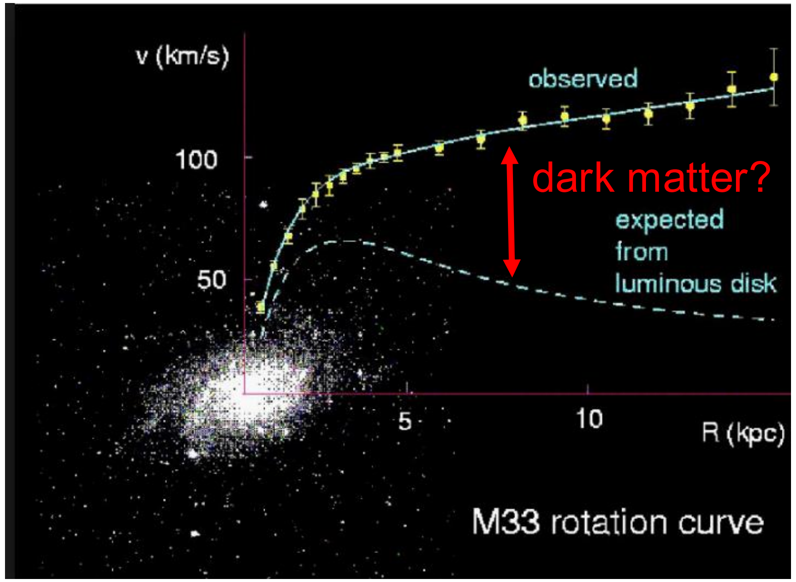
- Dark energy

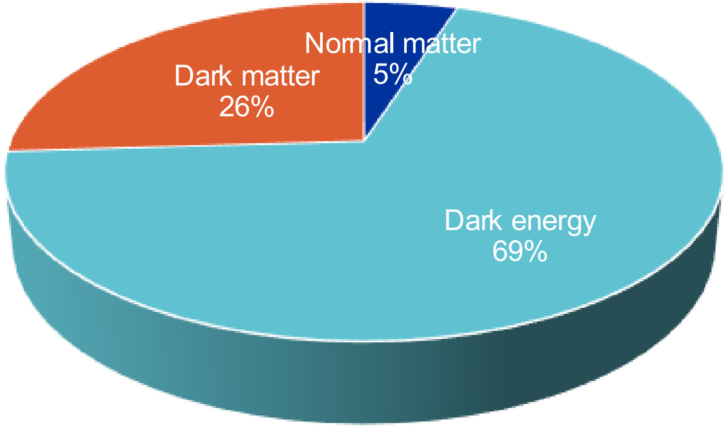
Introduced to explain why the universe's expansion is accelerating. Its nature and origin are still unknown.

- Matter - Antimatter asymmetry

The Big Bang should have produced equal amounts of matter and antimatter. So why is the universe made mostly of matter, where did the antimatter go?

- How to include gravity in the picture?





How can elementary particles be studied?

The instruments used at CERN are particle **accelerators** and **detectors**:

- **Accelerators** accelerate particle beams to high energies (due to relativistic effects their momentum and energy increase) to collide them with other beams or with fixed targets.

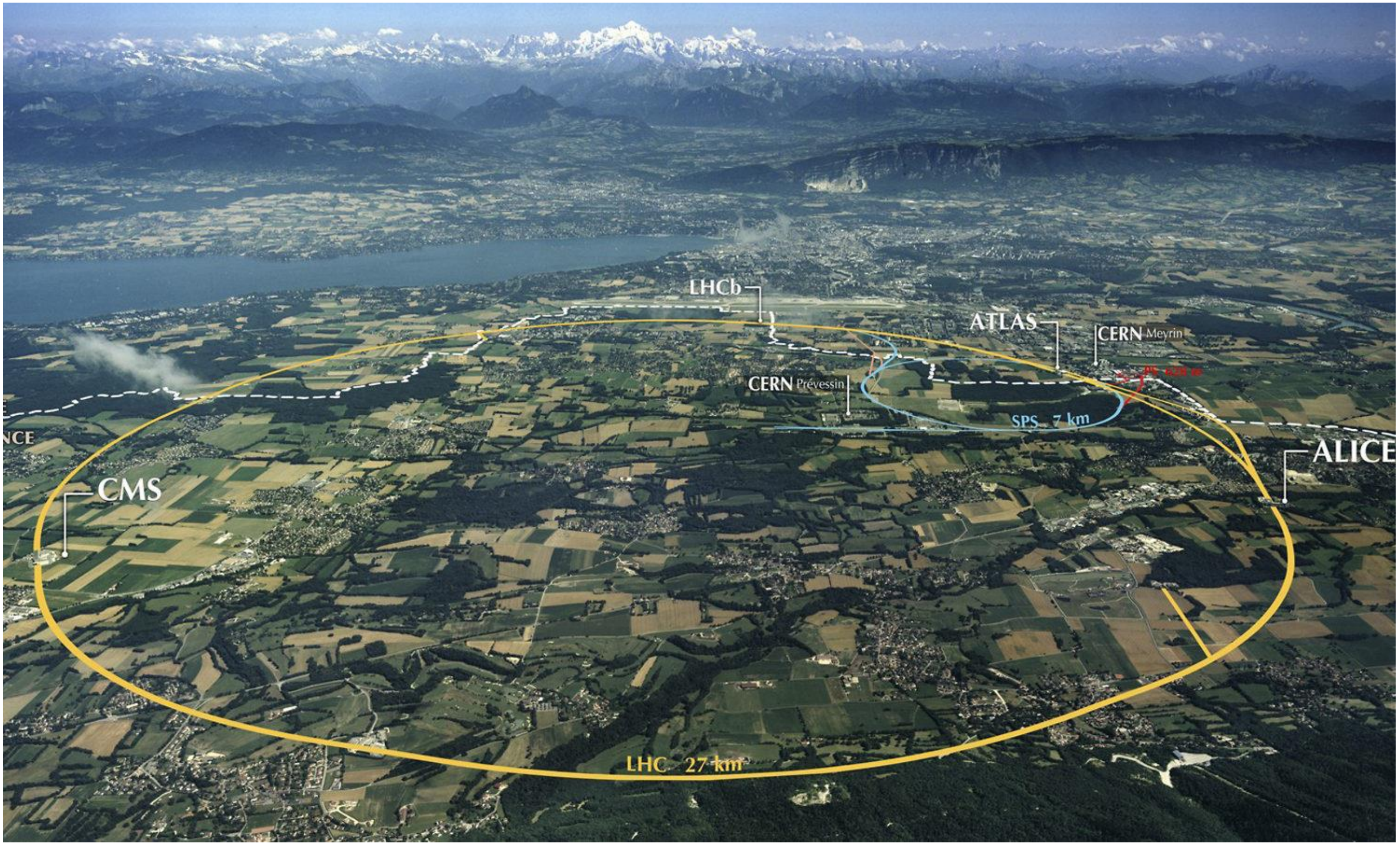
- When these high-energy particles collide, the energy concentrated at the collision point is converted into mass, according to Einstein's equation:

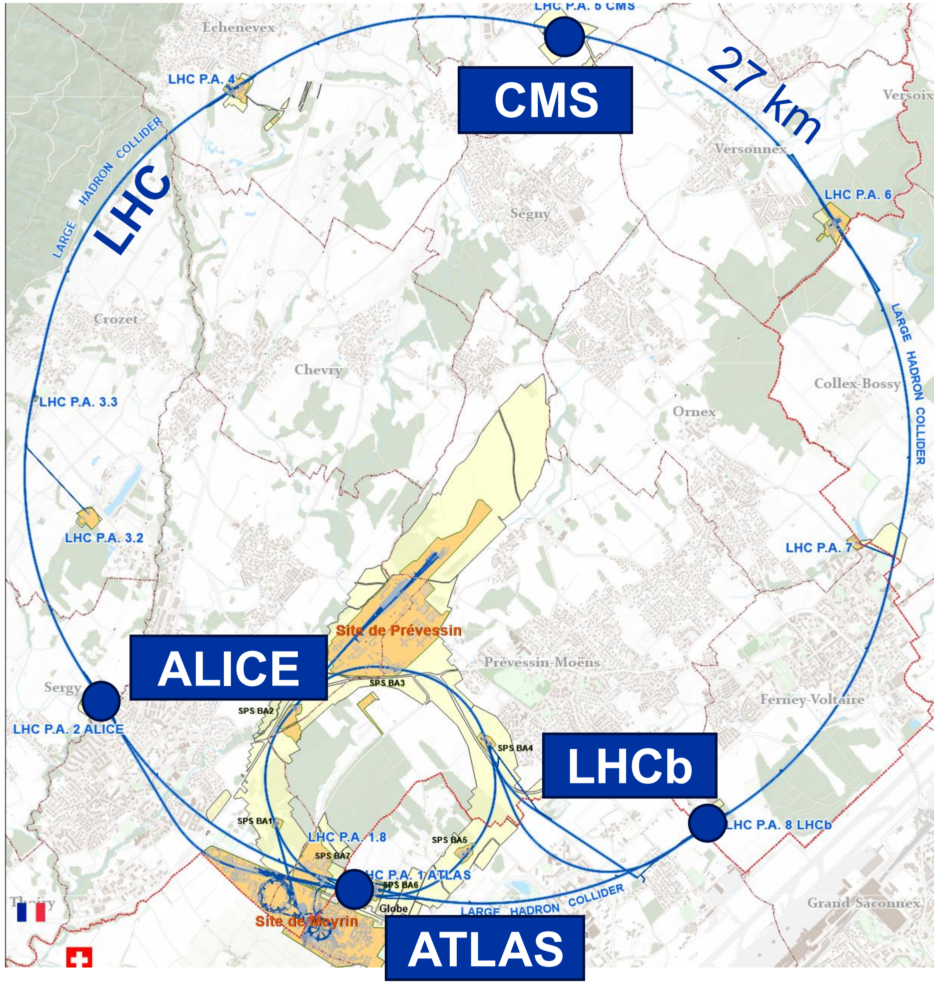
$$E = mc^2$$

- This allows the creation of particles that are much heavier than the ones being accelerated. These new particles quickly decay into lighter, more stable ones.

- **Detectors** record the tracks, energies, and momenta of the decay products (photons, electrons, muons, hadrons, etc.)

Accelerators at CERN – a bird's eye view





LHC in the Geneva basin

Large Hadron Collider - LHC

- **Large:**

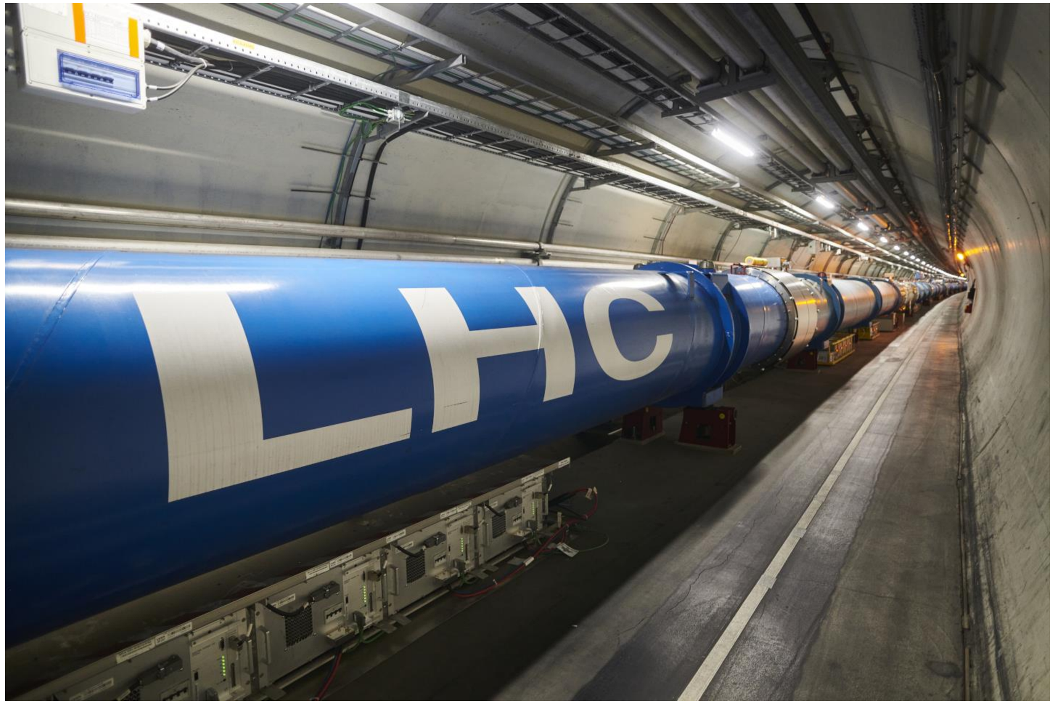
A circular accelerator 27 kilometers in circumference, located about 100 meters underground.

- **Hadron:**

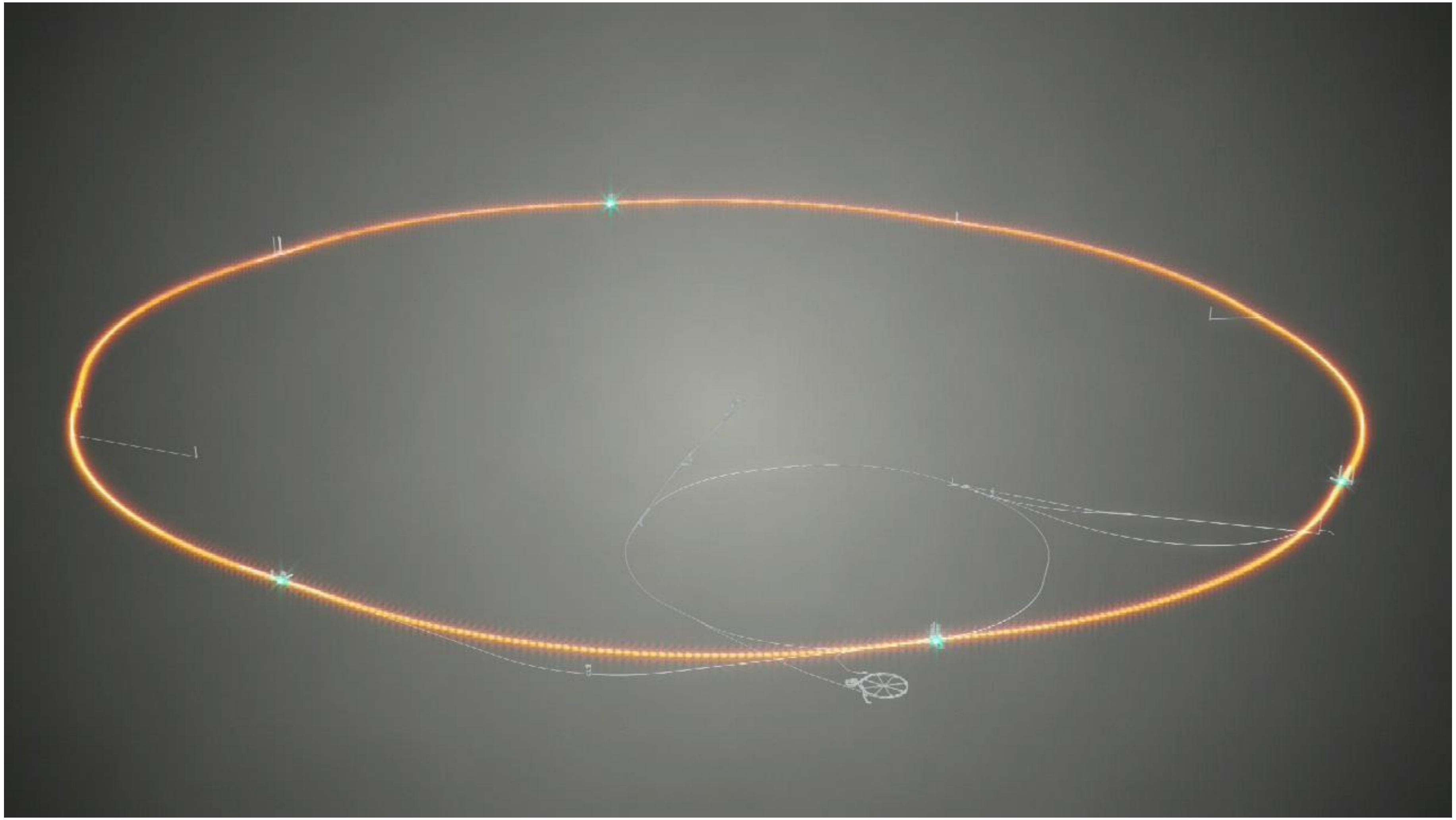
Accelerates particles made of quarks, such as protons or lead nuclei collectively known as hadrons.

