Metrology requirements for the realisation of the Future Circular Collider (FCC)

Hélène Mainaud Durand

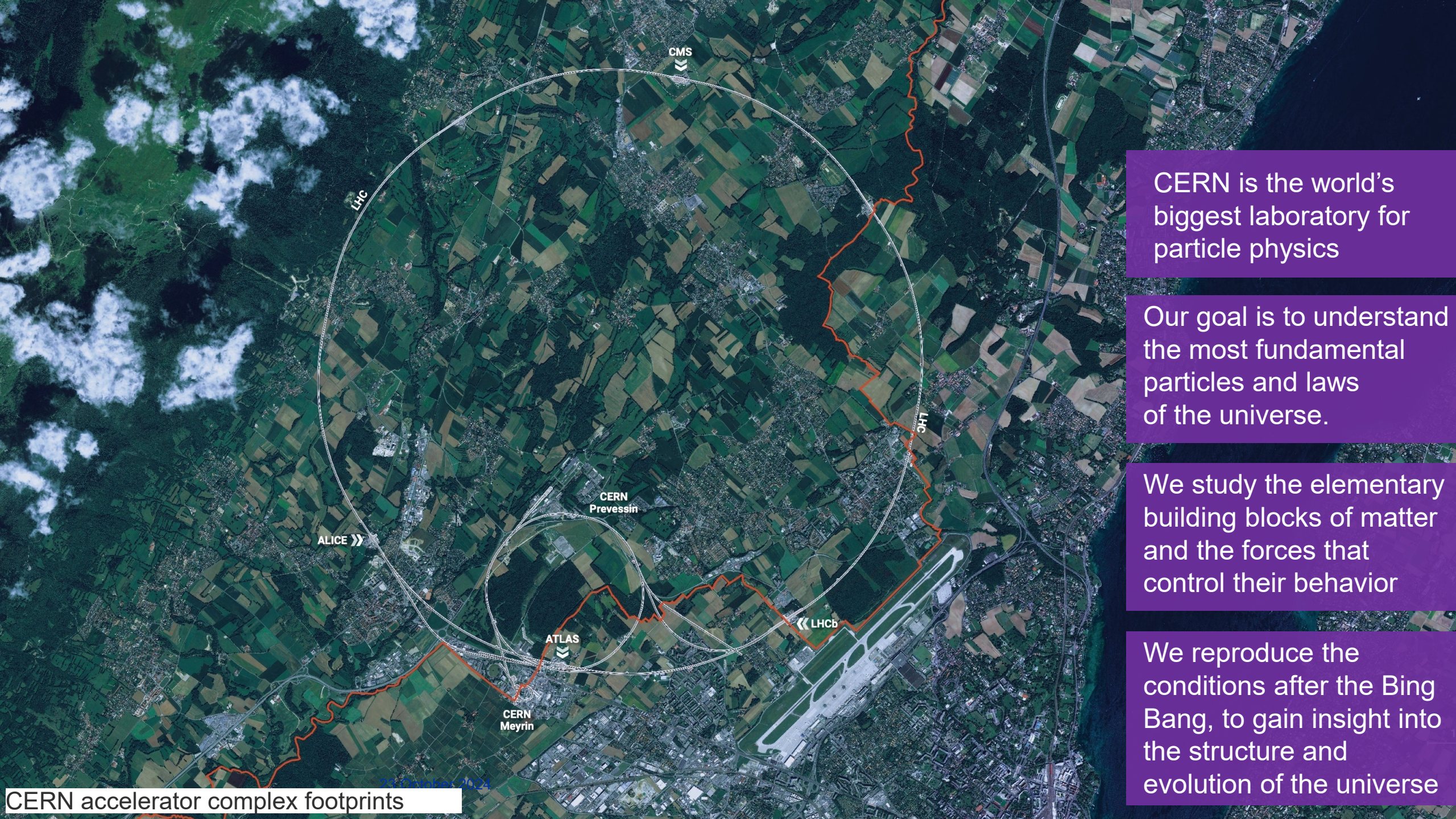
23 October 2024, EMN Advanced Manufacturing Open Stakeholder Meeting, PTB

Outline

- **Introduction to CERN and FCC study**
- **Metrology requirements for FCC**
- Alignment of components on specific supports
- Large scale metrology and geodetic aspects



New Science Gateway at CERN



CERN is the world's biggest laboratory for particle physics

Our goal is to understand the most fundamental particles and laws of the universe.

We study the elementary building blocks of matter and the forces that control their behavior

We reproduce the conditions after the Bing Bang, to gain insight into the structure and evolution of the universe

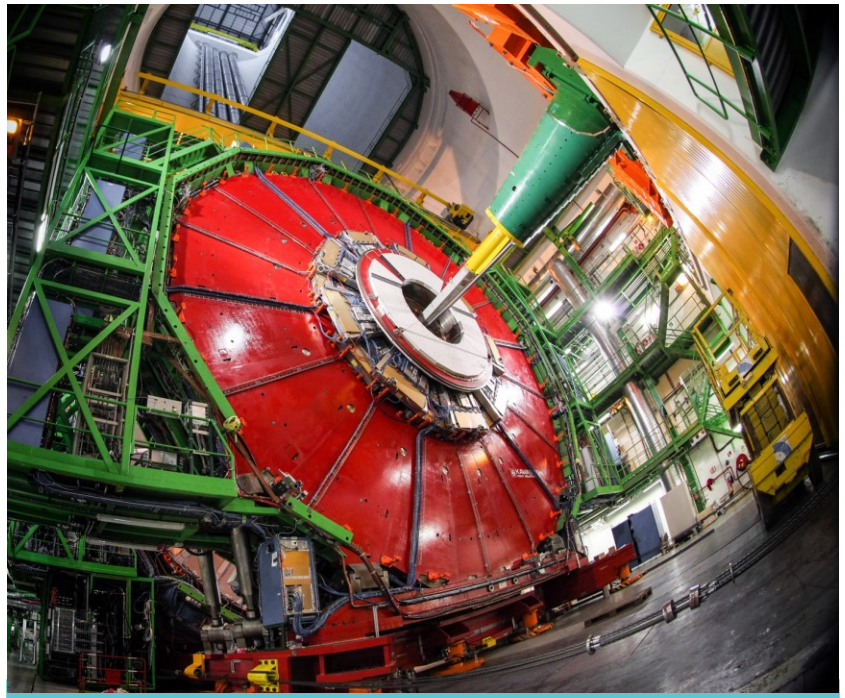
CERN accelerator complex footprints

3 main technical ingredients

1. The largest machines to study the smallest particles in the universe – relying on technology innovation and R&D to advance the limits of what is possible.
2. Detectors - giant 3D cameras
3. Computing power - Worldwide Computing Grid