- **Collider:**

Two counter-rotating beams of these particles are accelerated in opposite directions and brought to collide at specific Interaction Points, where large detectors (ATLAS, CMS, ALICE, LHCb) record the resulting events.



Large Hadron Collider - LHC



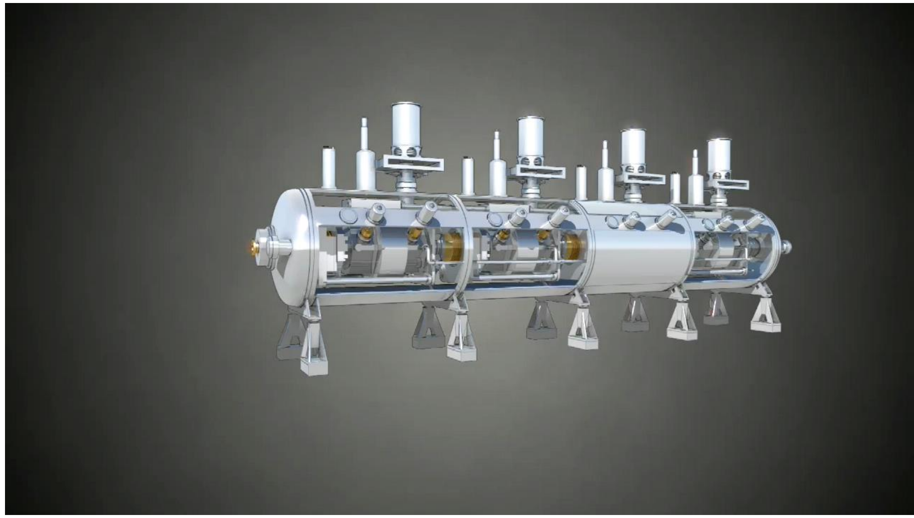
Large Hadron Collider - LHC

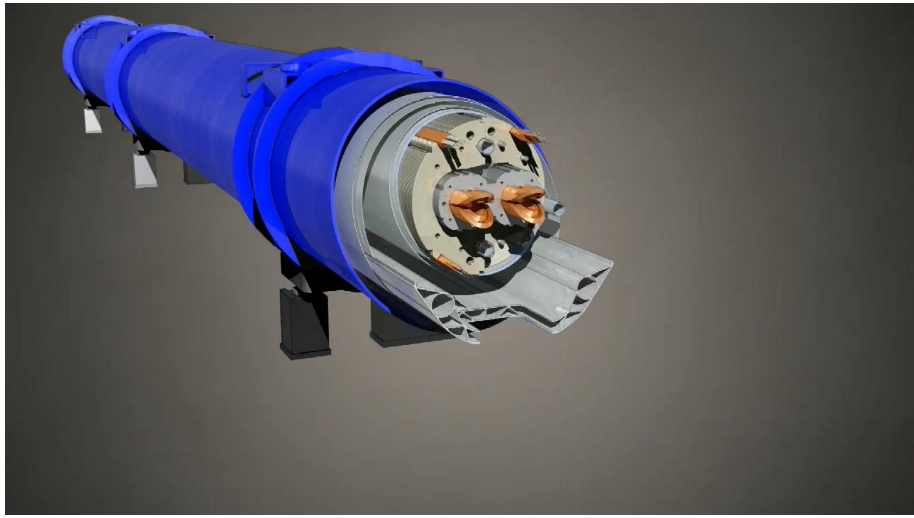
- Beams reach 99.999999% of the speed of light, colliding with a total energy of 14 TeV.
- At this speed, a proton in the LHC makes 11 245 circuits every second.
- Superconducting magnets, cooled to 1.9 K (–271.3 °C), produce fields up to 8.3 T to bend and focus the beams.

  1.9 K is colder than outer space, which is about 2.7 K!

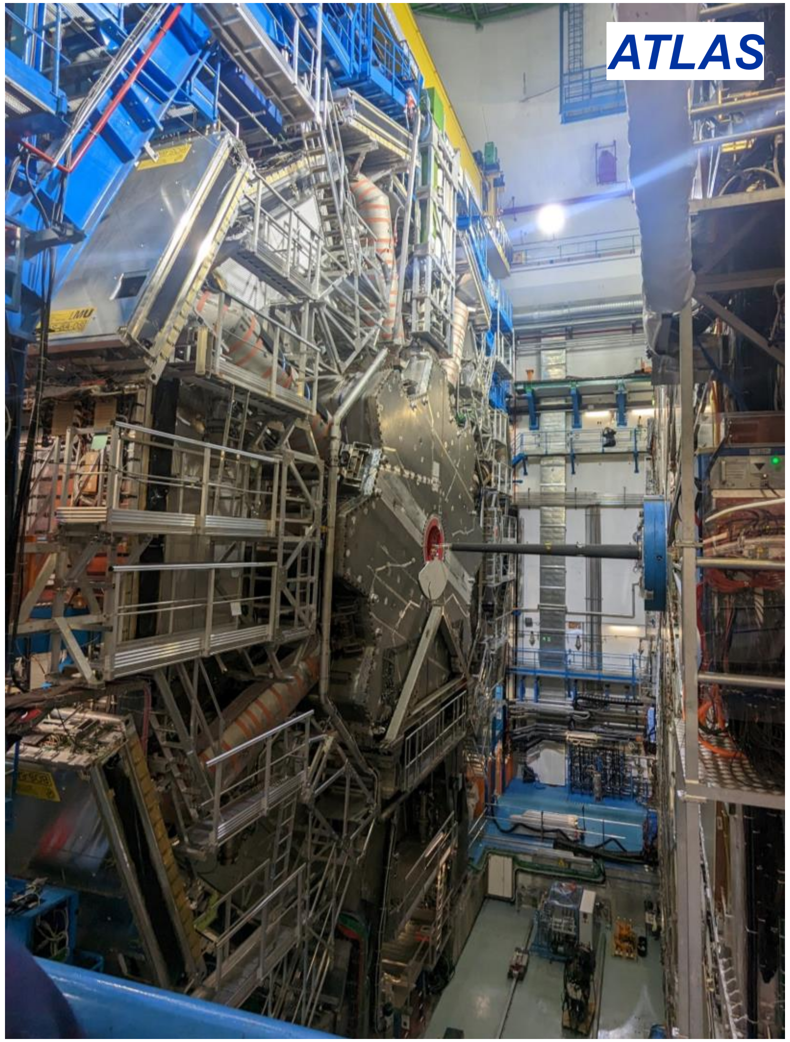
  8.3 T is 3000 times stronger than Earth's magnetic field
- Radio-frequency (RF) cavities accelerate the protons each turn.
- Each beam has 2808 bunches, each containing ~100 billion protons.

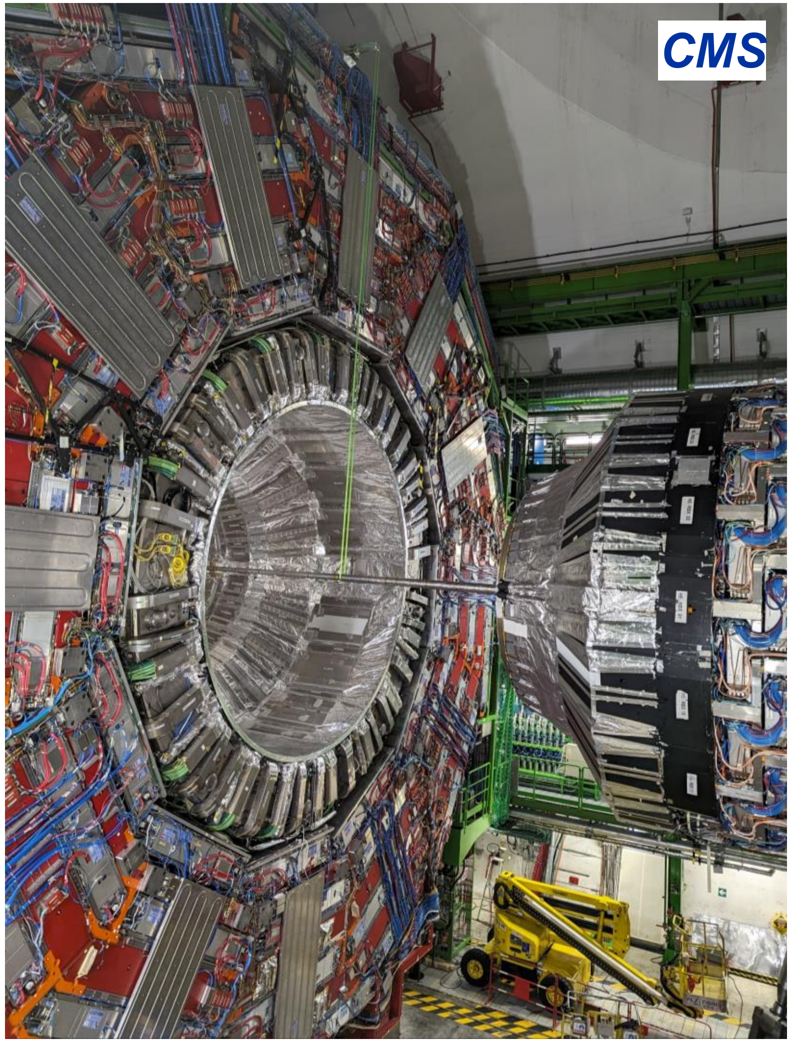
  when two bunches cross, only about 40 protons actually collide out of those 200 billion!
- That still means about 1 billion collisions per second overall.
- These collisions recreate energy densities and temperatures similar to those microseconds after the Big Bang, helping physicists explore the origin of matter and the fundamental forces.

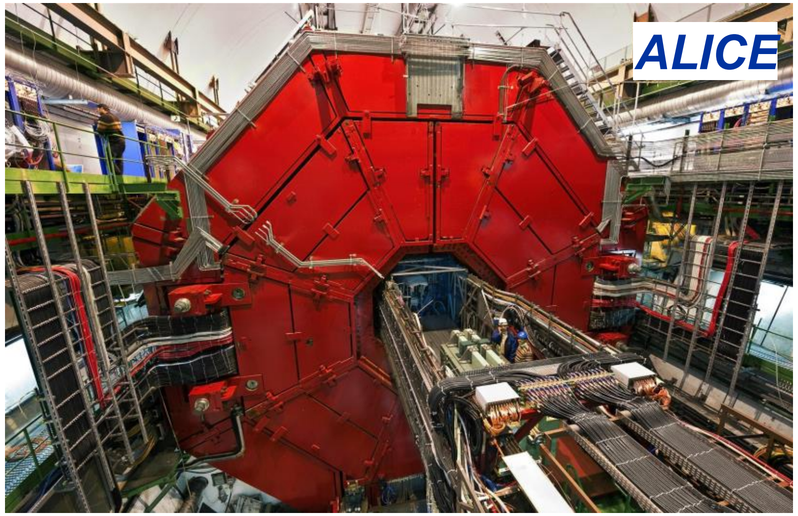




LHC Detectors







Surveying at CERN

The main role:

The components forming the accelerators and detectors/experiments must be aligned with tolerances on the order of +/- 0.2 mm

Accelerator alignment

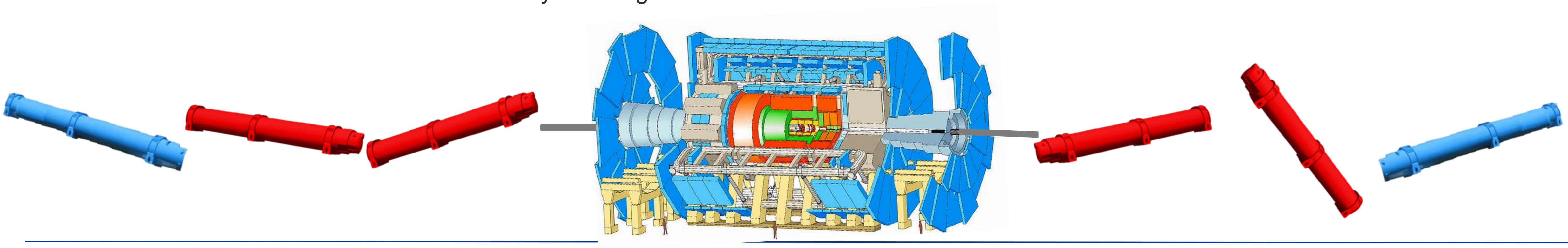
- The LHC is an extremely complex machine, consisting of superconducting magnets, beam transfer lines, straight and curved sections, and detector experiments.
- Thousands of components from a few hundred grams to several tons, made of different materials and working under various operating conditions.
- Subject to changing ambient conditions (temperature, humidity), strong magnetic fields, and radiation.
- Even the Earth itself moves over time (ground motions, tides).
- Meanwhile, particle bunches only a few micrometres wide must collide head-on with high precision

Therefore

- It is crucial to measure and know the position of every component as precisely as possible.

So that we can

- Align all components correctly relative to each other.
- Re-align any component when needed.
- Ensure the beam travels and collides exactly as designed.



Geodetic Metrology group

Accelerator Survey and Geodetic Measurements (ASG)

Experiment Survey and Alignment (ESA)

Future Projects (FP)

High Precision Alignment (HPA)

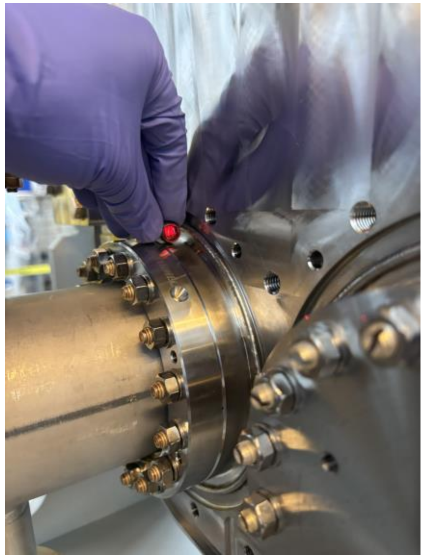
Acquisition Processing and Data Control (APC)

Areas of work:

- Accelerators (e.g., LHC, SPS, PS)
- Beam transfer lines connecting the machines
- Physics experiments and their detector systems

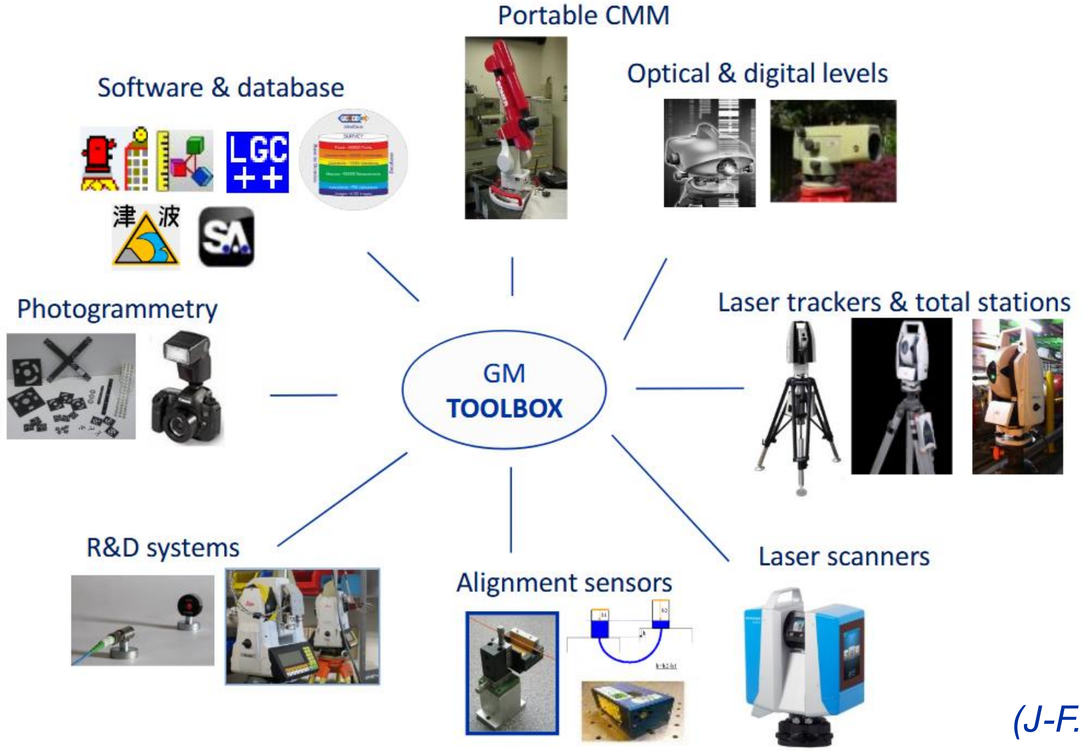
Scale of operations:

- Over 60 km of beam lines
- More than 40,000 accelerator components
- 20+ major experiments, each with thousands of sub-detectors requiring micrometre-level precision

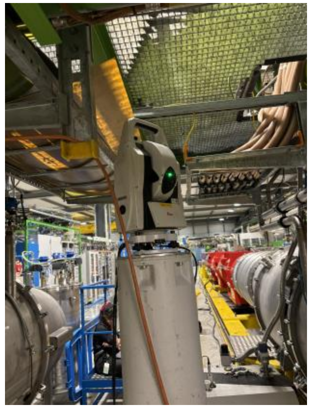


Survey toolkit

- Wide range of instruments, sensors, and software solutions to ensure precise measurements
- Most filed measurements are performed using laser trackers (±1 arcsec, 8 µm + 2.5 ppm)
- Resources for maintenance and validation.
- Specific sensors (see later)
- Special benches for sensor calibrations
- Wide range of software: commercial and in-house developments
- Dedicated SURVEY DB



(J-F. Fuchs)



Steps of alignment

On the surface

Definition of alignment tolerances

Strategy & Design - Network simulation - Datum

Select the most appropriate instrumentation

Installation and determination of surface geodetic network

Inside the tunnel

Time

Transfer of reference into the tunnel

Installation and determination of an underground geodetic network

Definition of the theoretical trajectory

Fiducialisation of the component

Absolute alignment of the components

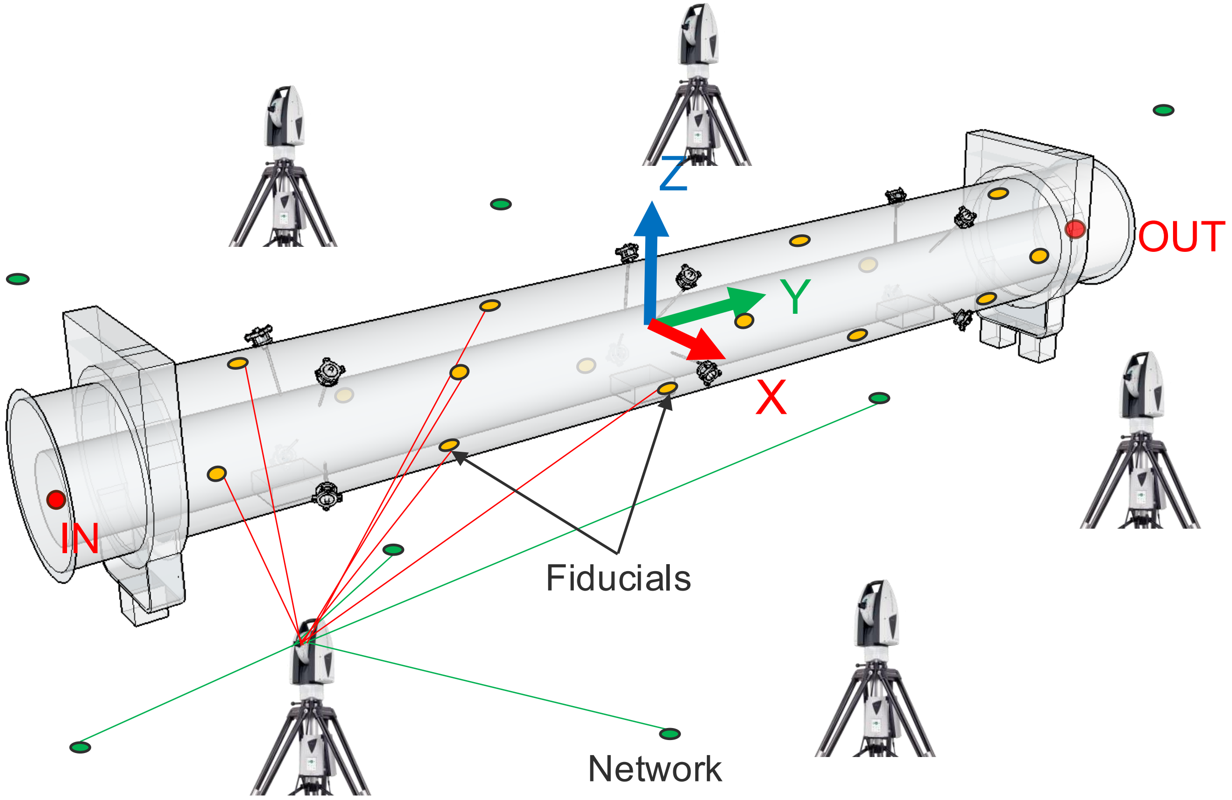
Relative alignment of the components

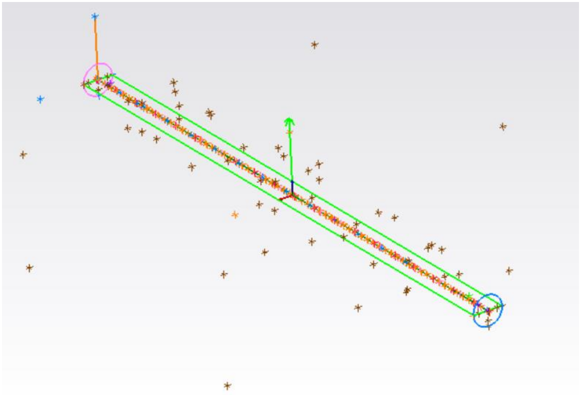
Maintenance of the alignment

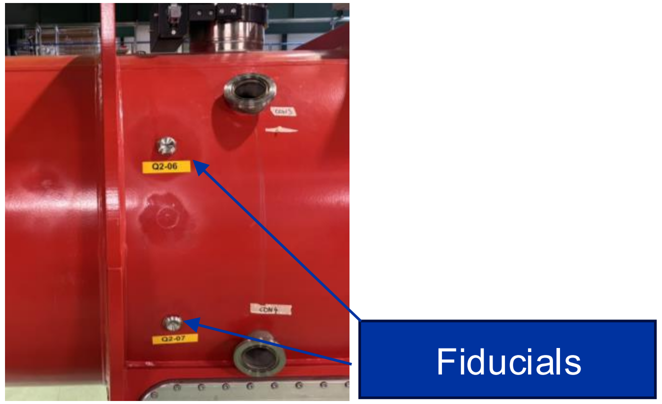
(J-F. Fuchs)

Accelerator alignment

- Each component goes through on a measurement called fiducialisation.
- Fiducialisation determines the reference axis (mechanic, magnetic, RF) of the component relative to its external alignment targets (fiducials) accessible for survey measurements.
- Measurements are performed using laser trackers, CMM, and similar high-precision instruments
- A local coordinate system is created that fits to the reference axis
- All the fiducials coordinates are expressed in this frame





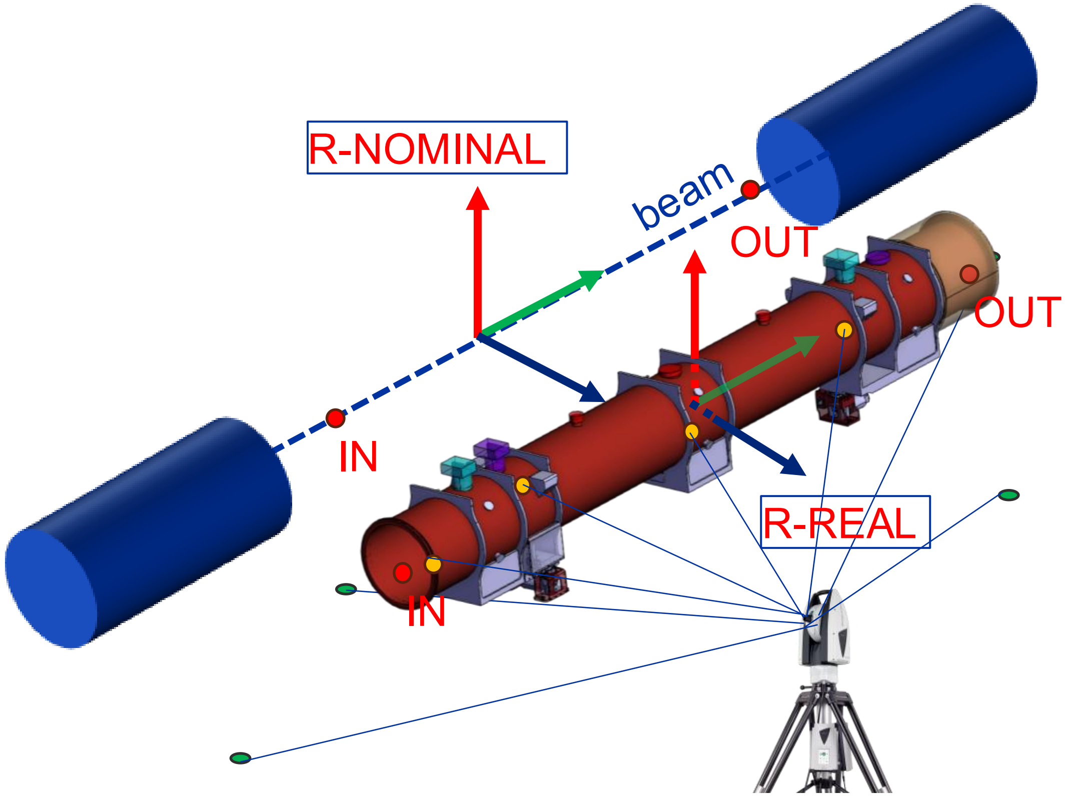


Accelerator alignment

- The XYZ coordinates of each fiducial in the CERN coordinate system (CCS) are calculated, based on the installation slot of the component in the tunnel.
- Theoretical component positions are marked in the tunnel and the components are installed at these marks.
- The goal is to place each component at its nominal position and orientation.

General approach:

- The laser tracker is positioned in the CCS using measured network points or fiducials on neighbouring components.
- In the CCS, the nominal local frame of the component can be constructed, since the nominal coordinates of the fiducials are known.
- After measuring the component's fiducials, the real local frame is constructed using the actual measurements.
- The alignment objective is to minimise the transformation between the nominal and real local frames (within tolerances) in 5 or 6 DoF.



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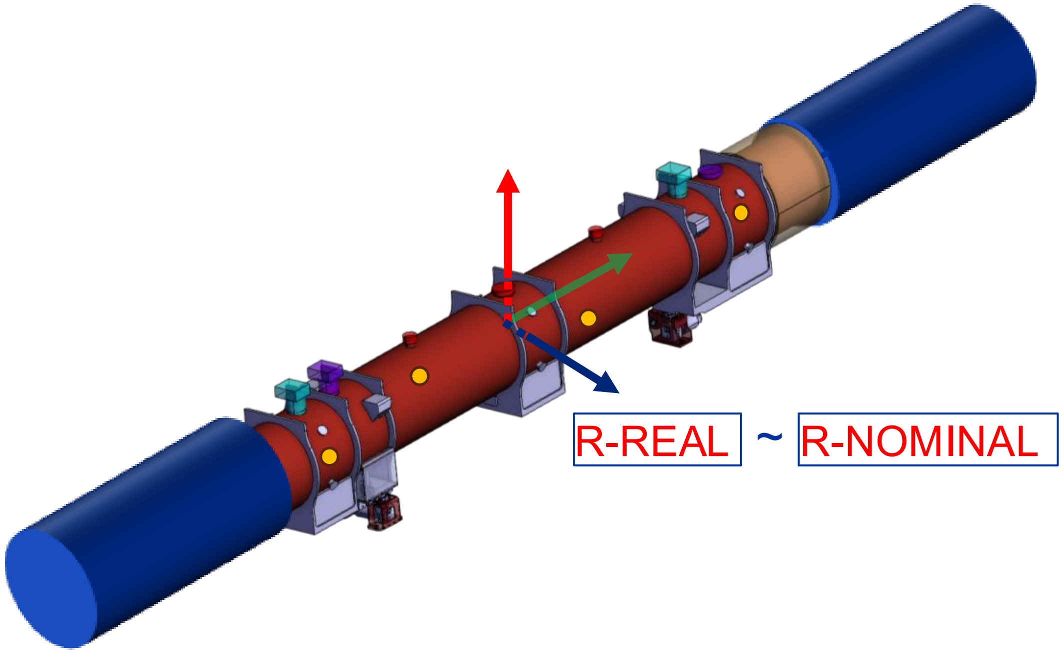


R-REAL ~ R-NOMINAL

Adjustment platforms

Jacks

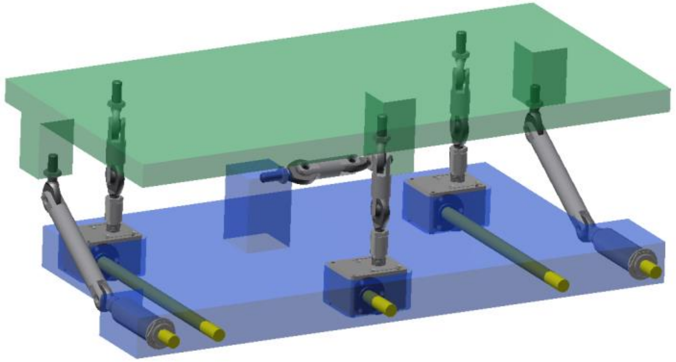
R & L adjustment

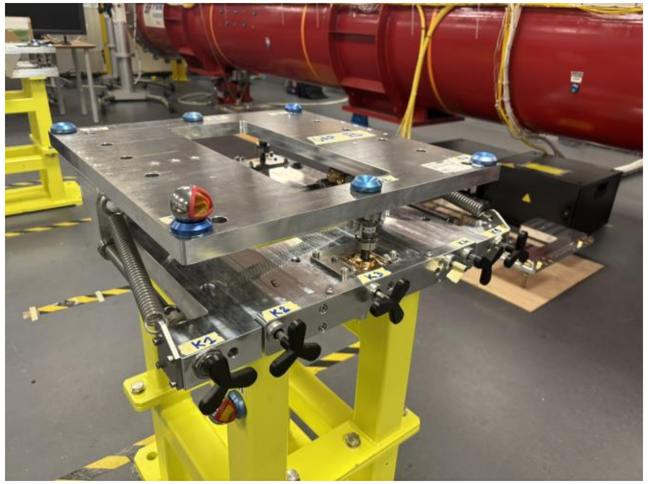
Vertical adjustment

(J-F. Fuchs)

UAP

- Kinematics of adjustment system framework.
- 5 or 6 DOF position adjustment
- Easy access from transport zone
- Option of remote adjustment using portable motorized adapters



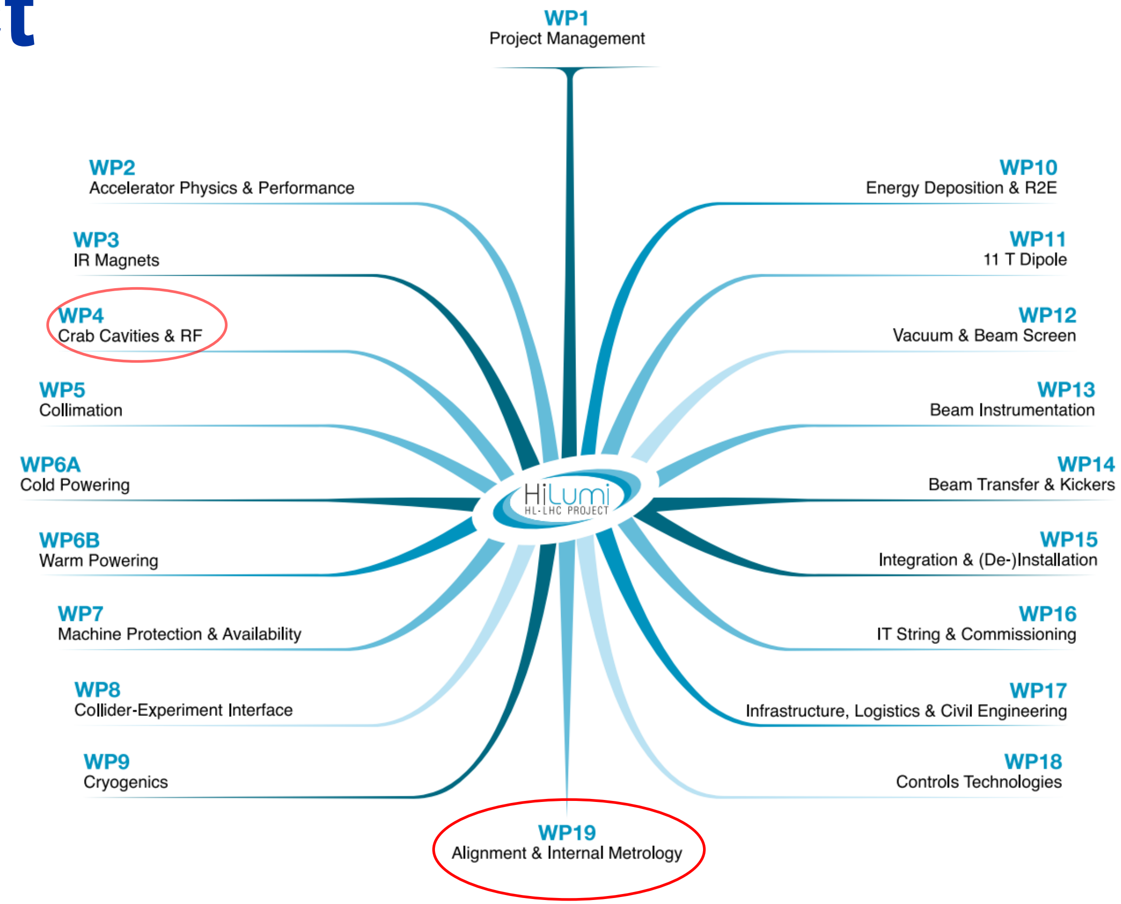


High-Luminosity LHC

HiLumi
HL-LHC PROJECT

High-Luminosity LHC project

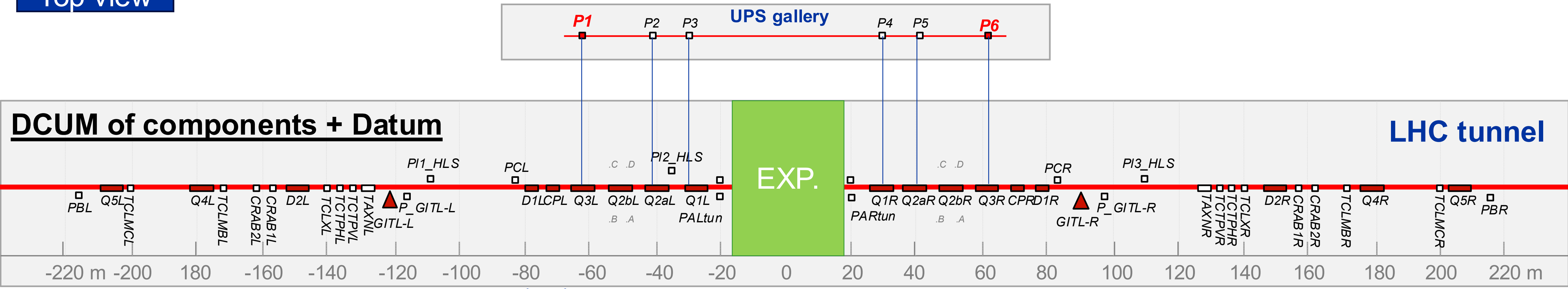
- Aims to increase the machine's luminosity (i.e. number of collisions) by a factor of between five and ten.
- Completely operational from 2030
- **How to achieve** it: squeeze the maximum number of particles into the smallest possible space at the interaction points.
- New components in total of 1.2 km around the CMS and ATLAS detectors will be installed (Crab Cavities, Quadrupoles, Collimators, etc.)
- Smaller beam size -> lower tolerances and more accurate alignment -> **F**ull **R**emote **A**lignment **S**ystem



luminosity: measure of the number of potential collisions per surface unit over a given period of time

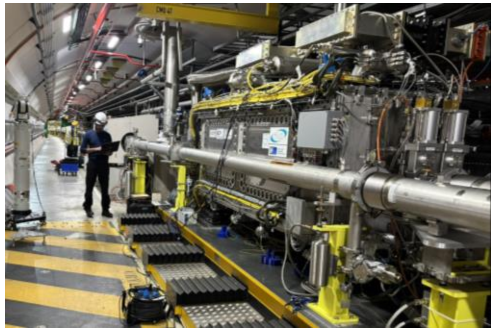
High-Luminosity LHC – component upgrades

Top view



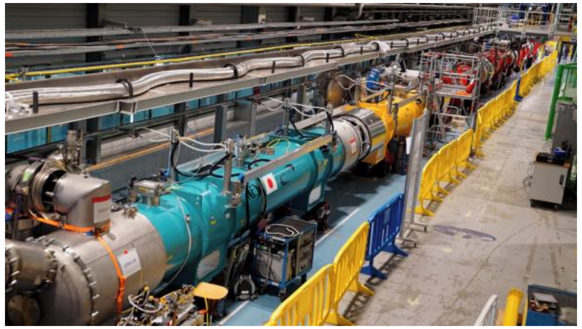
e.g.:

Crabs (in SPS)



Collimators (mock-up)

D1 & CP (in IT string)



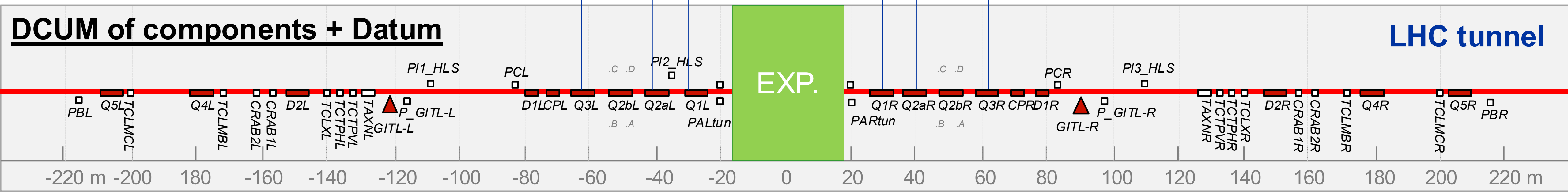
Low Beta quadrupole (on a test bench)

High-Luminosity LHC – Alignment tolerances

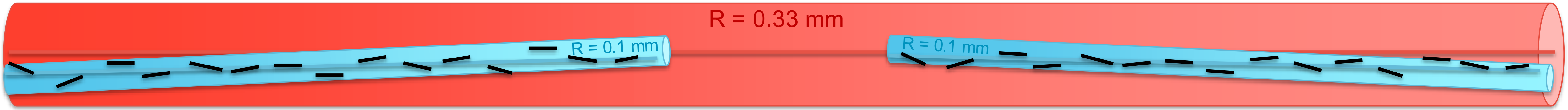
Top view

Alignment between Q1 and Q5 :
Limits : σ (1 sigma) < 0.1 mm

Alignment between Q5-left and Q5-right :
- Vertical Limits : σ (1 sigma) < 0.17 mm
- Radial Limits : σ (1 sigma) < 0.33 mm



Left | Right



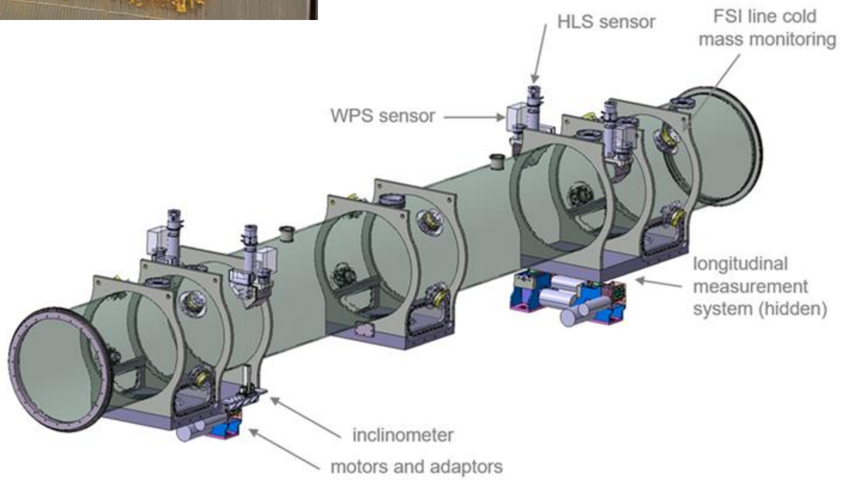
Alignment requirement
- Align all the components per EXP side : < 100 µm (1σ)
- Align all the components (Left and Right) : Vertical < 170 µm (1σ)
- Align all the components (Left and Right) : Radial < 330 µm (1σ)
- Roll : < 150 µrad (1σ)

(V. Rude)

High-Luminosity LHC – Full Remote Alignment System

Challenges

- The HL accelerator environment is going to be extremely harsh (TID apporx. 1MGy).
- Radiation-hard components are essential
- Cold mass displacement w.r.t vacuum vessel due to vacuum and cold



Objective of FRAS

- Remote determination and adjustment of component positions
- Reduce radiation exposure for surveyors (no tunnel access needed between YETS or LS).
- Requires: new sensors (simple, robust), software, etc.

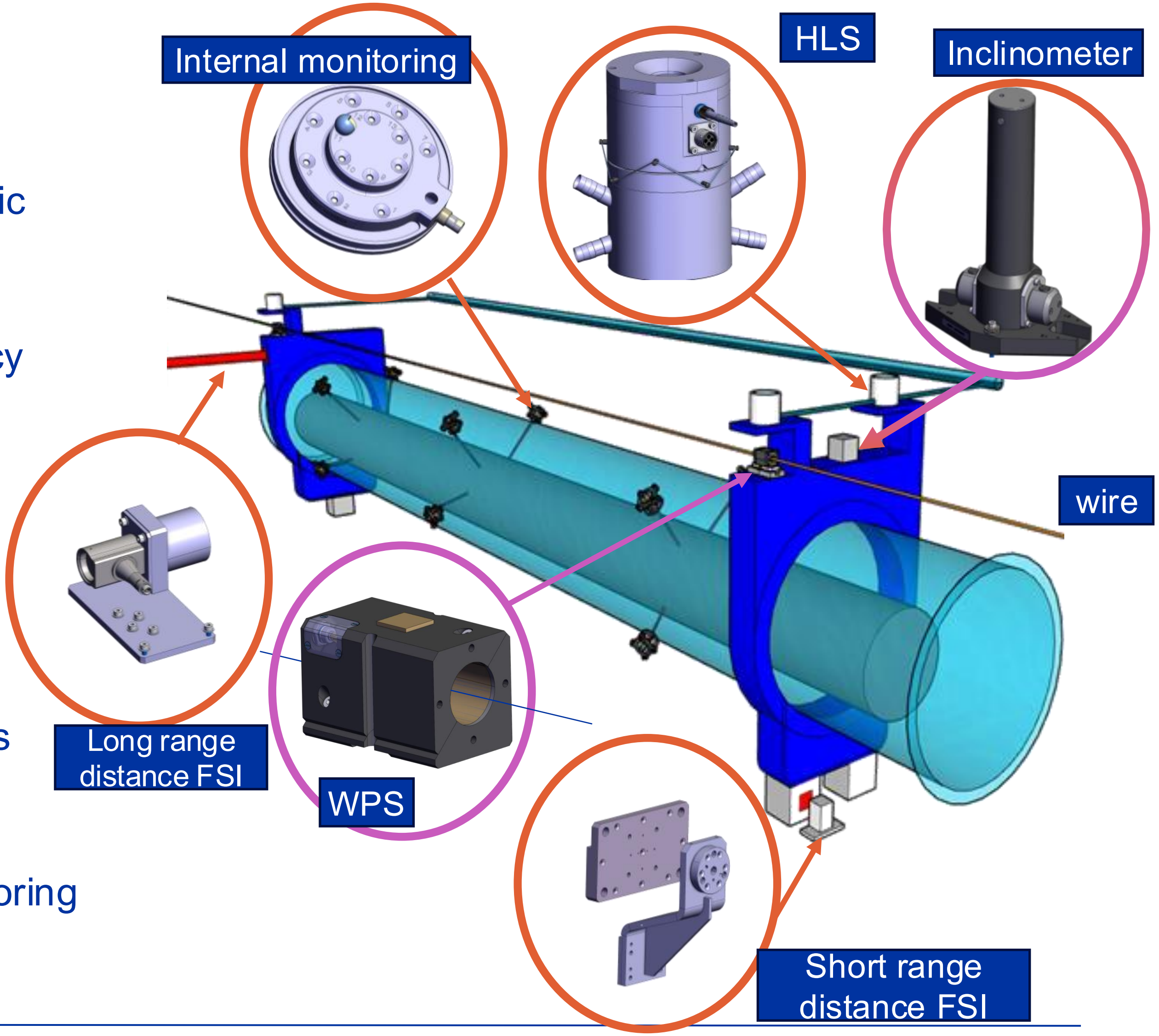
FRAS – Sensors & technologies

Capacitive technology

- **Wire Positioning Sensors (WPS):**
  Performing continuous radial and vertical offset measurements w.r.t. a stretched wire, within a micrometric resolution
- **Inclinometer**
  Measuring components Roll angle with ±10 µrad accuracy

Frequency Scanning Interferometry (FSI) technology

- **Hydrostatic Levelling Sensor (HLS):**
  Performing vertical offset measurements w.r.t. a water surface, within a micrometric resolution
- **Internal monitoring heads and targets:**
  Measuring distances between vacuum vessel and targets located on the magnet cold masses/CRAB cavities
- **Distance sensors**
  Radial position transfer through UPS galleries and monitoring of longitudinal position of components
- **Inclinometer**



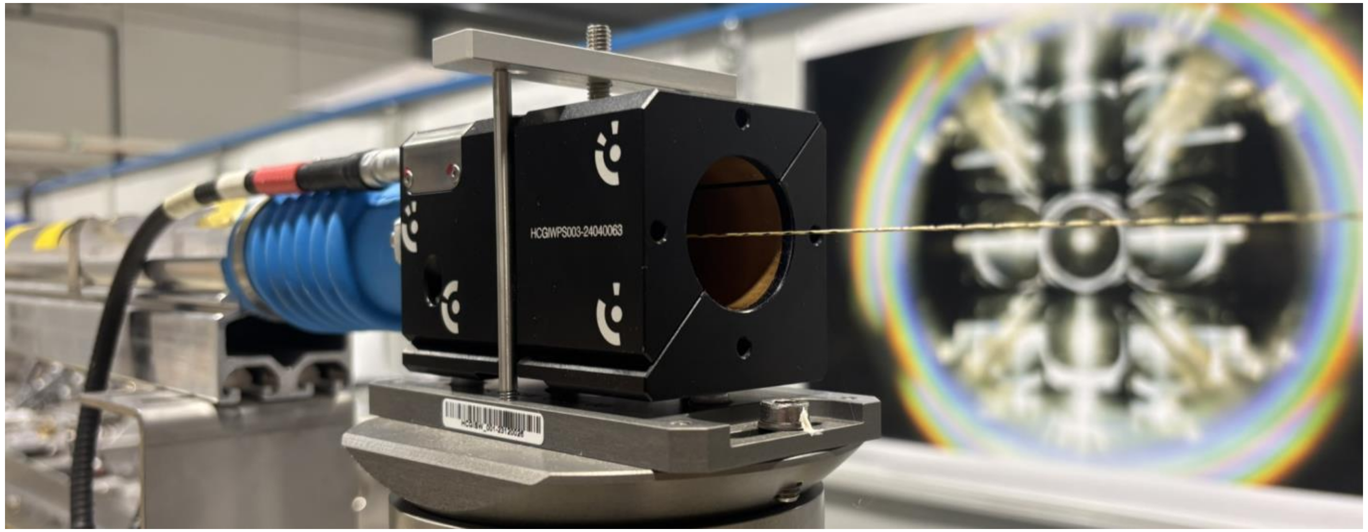
FRAS – Capacitive technology

- **Capacitance** is the ability of two conductors to store electric charges when a voltage is applied.
- **Capacitance increases when the conductors move closer** and decreases when they move apart. This distance-dependence is the core sensing principle used in sensors.
- As the permittivity of the medium is affected by external factors such as temperature and humidity, measuring and differentiating between multiple capacitances can largely cancel out these systematic effects.