ACCELERATORS

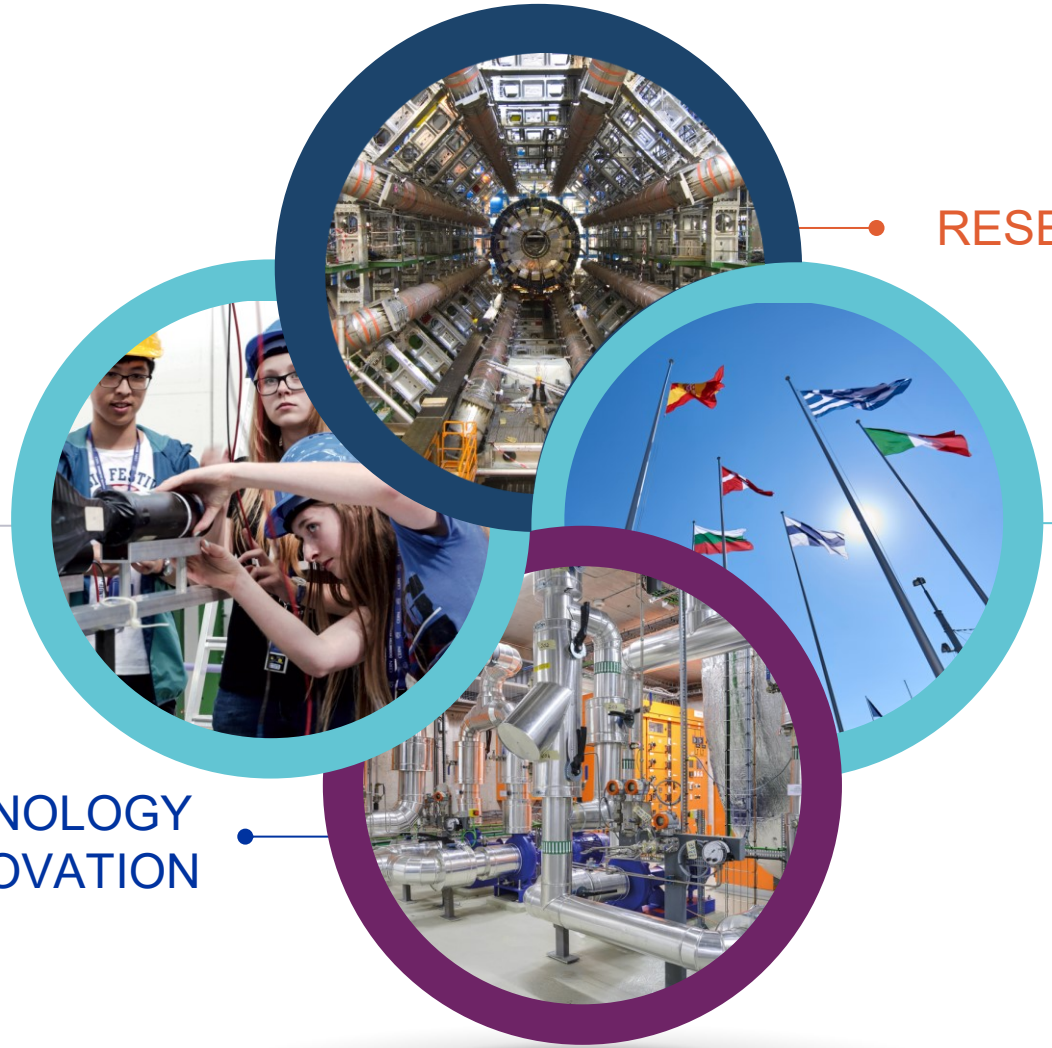


DETECTORS



COMPUTING

CERN’s mission stands on 4 pillars



RESEARCH

COLLABORATION

EDUCATION
& FORMATION

TECHNOLOGY
& INNOVATION

Science for peace

CERN was founded in 1954 with 12 European member states



24 Member states

3 States in accession to membership

8 associate Members

6 Observers

Around 50 ccoperation agreements with non-member states and territories



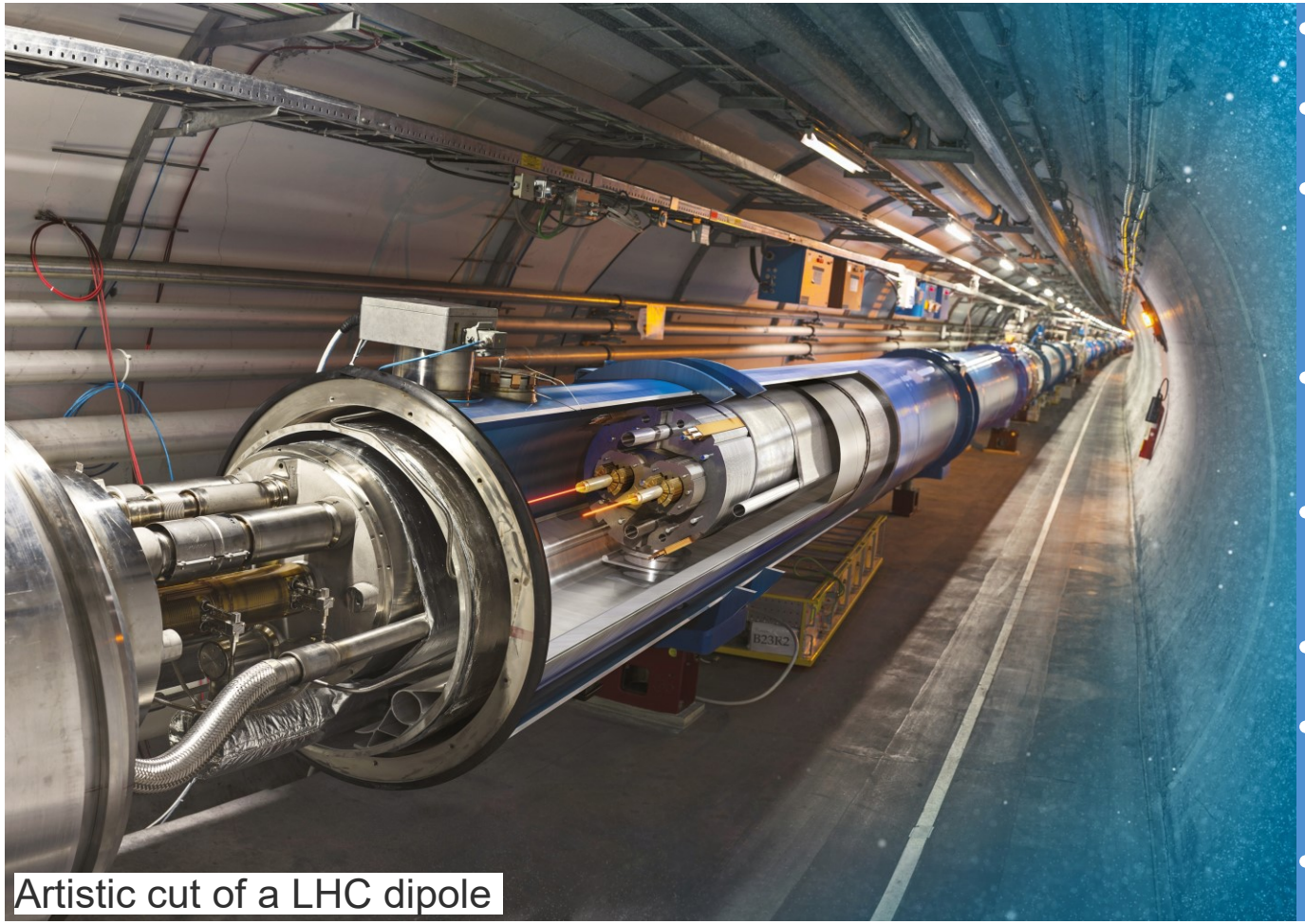
Geographical & cultural diversity
Users of **110 nationalities**
22.5 % women

CERN's annual budget: 1 200 MCHF (equivalent to a medium-sized European university)

As of 31 December 2023
Employees :
2 666 staffs, **1002** graduates

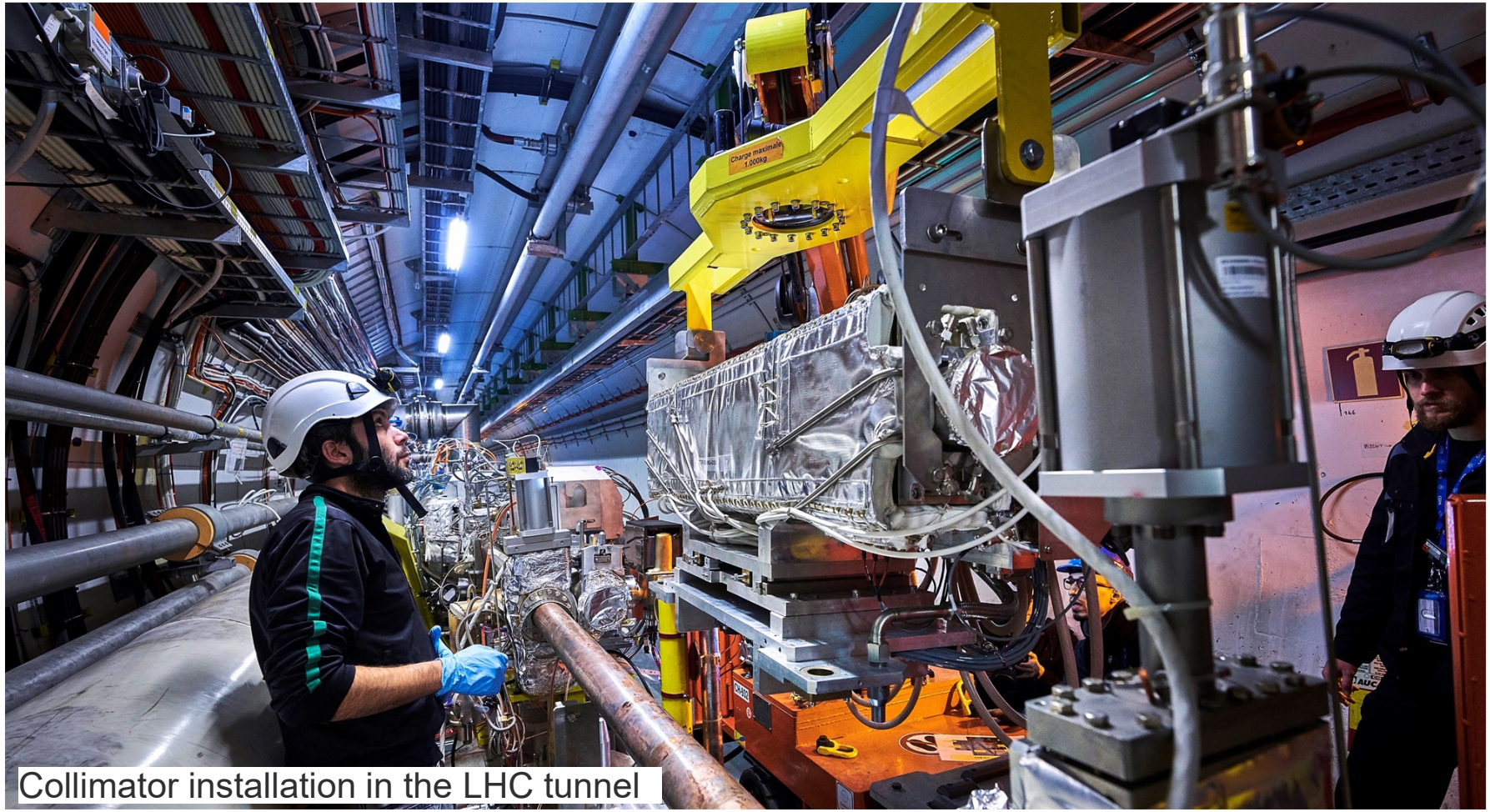
Associates **:**
12 370 users, **1 513** others

The Large Hadron Collider LHC


Artistic cut of a LHC dipole

- 27 km in circumference
- About 100 m underground
- 2 beams of trillions of protons travelling at 0.999999991 times the speed of light in opposite directions
- Superconducting radiofrequency system to accelerate the beams
- NbTi Superconducting magnets operating at - 271.3 °C to bend them in a circle
- Largest beam vacuum system worldwide
- Advanced powering, machine protection systems, beam diagnostics & control
- 4 Large experiments

Upgrade to the High-Luminosity LHC under way



Collimator installation in the LHC tunnel

The HL-LHC will use new technologies to provide 10 times more collisions than the LHC.

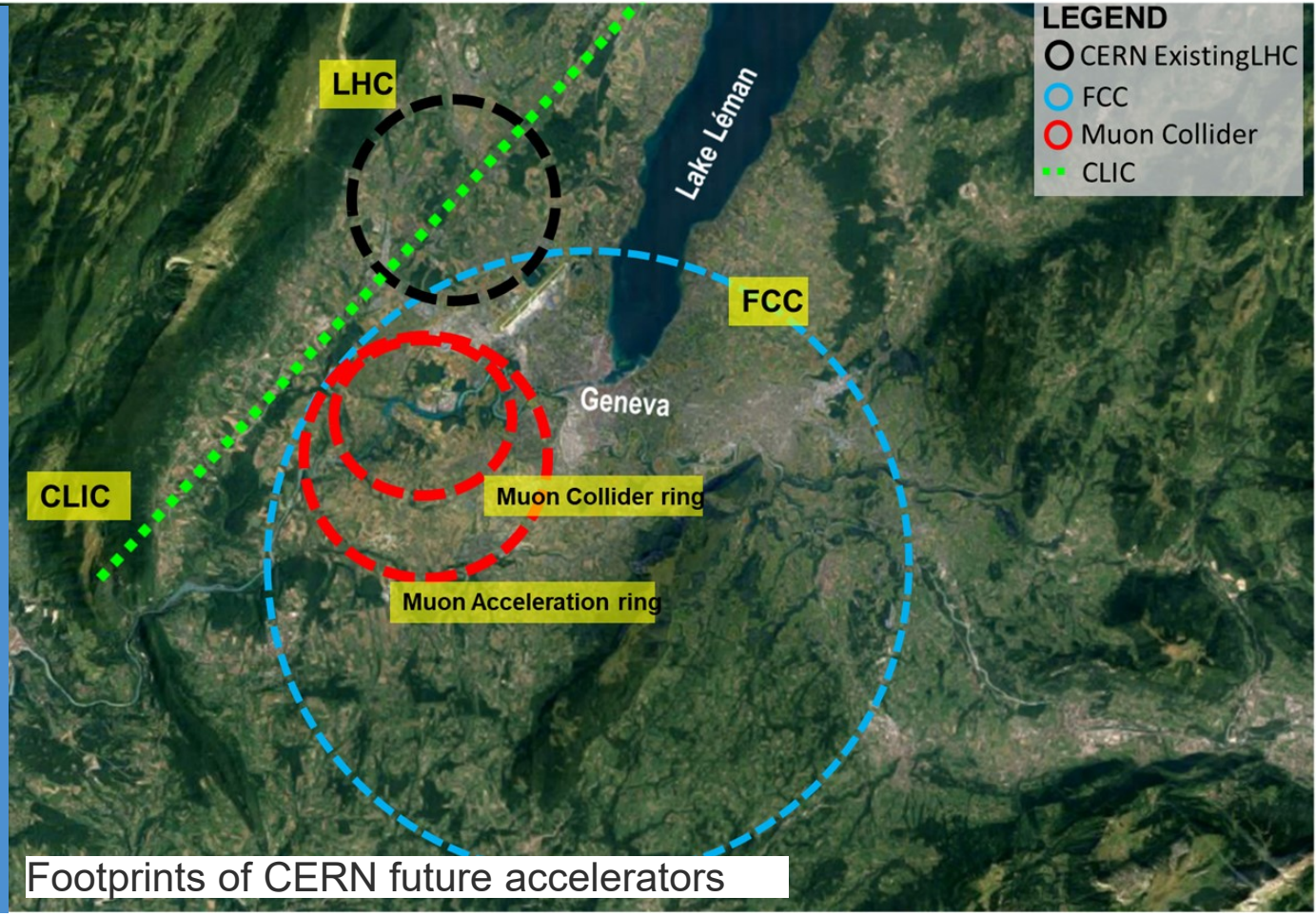
It will provide greater precision and discovery potential.

It will start operating in 2030, and run until 2042.

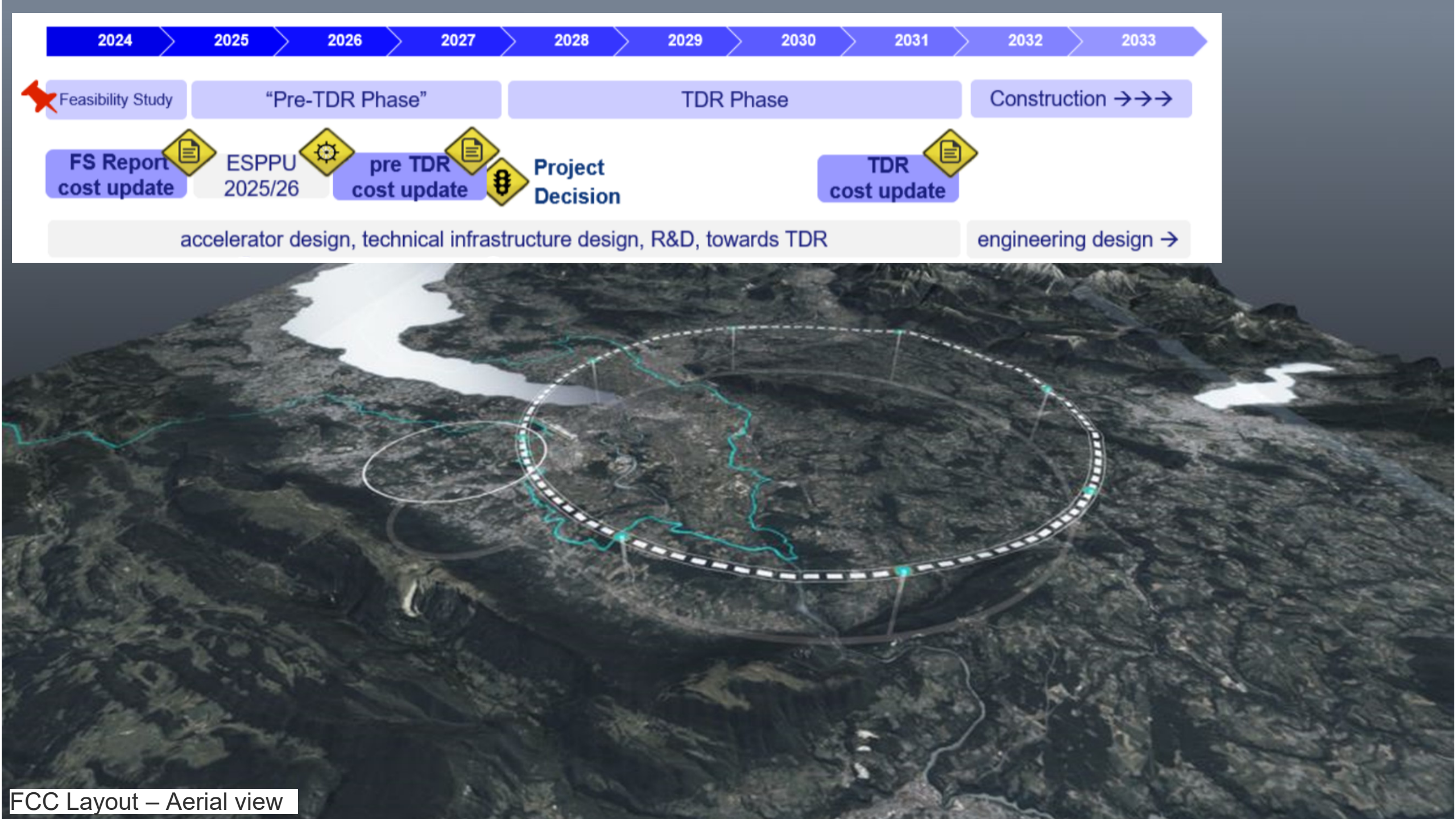
Scientific priorities for the future: a fertile ground of ideas

Implementation of the recommendations of the **2020 Update of the European Strategy for Particle Physics**:

- Fully exploit the HL-LHC
- Build a Higgs factory to further understand this unique particle
- Investigate the technical and financial feasibility of a future energy-frontier 100 km collider at CERN
- Ramp up relevant R&D
- Continue supporting other projects around the world



Footprints of CERN future accelerators

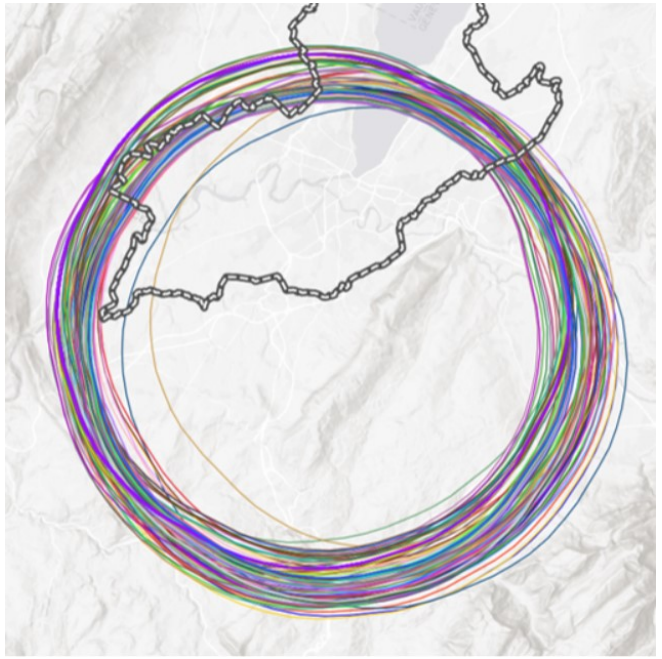


FCC Layout – Aerial view

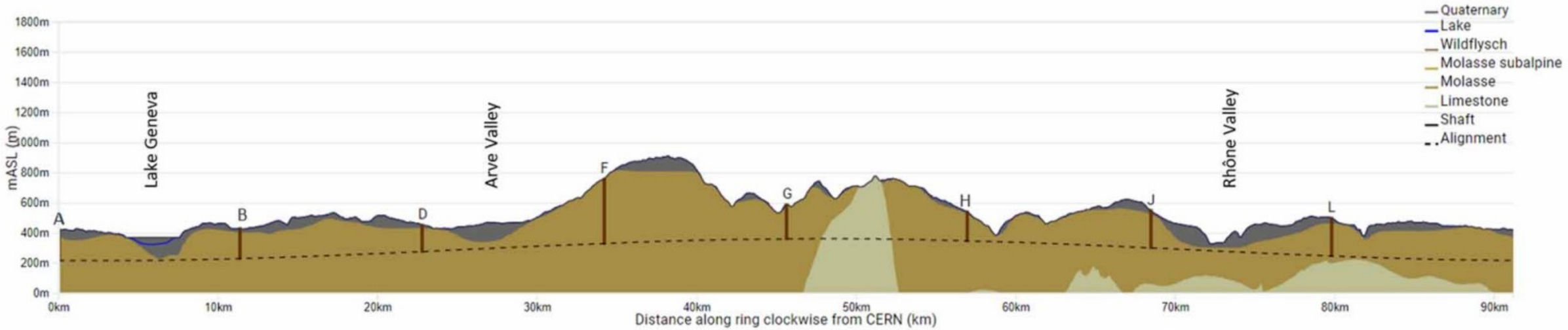
Status of the FCC study

- 100 implementation scenarios analysed, with **1 reference scenario chosen**, based on geology, surface constraints (land availability, access to roads), environment (protected zones), infrastructure (water, electricity, transport), machine performance, etc.