Capacitance C between two conductors:

$$C = \frac{\varepsilon_0 \varepsilon_r S}{h}$$

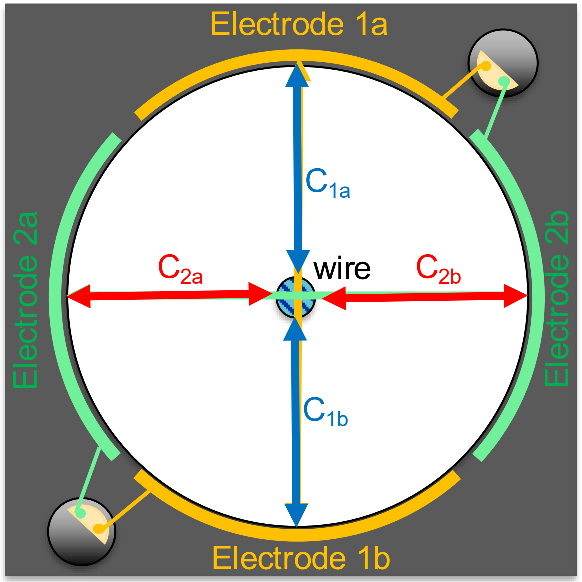
ε_0 = permittivity of free space
ε_r = relative permittivity of the material between conductors
S = effective electrode area
h = distance between conductors

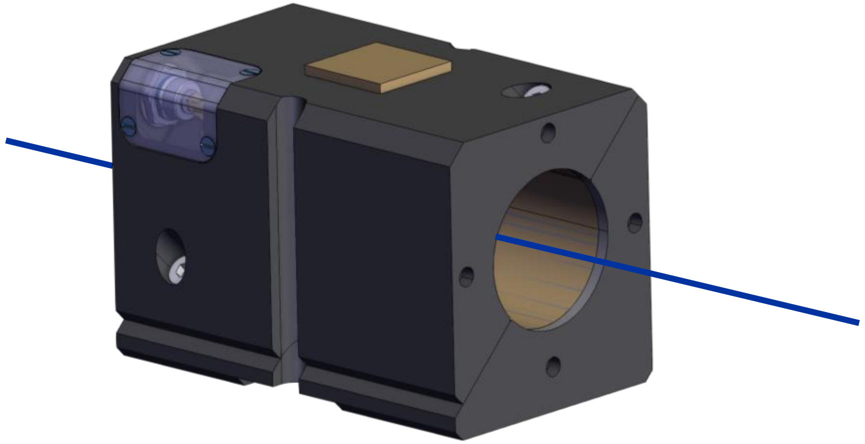


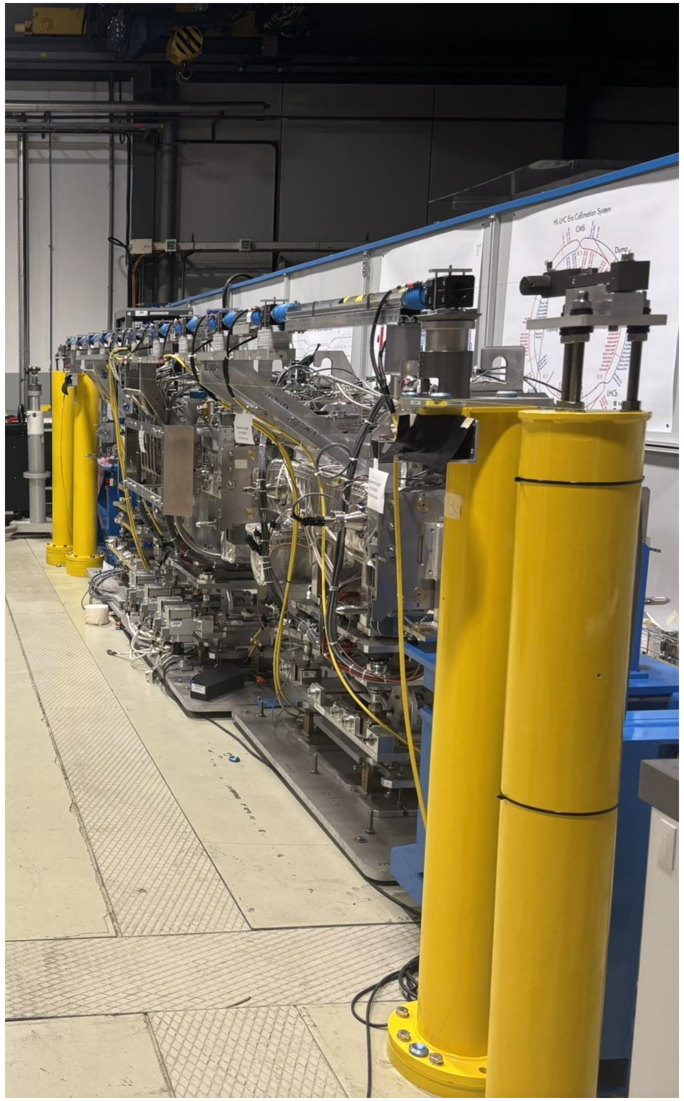
(P. Sarvade)

FRAS – Capacitive technology – WPS

- In the **W**ire **P**ositioning **S**ystem (WPS), capacitance is measured four times (C_{1a}, C_{1b}, C_{2a}, C_{2b}).
- For each C, the **two conductors** are **an electrode** and **the** grounded (0 V) **wire**.
- Then the vertical and the horizontal capacitance pairs are differentiated.
- This results in one differential capacitance for the horizontal position of the wire relative to the electrodes and one for the vertical position.

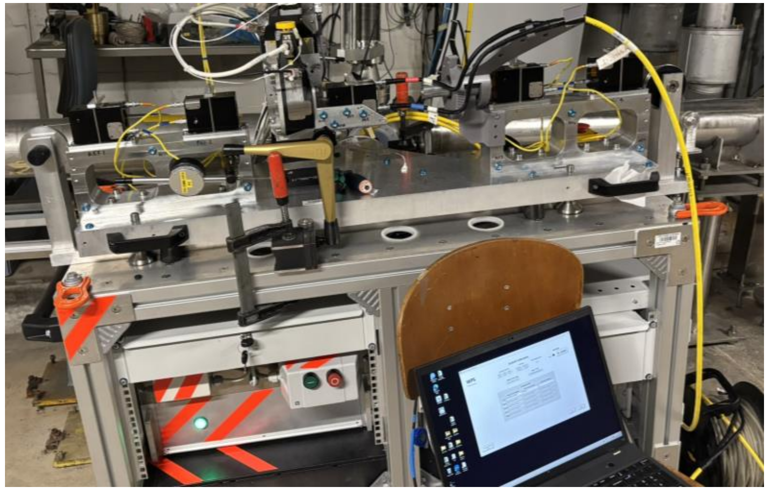


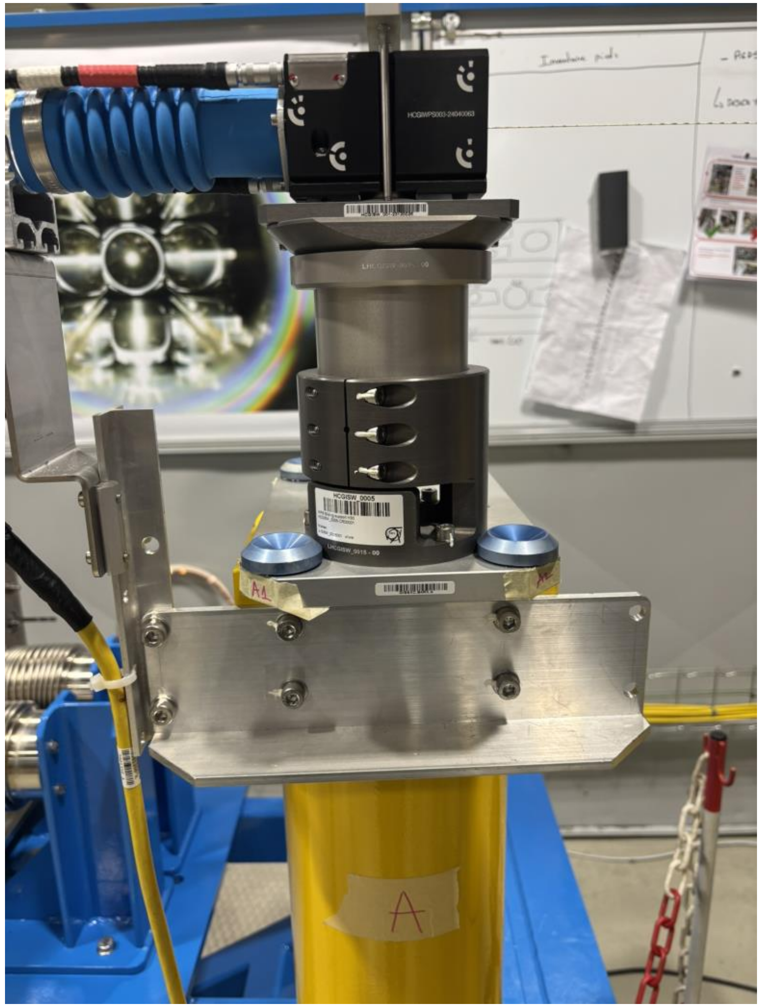




FRAS – Capacitive technology – WPS

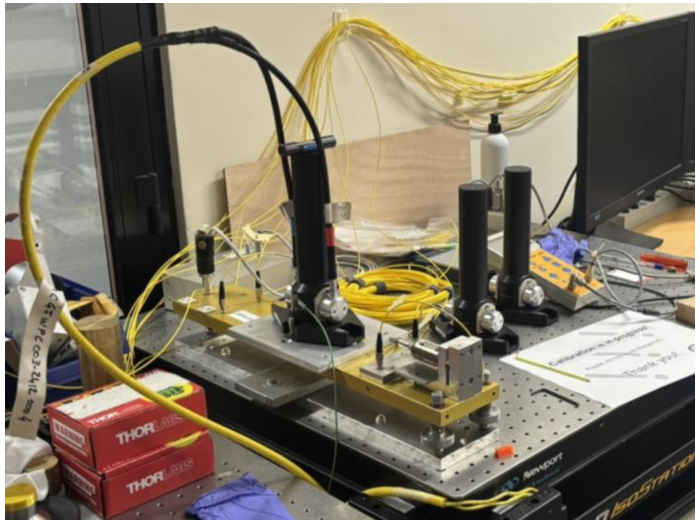
- Before deploy, a unitless digital signal is converted to vertical and horizontal values in mm during a complex calibration process.
- Repeatability : +/- 1 µm (1 σ), **Accuracy : 5 µm (1 σ)**, Range : +/- 5 mm
- The sensors are fixed on the components (in total 276 for FRAS) and continuously monitor the position w.r.t. a starched wire
- Wire: conductive, rad-hard, homogeneous shape, great meachnical strength and consistent linear mass, analytical model for sag
- With automatic wire replacement

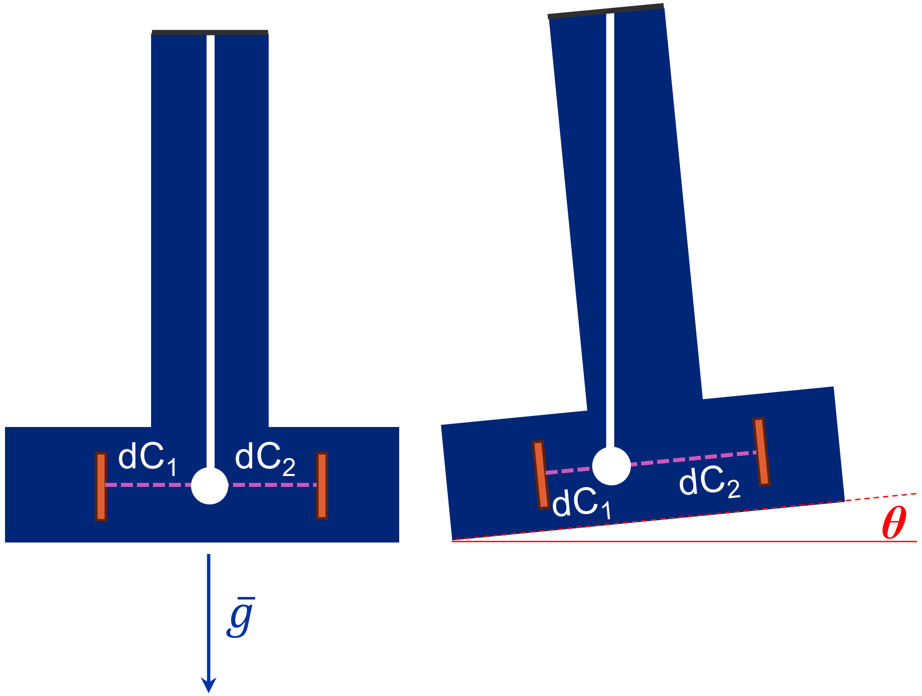




FRAS – Capacitive technology – Inclinometer

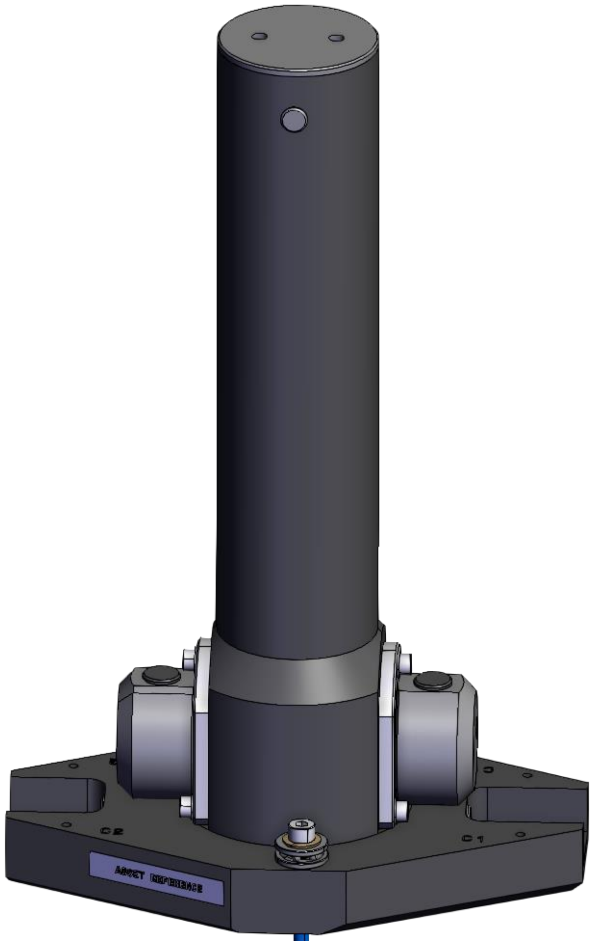
- Measures angle along one axis using a pendulum that always aligns with gravity (Roll angle of components).
- Capacitive technology measures the distance between the pendulum end and electrodes.
- There are four electrodes, forming two differential capacitances (one for each side).When the component tilts, the pendulum moves closer to one side and farther from the other.
- This change is measured and can be converted into an angle thanks to a calibration process done beforehand.





FRAS – Capacitive technology – Inclinometer

- Range: +/- 12.6 mRad, Resolution: 1 µRad, Accuracy: in development



FRAS – FSI technology

The **F**requency **S**canning **I**nterferometry (FSI) is similar to a Michelson interferometer, but the constant frequency laser is replaced by a swept laser source. This means the laser frequency (ν) is linearly changing over time:

$$\nu(t) = f_0 + \alpha t,$$

where $\alpha = d\nu/dt$ is the laser frequency change in time, f_0 is the optical frequency of the laser at time t_0.