- A "**pre-TDR**" phase (2025-2027) will be launched soon to further develop the civil engineering, the technical components and their integration, with the aim to provide a consolidated cost estimate with reduced uncertainties.
  - **Perform a detailed R&D and design study of main technical components and civil engineering**
  - Full project integration study
  - Environmental impact study



FCC implementation scenarios

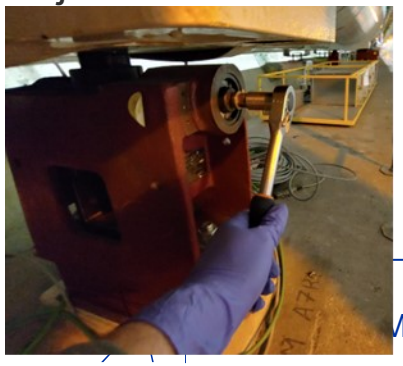
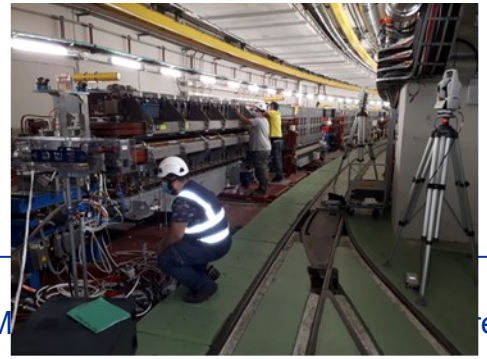
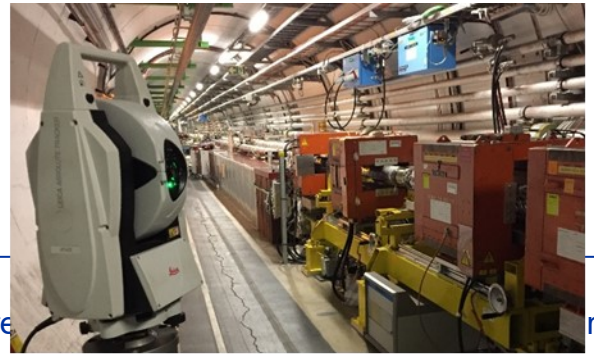


FCC longitudinal section

L. Bromiley, J. Osborne, FCC-ee Civil Engineering and infrastructure studies, eeFACT2022, Frascati, Italy, 2022

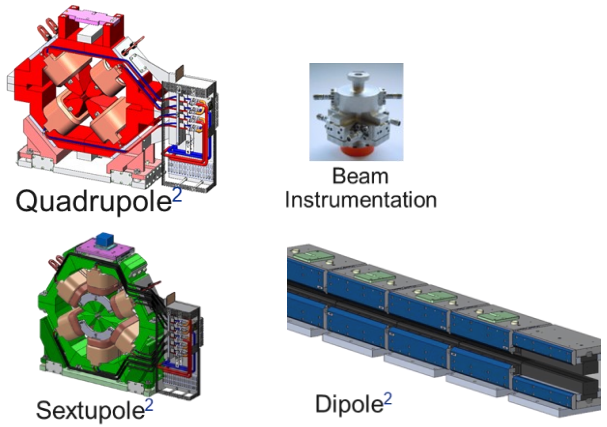
- **Introduction to CERN and FCC project**
- **Metrology requirements for FCC, through different cases:**
  - Alignment of components on specific supports
  - Large scale metrology and geodetic aspects

Adjustment & measurement activities at CERN

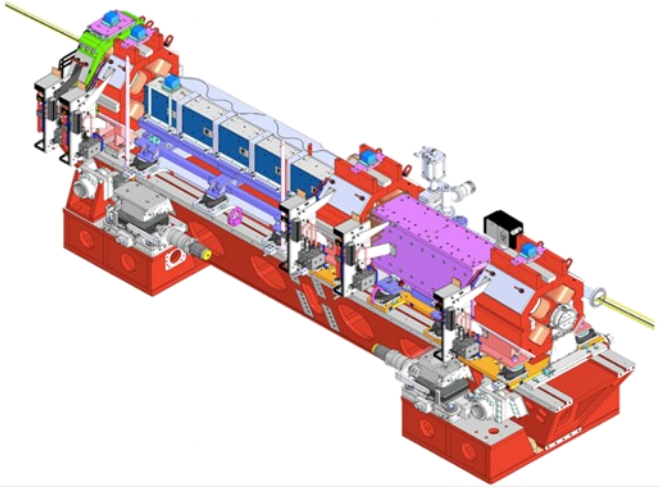






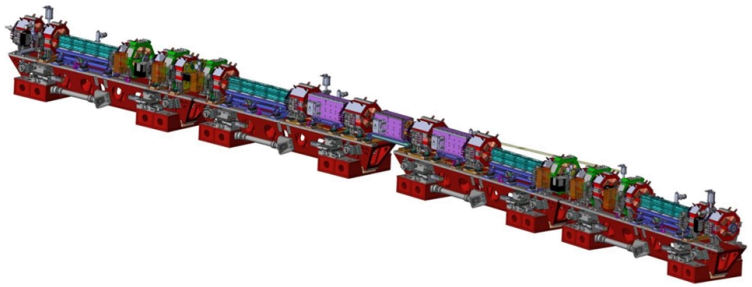
Alignment of components on specific supports



Accelerator components

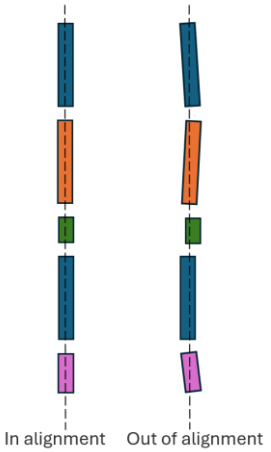


Alignment of components on a girder



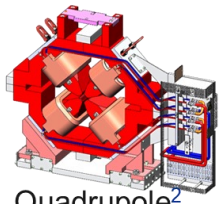
Alignment of girders in the tunnel

- According to the oxford dictionary, **alignment** means “an arrangement in which two or more things are positioned in a straight line”.
- In the context of an accelerator, the things are magnets (quadrupoles, sextupoles, dipoles), beam instrumentation, etc.
- Example of components from ESRF Extremely Brilliant Source, as no components are already designed for FCC

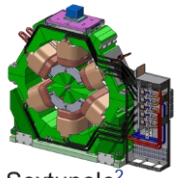


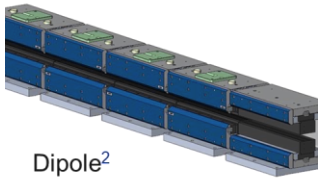
[2] **David Martin, “Alignment of the ESRF Extremely Brilliant Source (EBS)”, International Workshop on Accelerator Alignment, Fermilab, USA, 2018**

Alignment of components on specific supports


Quadrupole[2]


Beam Instrumentation

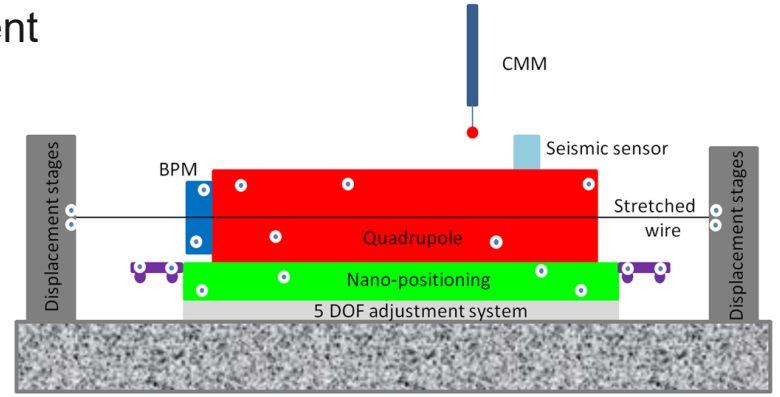

Sextupole[2]


Dipole[2]

Very important number of components:

- ~ 6 000 quadrupoles
- ~ 9 000 sextupoles
- ~ 13 000 dipoles
- ~ 6 000 Girders (~ 120 girders at ESRF)
- A lot of beam instrumentation

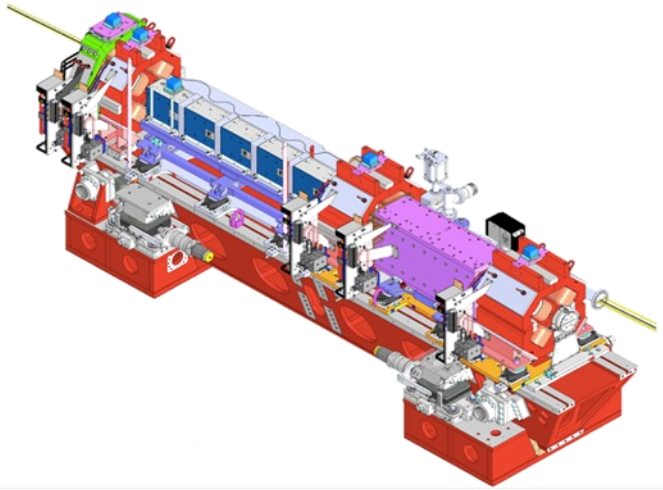
- **Manufacturing, quality control & logistics** of such components will be challenging given their number
- **Fiducialisation strategy** will be key
  - Determination of the **functional axis** (magnetic axis, electro-magnetic axis, electrical zero, etc.) of an accelerator component with respect to external targets «fiducials».
  - The accelerator components will be aligned later in the tunnel using these fiducials as their functional axes will not be accessible anymore
  - Different methods developed to perform this step within a few micrometers uncertainty of measurement



High accuracy fiducialisation of component

H. Mainaud Durand, "Main achievements of the PACMAN project for the alignment at micrometric scale of accelerator components", IPAC'17, Copenhagen, Denmark, May 2017

Alignment of components on specific supports



- **Metrology requirements:**
  - All functional axes of components aligned in the reference frame of a girder within ± 50 µm (1σ)
  - Integrating all errors:
    - The fiducialisation of components, including opening/closing of magnets
    - The girder: its reference frame, its rectitude
    - Impact of transport, etc.

- **Various solutions to study**, especially for the girder design, supporting adjustment systems and pre-alignment strategy, depending on different parameters

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

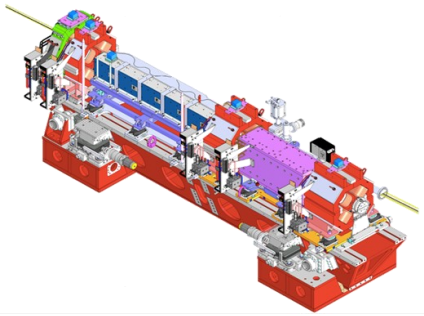
General constraints
- Access (installation, alignment, maintenance)
- Space
- Radiation level
- Thermal stability
- Stability of the tunnel floor, ground motion

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



- ✓ Develop safe concepts
- ✓ Reduce the environmental impact
- ✓ Identify challenges and propose solutions
- ✓ Cost optimization
- ✓ Reach physics objectives

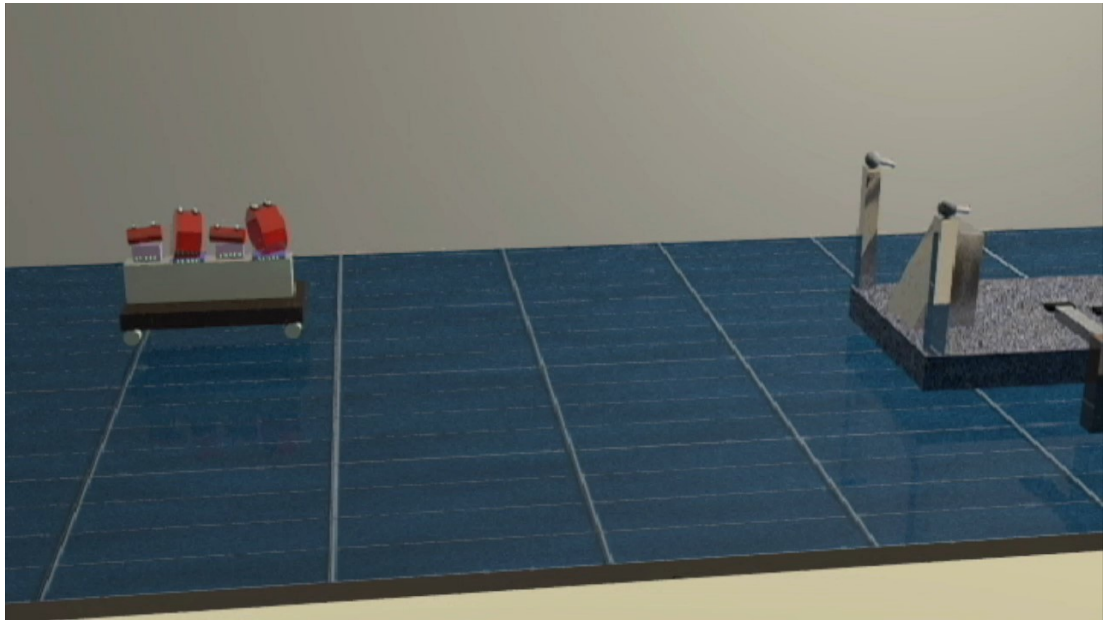
Alignment of components on specific supports



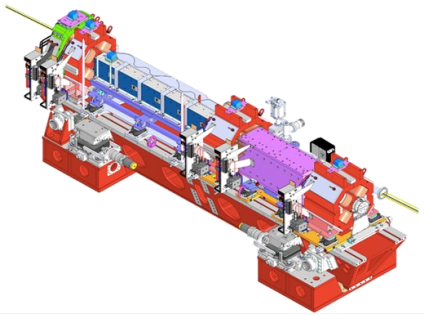
Examples of **scenarios**, explored for the CLIC PACMAN study, **to be extrapolated** to the FCC project:

- Scenario 1: Automated pre-alignment of components - already fiducialised - on a girder
- Scenario 2: Automated pre-alignment of components - non fiducialised - on a girder

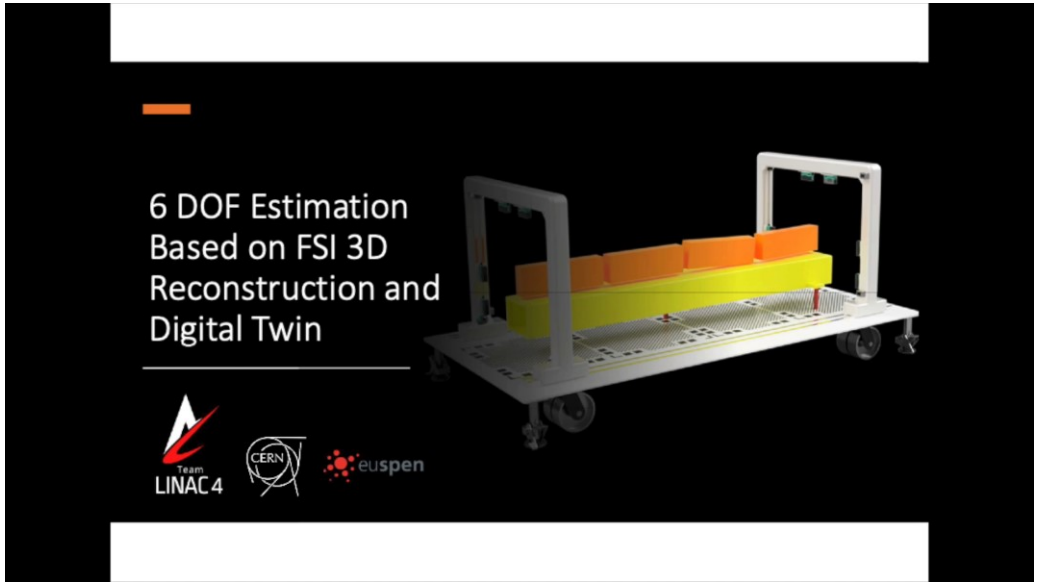




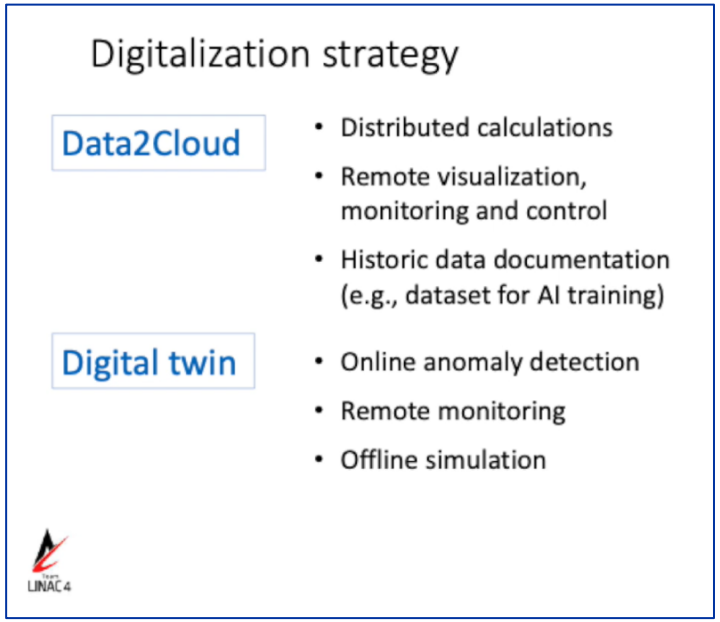
Alignment of components on specific supports



- Digitalization will be key.
- Importance of developing a hardware digital twin and having a real size mock-up to simulate all alignment deformations (thermal impact, tunnel temperature gradient, cooling of components, mechanical constraints from the adjustment systems)



From euspen 22 Student Talent programme

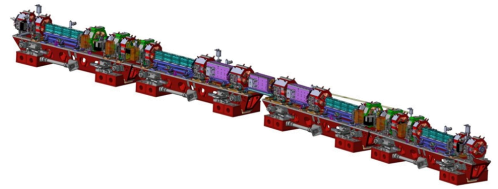


- **Introduction to CERN and FCC project**
- **Metrology requirements for FCC, through different cases:**
  - Alignment of components on specific supports
  - Large scale metrology and geodetic aspects