When the laser sweeps in frequency, the reference signal from the reference arm and the delayed signal from the target no longer have exactly the same optical frequency. The delay $\tau = \frac{2D}{c}$ causes an instantaneous frequency difference called beat frequency:

$$\Delta\nu = \nu(t) - \nu(t - \tau)$$

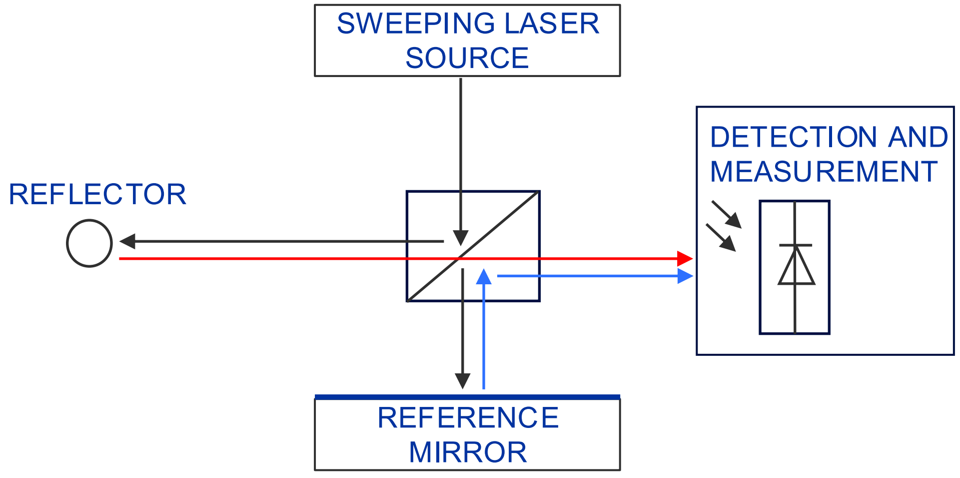
$$\Delta\nu = \boldsymbol{f_{beat}} = f_0 + \alpha t - [f_0 + \alpha(t - \tau)] = \boldsymbol{\alpha\tau},$$

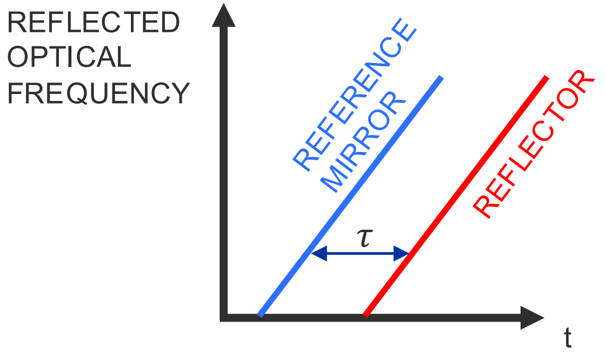
which is the detected in the interference signal:

$$I(t, \tau) = A\cos[2\pi(\boldsymbol{\alpha\tau} + f_0\tau)],$$

where A is the magnitude of the signal. f_{beat} can be determined by applying an FFT to the signal, then the corresponding distance can be calculated:

$$f_{beat} = \alpha\frac{2D}{c} \rightarrow D = c\frac{f_{beat}}{2\alpha}$$

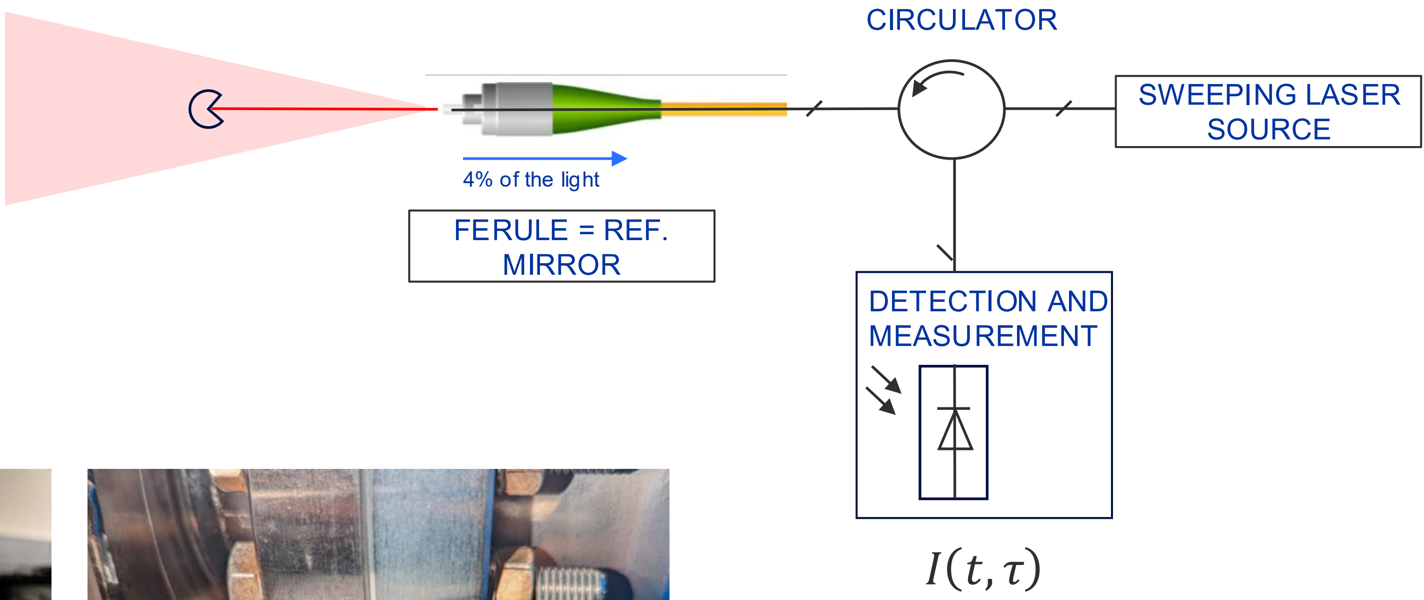


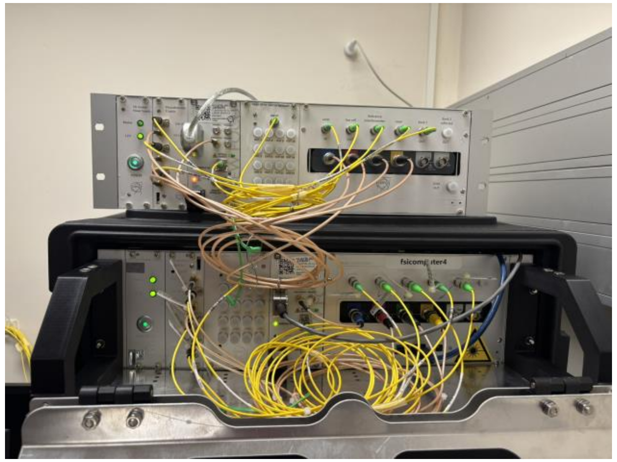


Sosin, M.; Cobas, J.D.G.; Isa, M.; Leach, R.; Lipiński, M.; Rude, V.; Rutkowski, J.; Watrelot, L. An Interferometric Multi-Sensor Absolute Distance Measurement System for Use in Harsh Environments. *Sensors* **2025**, *25*, 5487. https://doi.org/10.3390/s25175487

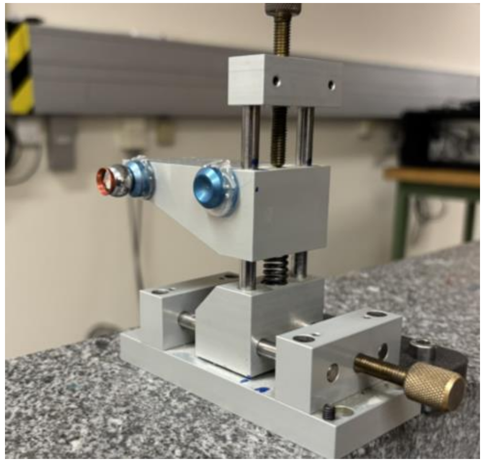
FRAS – FSI technology

- All the sensor applications uses a circulator and an optic fibre ferrule tip for a compact configuration.
- The fibre ferrule tip acts as both the beam splitter and the reference mirror
- It reflects ~4% of light, forming the reference arm, while directs the remaining ~96% of light toward a reflective target
- Manyfor reflectors: CCR, Glass sphere, water surface
- Divergent or collimated beam

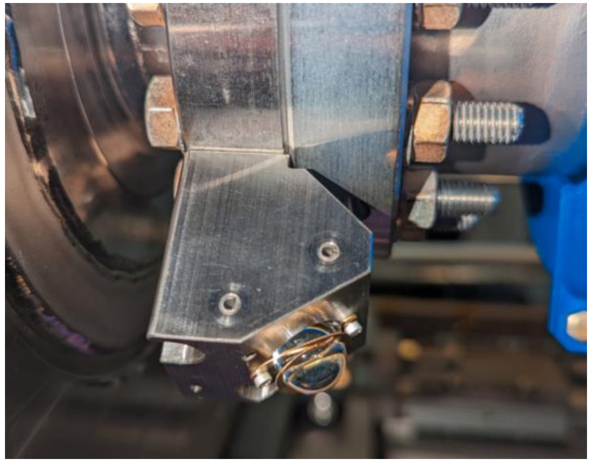




FSI devices



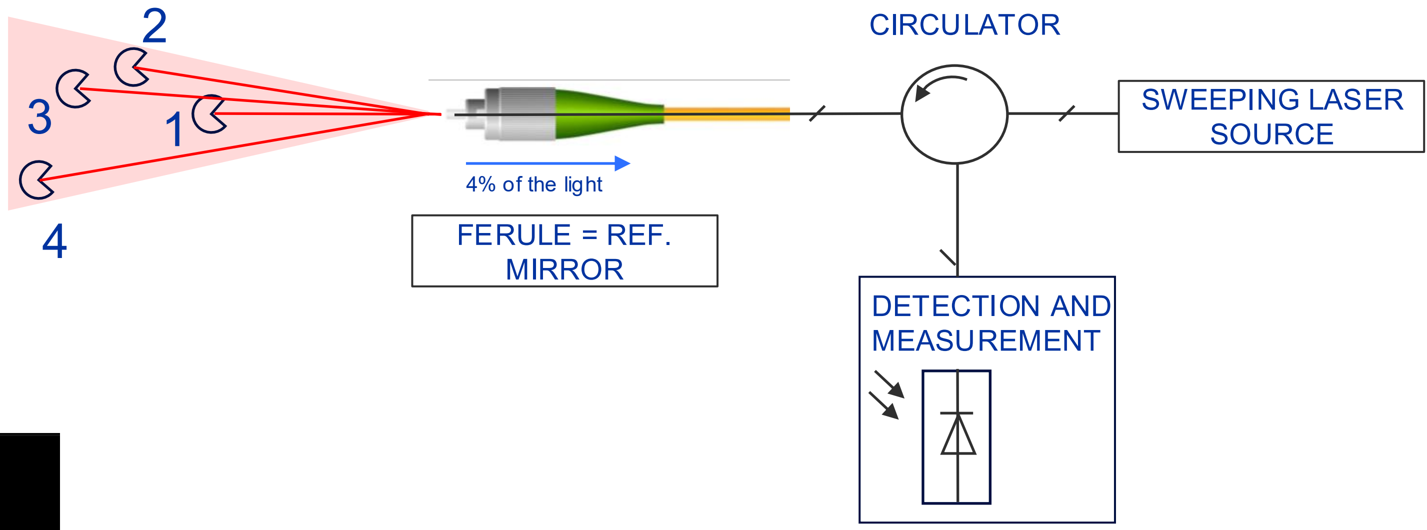
CCR target



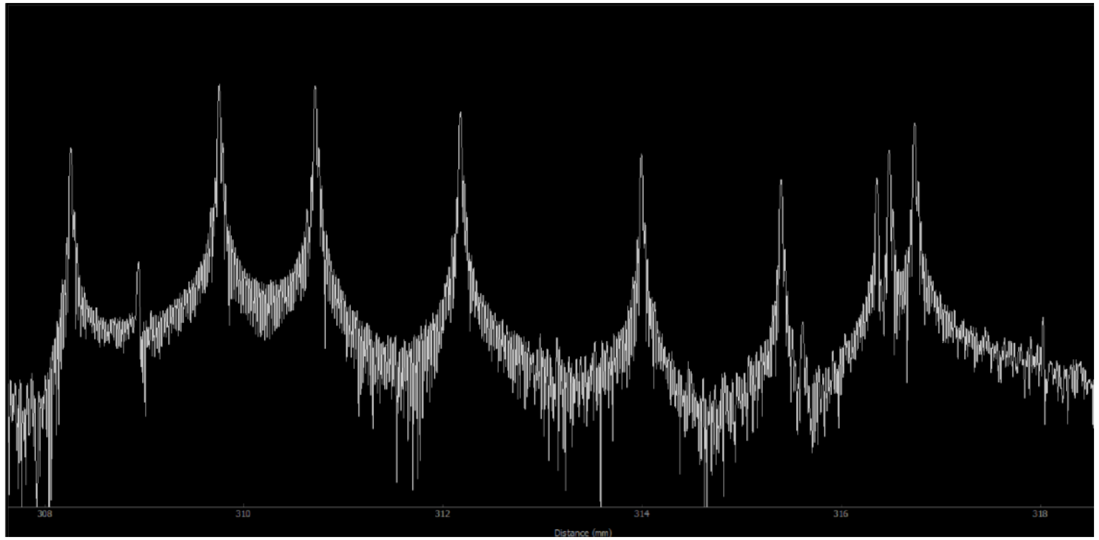
Glass sphere target

FRAS – FSI technology

- A key advantage is that reflections from multiple targets produce individual beat frequencies, meaning that FSI is capable of making simultaneous multi-distance measurements.
- Uncertainty (95%) = 0.5 μm/m



$$I(t,\tau) = I(t,\tau_1) + I(t,\tau_2) + I(t,\tau_3) + \cdots$$



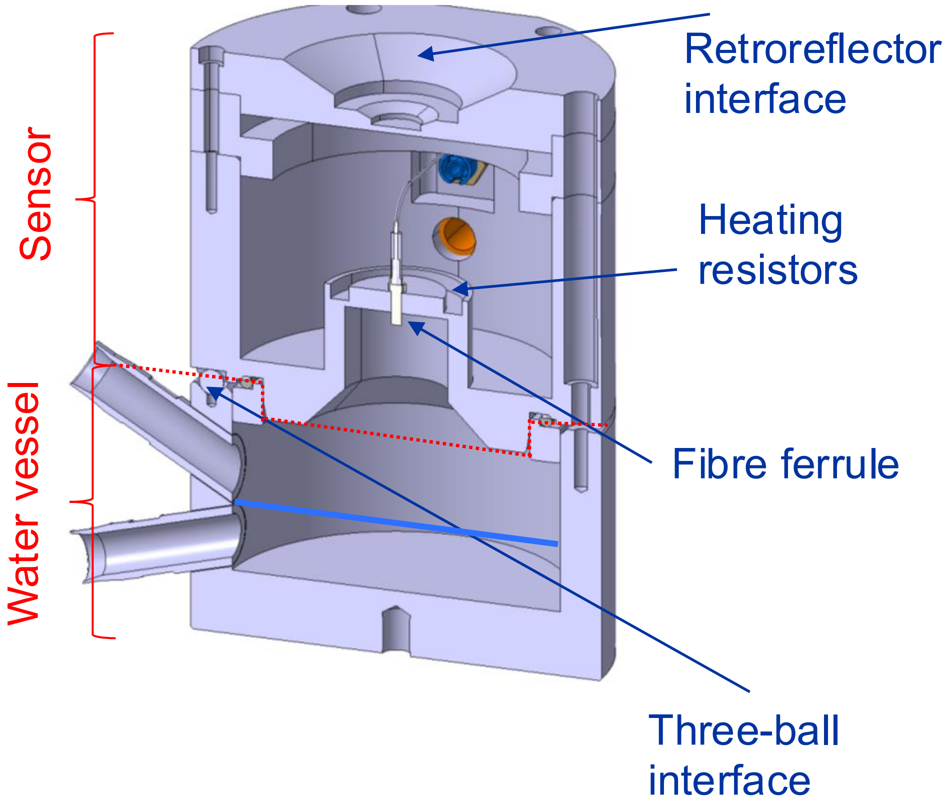
$$D_i = c\frac{f_{beat_i}}{2\alpha}$$

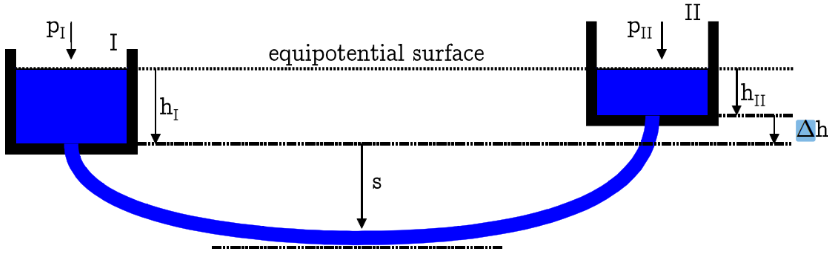
Multi target FFT result

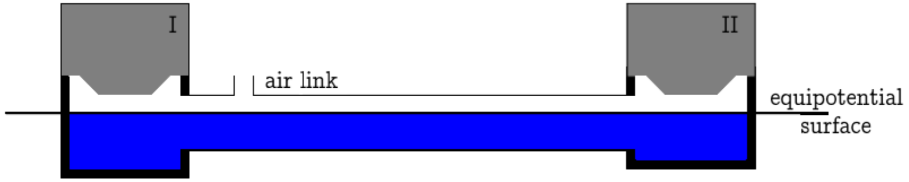
FRAS – FSI technology – HLS

Hydrostatic Levelling System (HLS)

- The system based on the communicating vessels with water network = reference surface
- 1 sensor is installed on top of each vessel to measure the distance to the water surface contactless
- Distance measurement is done by FSI between the fiber ferrule and the water surface which acts as a reflector
- Simple optical design: ferrule + water surface = interferometer
- Sealed water–air system: each sensor is paired with a water vessel connected to the HLN via two tubes (water + air).
- Local ferrule heating prevents condensation and signal loss.
- The system will pride the vertical reference connecting each side of the experiments with one common network



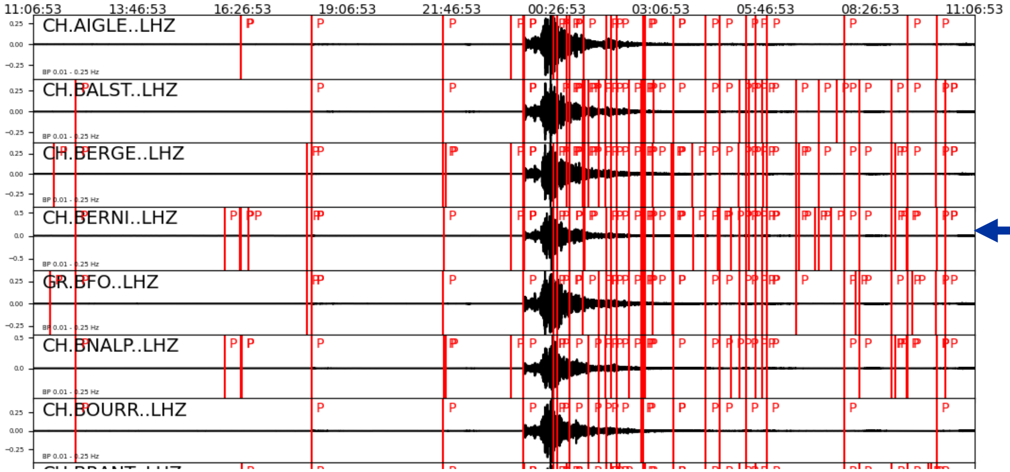




A. Herty, "Micron precision calibration methods for alignment sensors in particle accelerators", Nottingham Trent Univ., Nottingham,U.K., 2009.