LHC tunnel

Large scale metrology & geodetic aspects



Tunnel Circumference: 90.7 km

Excavated vol: 6.2M m^3 (In the ground)

Access shafts: 12

Construction shafts: 1

Large experiment sites: 2

Small experiment sites: 2

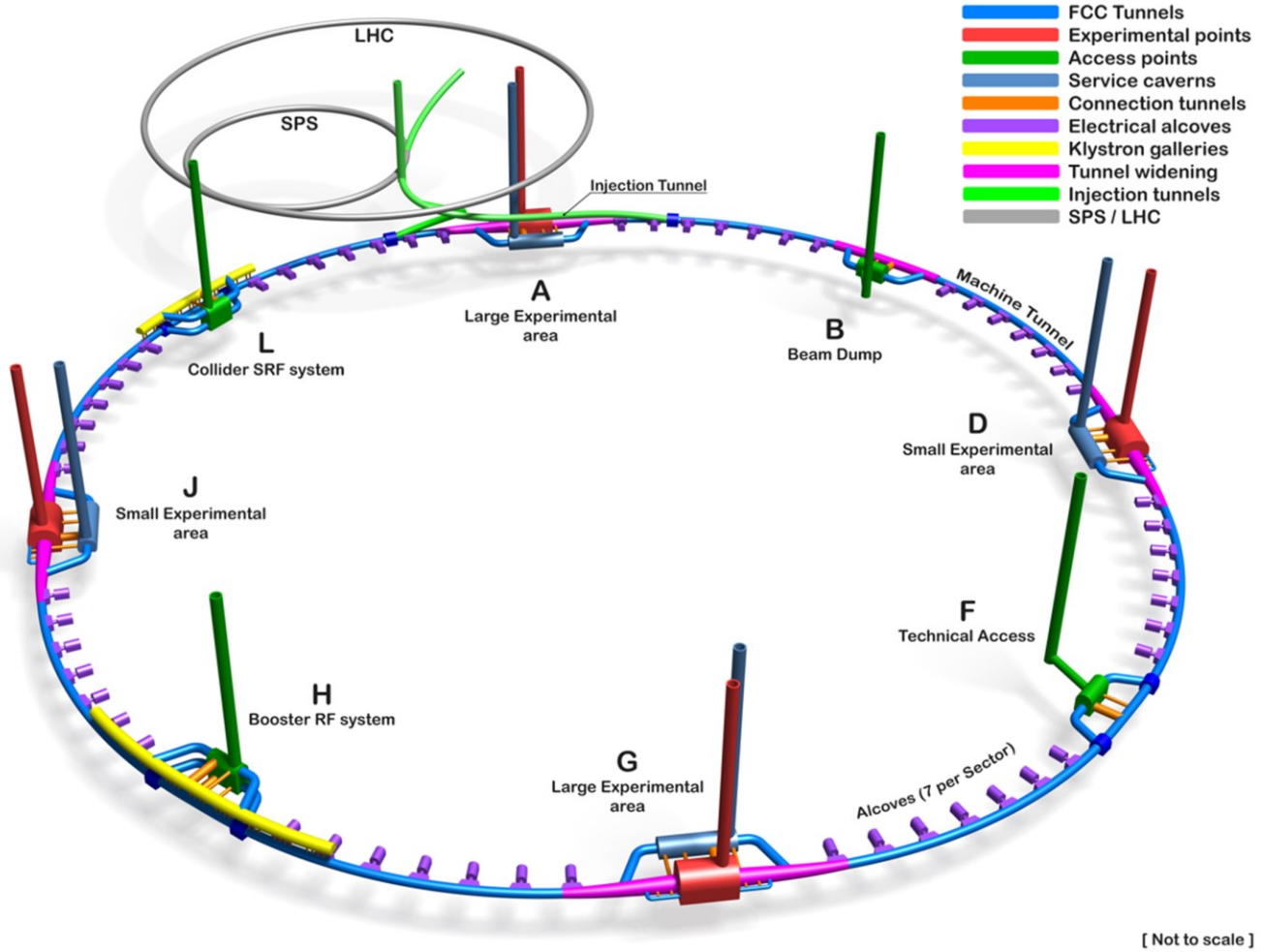
Technical sites: 4

Deepest shaft: 400m

Average shaft depth: 243m

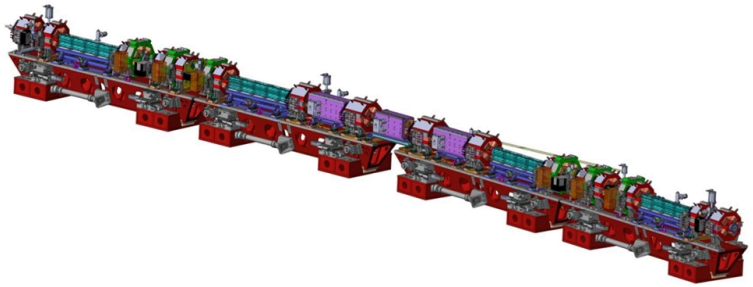
Total concrete volume: 1.9 M m^3

Steel weight: 130,000 metric tonnes



FCC schematic diagram (A. Navascues Cornago)

Large scale metrology & geodetic aspects



Charles et al. *EPJ Techniques and Instrumentation* (2023) 10:8
https://doi.org/10.1140/epjti/s40485-023-00096-3
EPJ.org
EPJ Techniques and Instrumentation
RESEARCH ARTICLE Open Access

Alignment & stability challenges for FCC-ee

Tessa K. Charles[1,2*], Bernhard Holzer[3], Rogelio Tomas[3], Katsunobu Oide[3,4], Léon van Riesen-Haupt[5] and Frank Zimmermann[3]

- Requirements from physicists (to be confirmed):

Table rms misalignment values used in simulations presented in this paper. The definition of the misalignment parameters are defined in Fig. 2. Note that values are not tolerance specifications, as there is an ongoing iterative process to determine the alignment level achievable and the acceptable machine performance

Type	ΔX (μm)	ΔY (μm)	ΔPSI (μrad)	ΔS (μm)	ΔTHETA (μrad)	ΔPHI(μrad)
Arc quadrupoles*	50	50	300	150	70	70
Arc sextupoles*	50	50	300	150	70	70
Dipoles	1000	1000	300	1000	0	0
Girders	150	150	–	1000		
IR quadrupole	100	100	250	250	70	70
IR sextupoles	100	100	250	250	70	70

* misalignments relative to girder placement

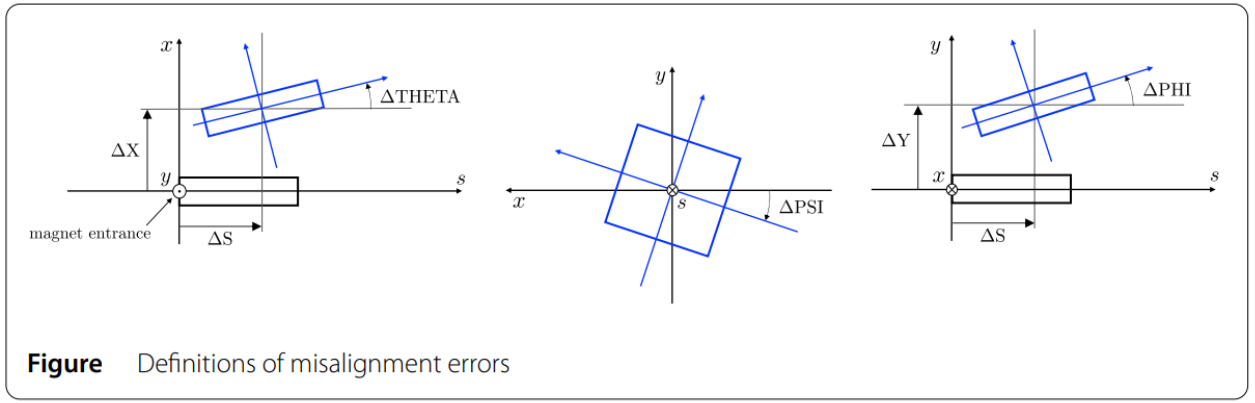
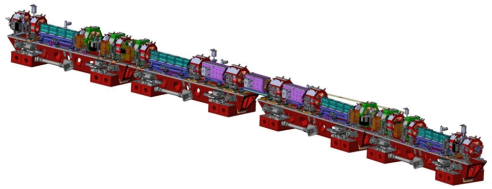


Figure Definitions of misalignment errors

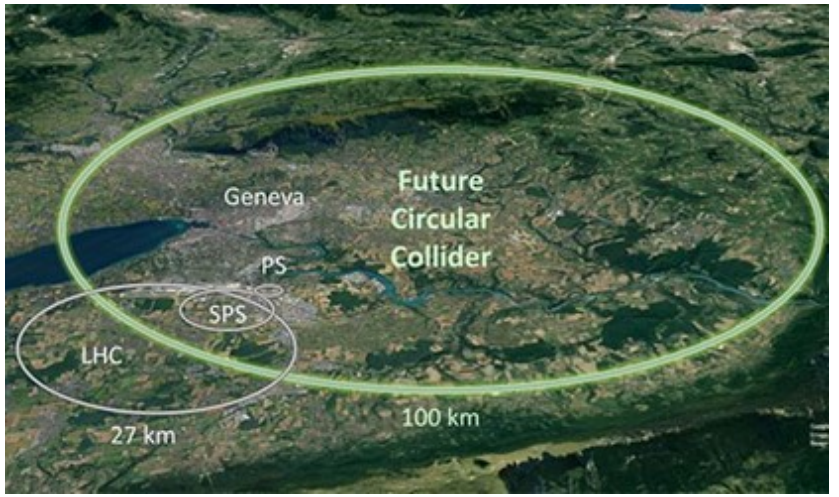
- Propose a **common process** to establish and define misalignment errors between physicists, surveyors, equipment owners, design office and control/quality services.