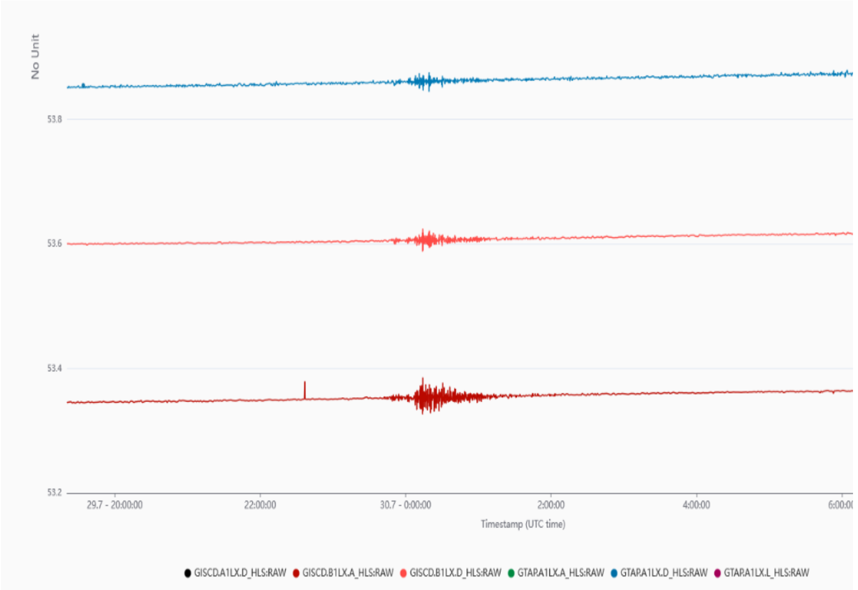
FRAS – FSI technology – HLS

- Extremely sensitive
- Kamchatka earthquake (8.8 M) near Russia, 30th July 2025
- Detected by HLS sensors



Swiss seismometers

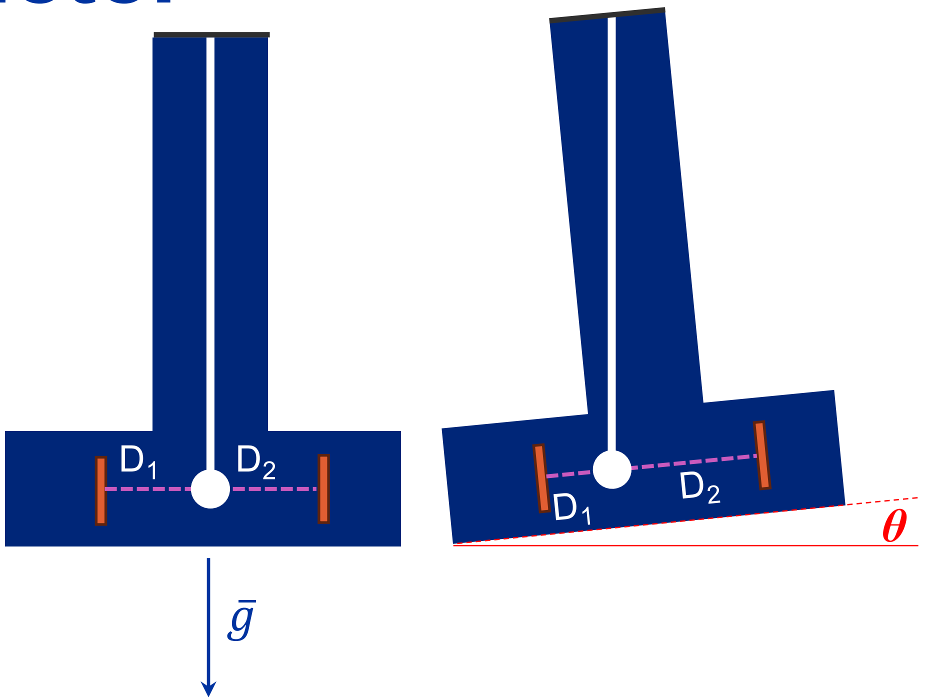
HLS sensors

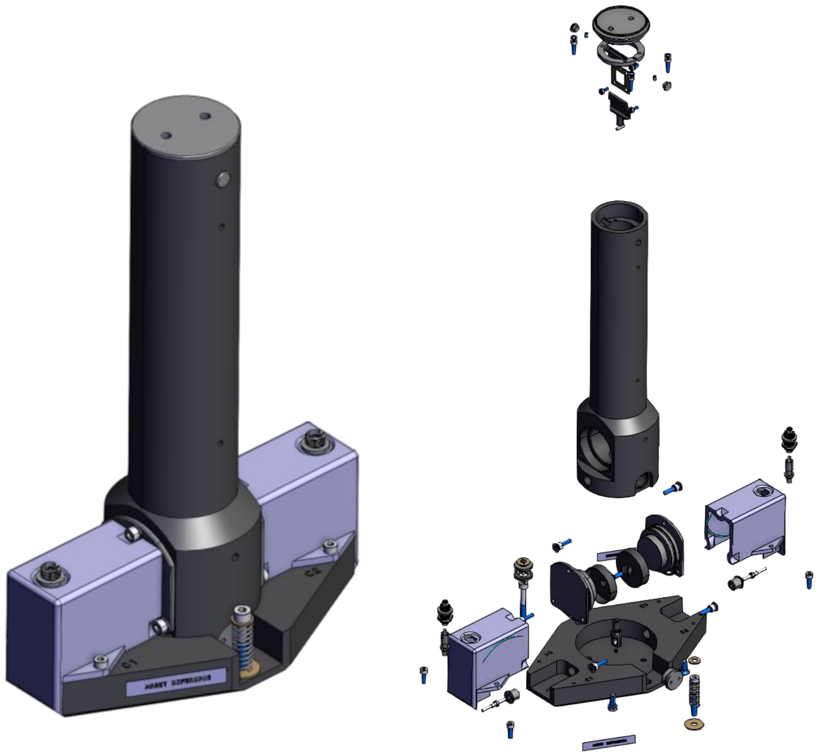


(J. Rus)

FRAS – FSI technology – Inclinometer

- Follows the same mechanical principle as the capacitive one
- FSI distance measurement to the end of the pendulum from two sides.
- Hermetic sensor body, protecting the mechanical part from dust and humidity.

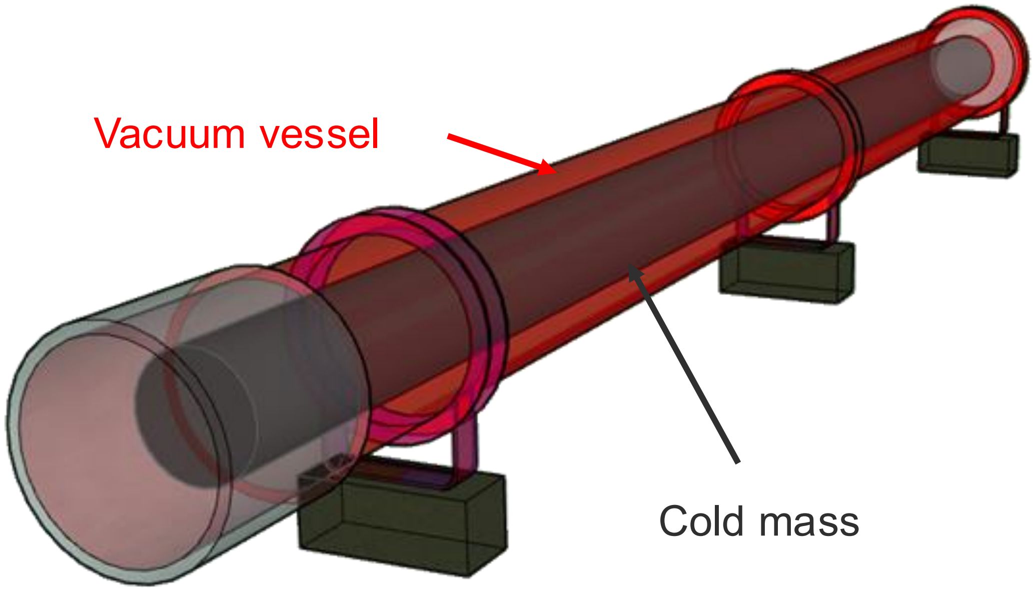




Glass ball reflector at the bottom of the pendulum

FRAS – FSI technology – Internal monitoring

- The internal part of components called cold mass going through a complex displacement during the vacuum and cool down.
- At some components (e.g.: crab cavitis, quadrupoles) it is essential to monitor the displacement and align the displaced axis.
- This process is called internal monitoring.

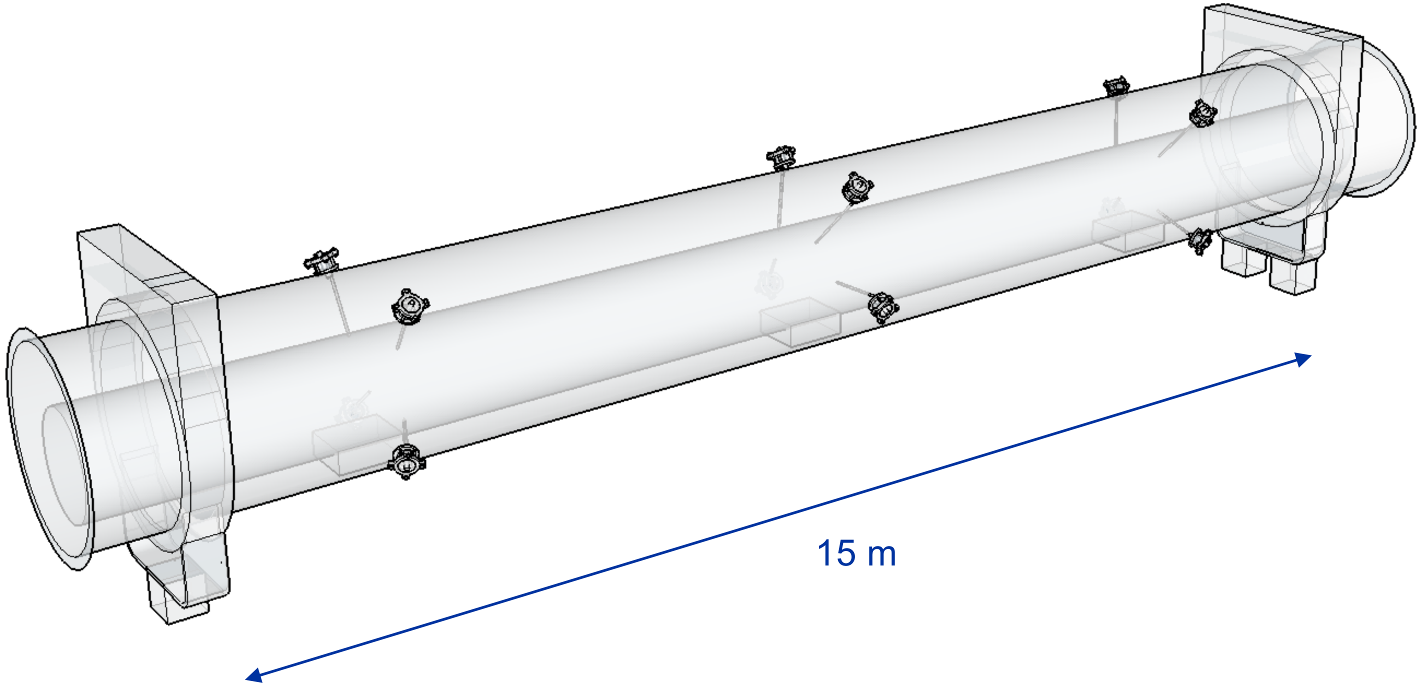


Environment :

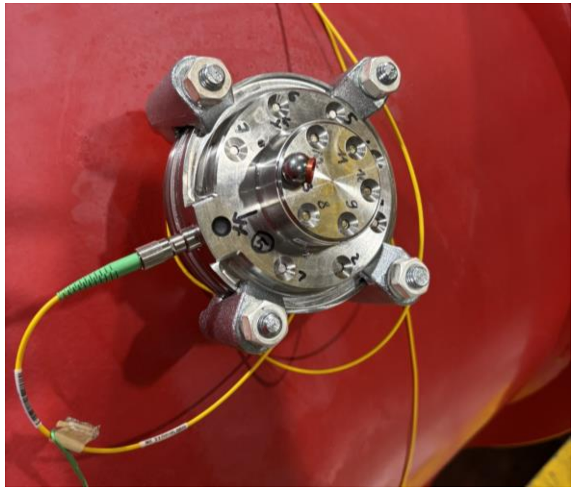
- Temperature : 1.9 K (Cryogenics conditions) ≈ - 271°C
- Vacuum : 10^{-6} mBar
- Radiation : 1 MGy / 15 year

FRAS – FSI technology – Internal monitoring

- The monitoring is based on FSI measurements
- Distances are measured from the heads, to the targets, which are installed on the cold mass.



FSI head



FSI target

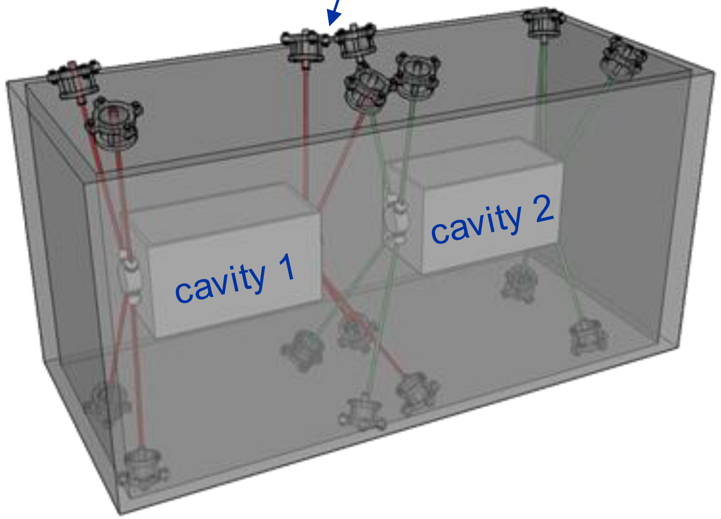
Least square adjustment : 12 observations for 9 unknowns

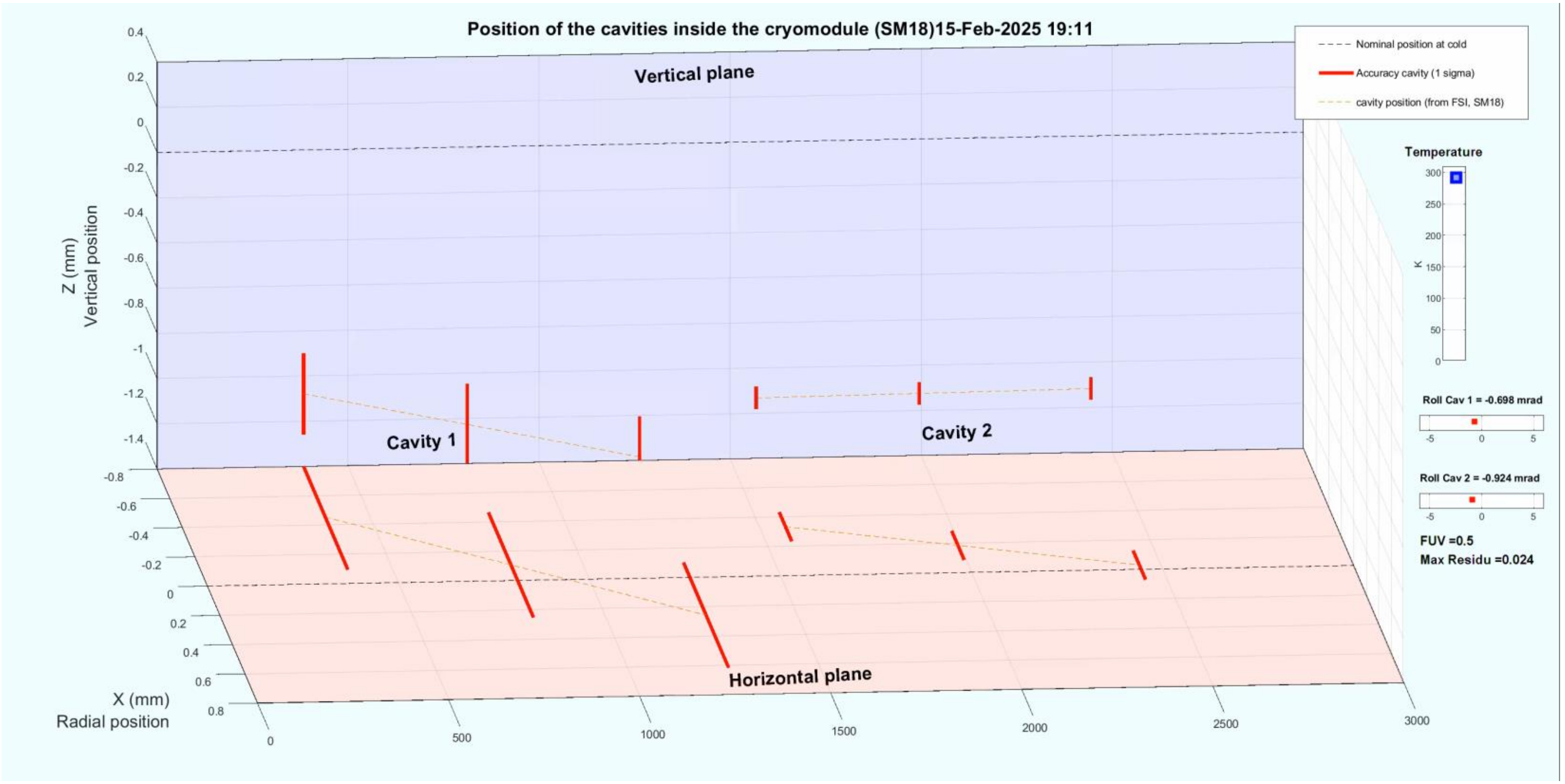
V. Rude, et.al., "3D calculation for the alignment of LHC low-beta quadrupoles", IWAA 2022, Geneva, Switzerland.

FRAS – FSI technology – Internal monitoring

Crab Cavity cryomodule

FSI heads





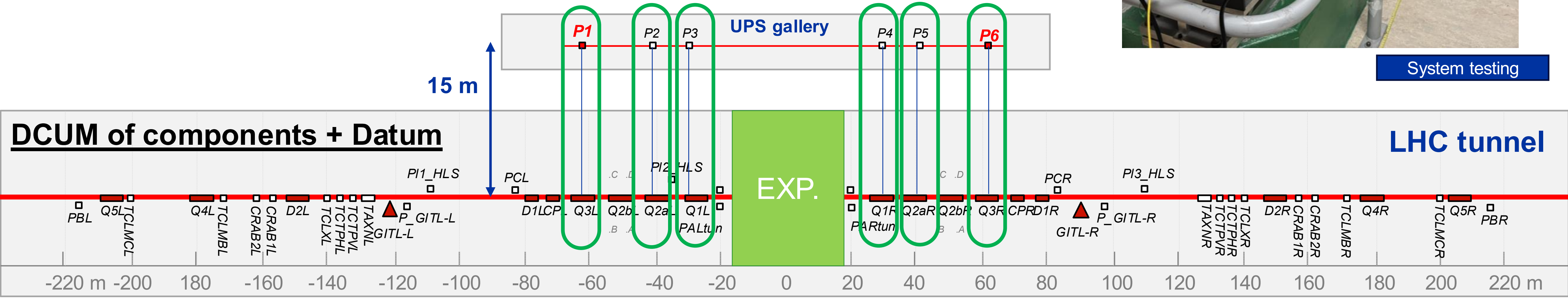
<u>Least square adjustment</u> : 8 observations for 7 unknowns / cavity

(P. Sarvade)

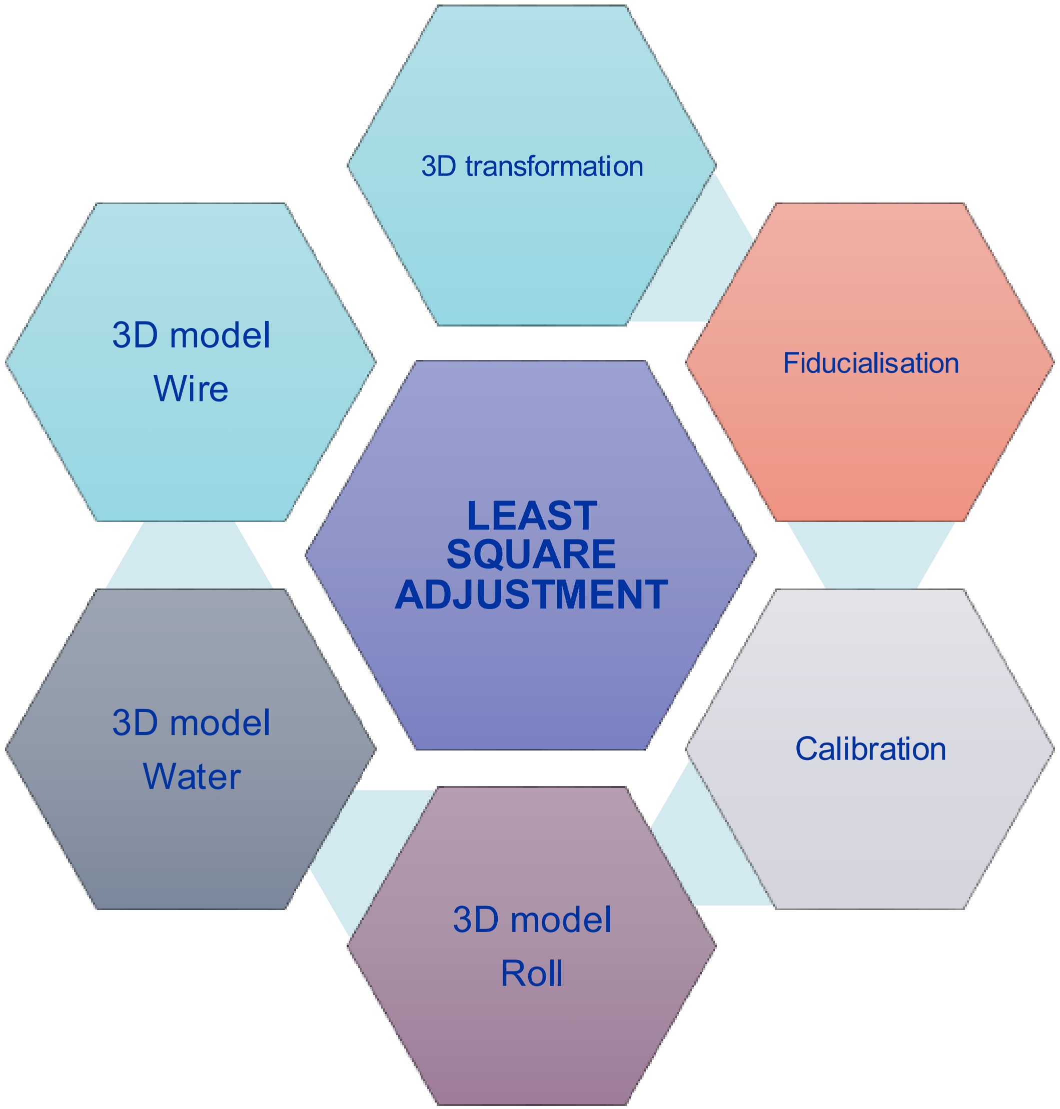
FRAS – FSI technology – Long distance FSI

- Establishes a connection between the LHC tunnel and the UPS gallery.
- The long-distance FSI sensor transmits information about the radial position of FRAS components, determined using multiple stretched wires across the experimental area.
- Measurements link the left Q1–Q5 FRAS zone wire position to the right Q1–Q5 FRAS zone wire position through an adjoining UPS gallery wire.
- To meet FRAS alignment requirements, the measurement uncertainty must be better than 20 µm (k = 1) over a distance of approximately 15 m.

System testing



FRAS – Computation



<u>Observations :</u>

- WPS, HLS, Inclinometers

<u>Main Parameters :</u>

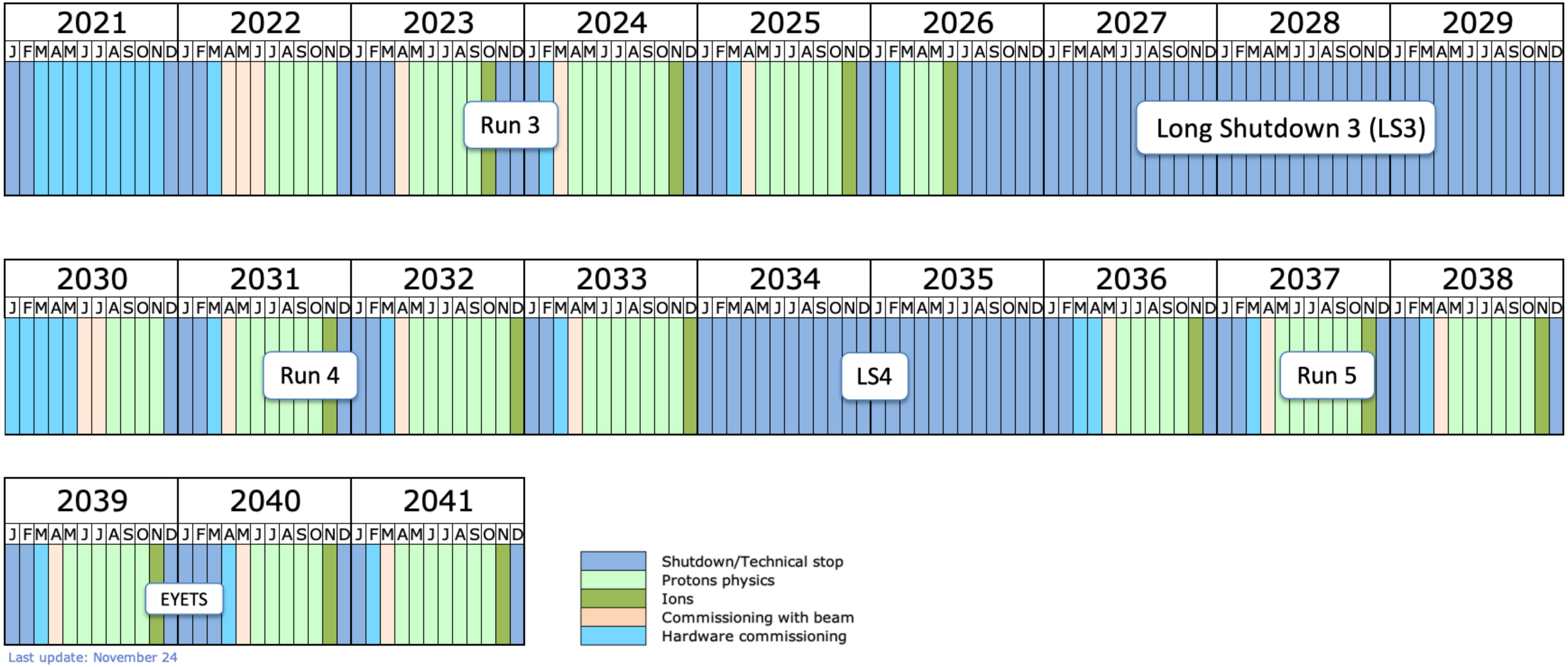
- Fiducialisation, calibration, etc.
- 3D positions of the components
- Positions and Sags of the wires
- Heights of the water networks

Dedicated real time open-source LGC (*Logiciel General Compensation*) software package developed within BE-GM

~100 000 config. parameters for FRAS
1150 sensors and components

(M. Sosin)

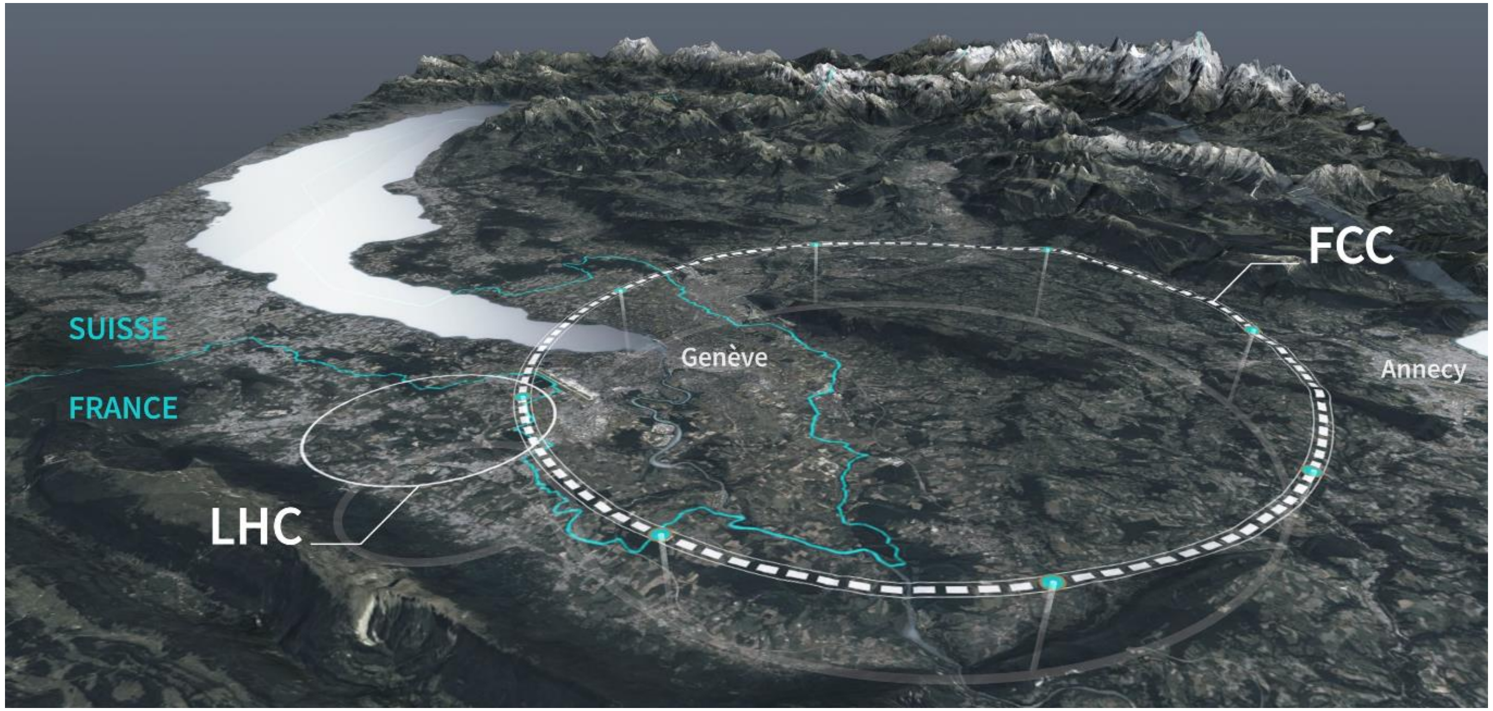
LHC timeline



Looking into the future

Future Circular Collider

- 91km circular accelerator
- 200m below the earth
- 4 large experiments
  - 1st stage – Lepton collider – 10 years
  - 2nd stage – Hadron collider – 15 years
- Hadron Collider to have an energy around 100TeV (as compared to the LHC's 14TeV)



cern.ch