Geodetic aspects

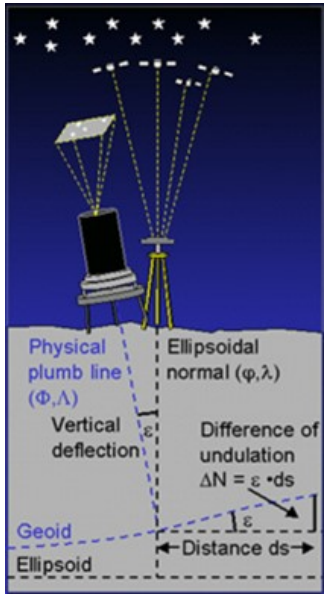


- Requirements & challenges:
  - FCC **10 times larger** than LHC
  - LHC reference frames and infrastructure go back to LEP (1980s)
  - The installation of component girders will start before the final completion of the whole tunnel ring, i.e. without a complete underground geodetic network
  - FCC located underground, below Swiss and France, in an inclined plane.
  - The major part of survey instrumentation and alignment sensors refer w.r.t. gravity
  - Two surfaces to model the Earth: ellipsoid and geoid. It will be very important to determine the link between both at the highest accuracy.
- Directions of studies (through collaboration)
  - Determination of a **high-precision gravity field model** for the FCC region
  - Improvement of the **Geodetic reference frames** and the geodetic infrastructure

H. Mainaud Durand et al., "Geodetic, Survey and alignment challenges of the FCC-ee", 2024 JINST 19 T02006



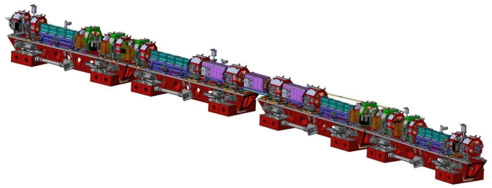
FCC footprint





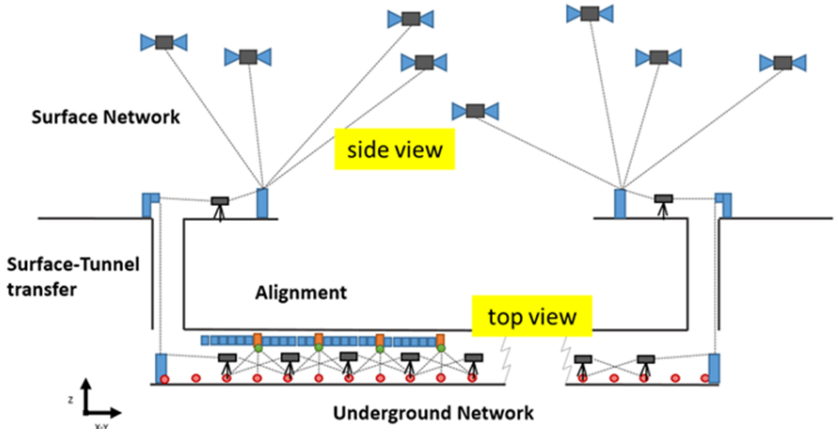
Astro-zenithal measurements

Large scale metrology

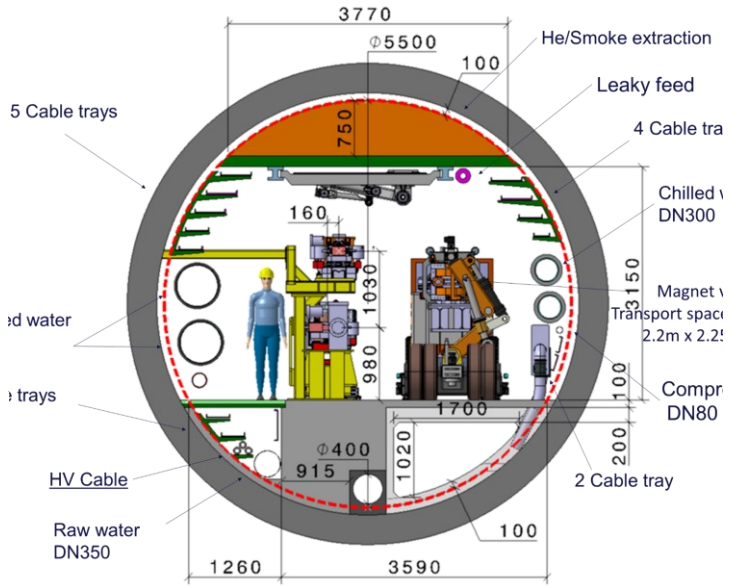


- Challenges:
  - Narrow configuration of the collider underground
  - Important **propagation of error** between 2 access pits.
  - Very high number of components to align, within very tight tolerances
  - Brand new tunnel, in which we will not know the stable and unstable area
  - **Harsh tunnel environment** (magnetic fields, radiations, temperature gradients, etc.
  - Very limited space for cables and infrastructure in the tunnel
- Directions of studies:
  - **Automation** of measurement
  - Development of alignment solutions and sensors, fulfilling the following requirements:
    - Based on straight references (laser beam, stretched wire)
    - Based on **optical fibers**
    - For harsh environment





Alignment steps



FCC tunnel cross-section

Next steps

- **An accelerated program of research has been launched, to be able to conclude on:**
  - The feasibility of the FCC study in March 2025
  - A pre-Technical Design Report (TDR) phase. This will bring the study to the level needed by CERN council to take a decision at end 2027 on whether or not FCC should be approved, including further developments of the civil engineering and technical components (and their integration), to provide a consolidated cost estimate with reduced uncertainties.
- **Sustainability will be a key aspect of the project**
  - All designs and R&D will be focused on carbon footprint optimization
    - With energy savings to reduce the power demand and energy consumption
    - With reduction of material needed.



Highlights from the CERN's 70th anniversary





Ursula von der Leyen • 3rd+
President of the European Commission
2w •

+ Follow

As the global science race is on, I want Europe to switch gear.

CERN's story shows that European unity is our greatest asset in this.

We must put research and innovation at the heart of Europe's economy.

We need more partnerships between research and business.

More ideas that go from the laboratory to the factory.

Our scientists must be able to find the resources they need right here in Europe.

This is why I want to increase research spending in our next budget.




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CERN Science portal



CERN’s new flagship project for science education and outreach.

A place for visitors of all ages.

Immersive exhibtions, hands-on learning, events and much more

Every year, CERN welcomes the next generation of scientists providing them training and experience

More than 3000 doctorate students

600 PhD theses achieved per year

300 students for the summer school



~ 800 graduates working in applied physics, research, engineering and informatics

~ 200 doctorate and technical students in applied physics, engineering and informatics

Organization of schools for 3rd Cycle students

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

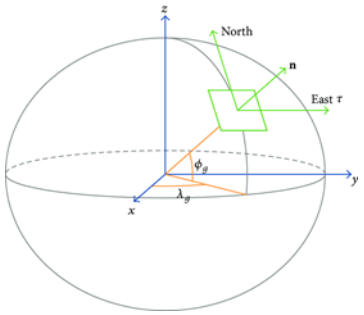
We provide metrology and alignment for components installed in the accelerators, their beam transfer lines and physics experiments throughout the CERN.

Nearly 60 km of beam lines!



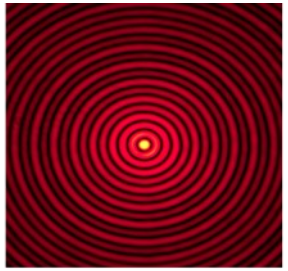
Permanent monitoring

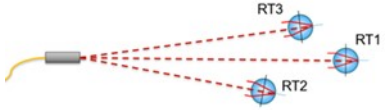
~ 7500 accelerator components



Geodetic aspects

20 experiments





R&D



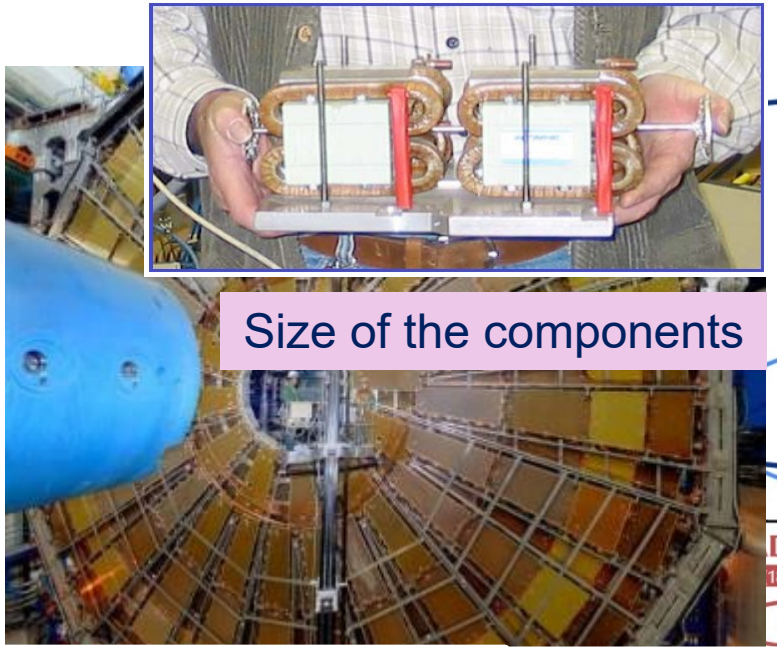
Georeferenced scans

Thousands of sub-detectors!

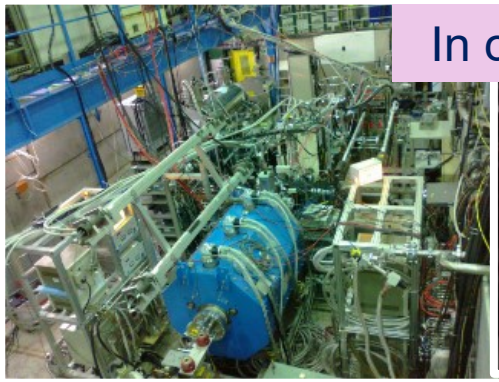


Associated software

GM – Geodetic Metrology -- Our day to day challenges --



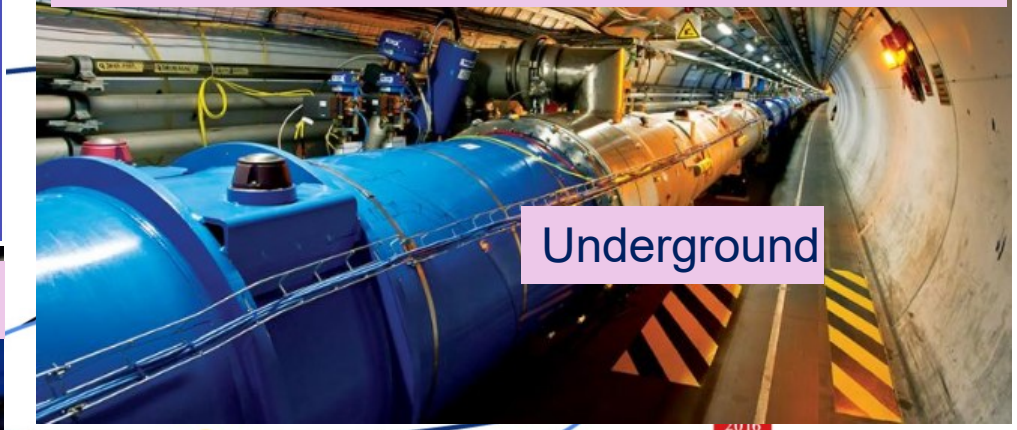
Size of the components



In crowded area



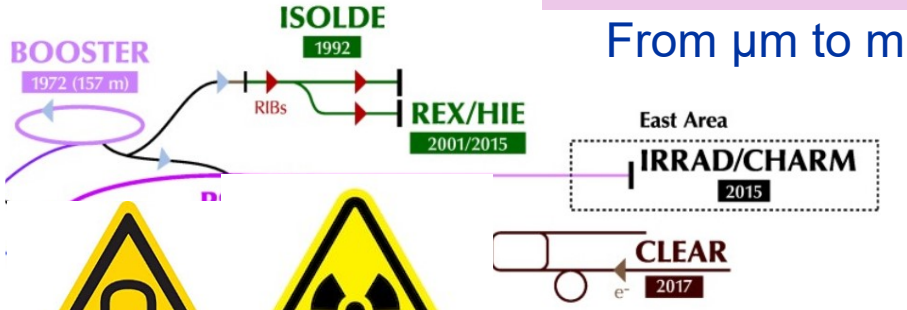
Difficult configuration: straight and narrow



Underground

Accuracy and precision

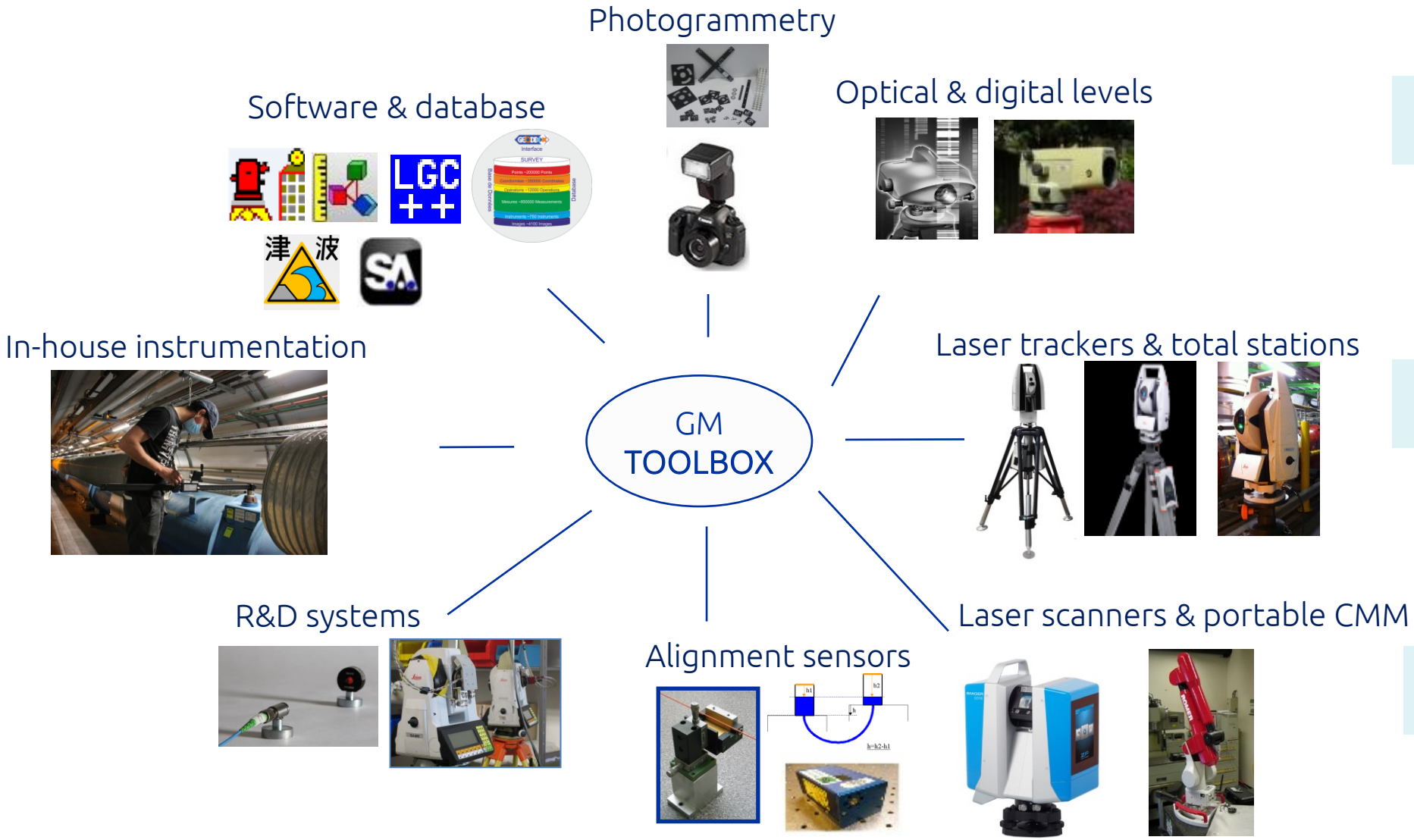
From µm to mm…



Severe environment…

Scale

GM – Geodetic Metrology -- More information -

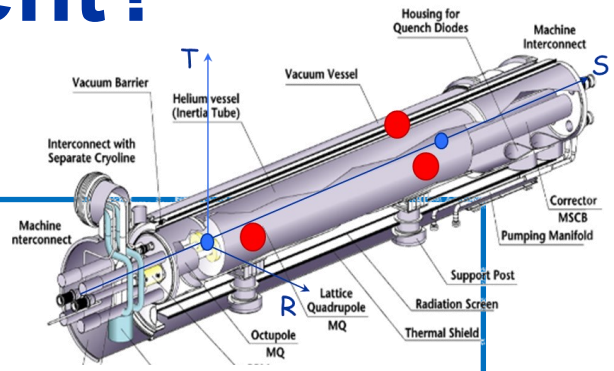


Adjustment solutions dev.

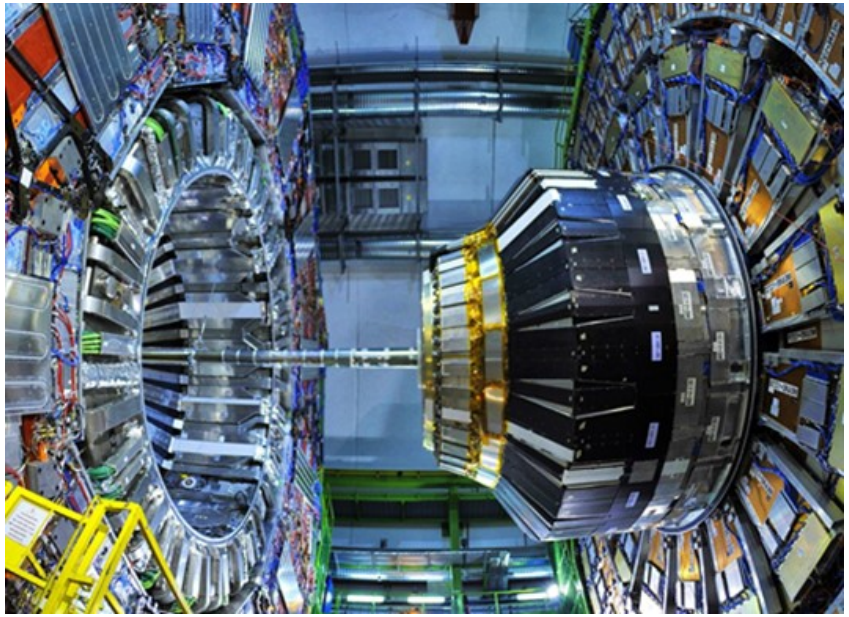
Expertise & consultancy

Knowledge Transfer

Why do we need high precision alignment?



Control of the assemblies



CMS detector

Fiducialisation process

