THE FCC-EE ALIGNMENT: QUESTIONS, ANSWERS, AND CHALLENGES

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Many thanks to :
Hélène Mainaud Durand, Andreas Herty, Dirk Mergelkuhl, Vivien Rude

Summary

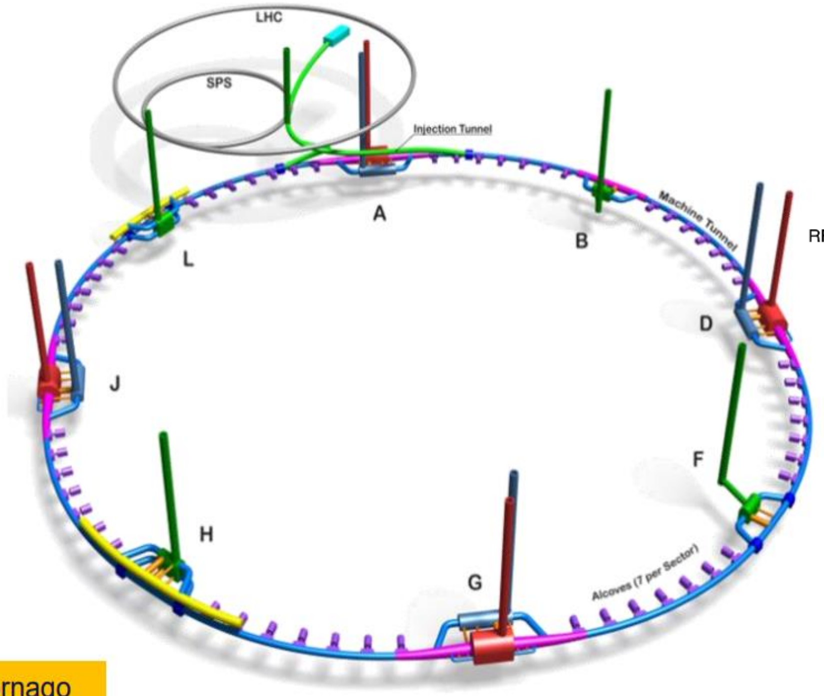
Reminder of the FCC situation

Experience of the LHC + challenge to face in the FCC

Proposition and ideas

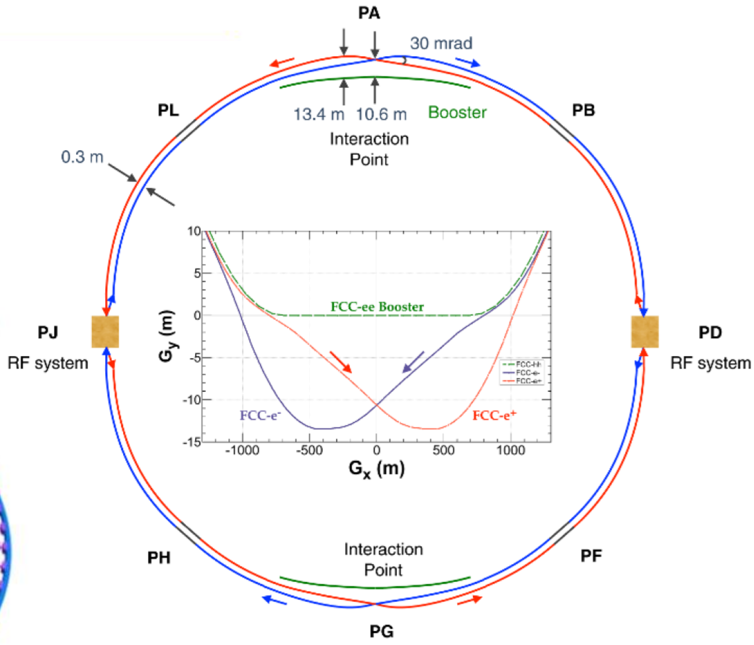
FCC-ee design

- FCC Tunnels
- Experimental points
- Access points
- Service caverns
- Connection tunnels
- Electrical alcoves
- Klystron galleries
- Tunnel widening
- LHC



Only schematic, and not to scale.

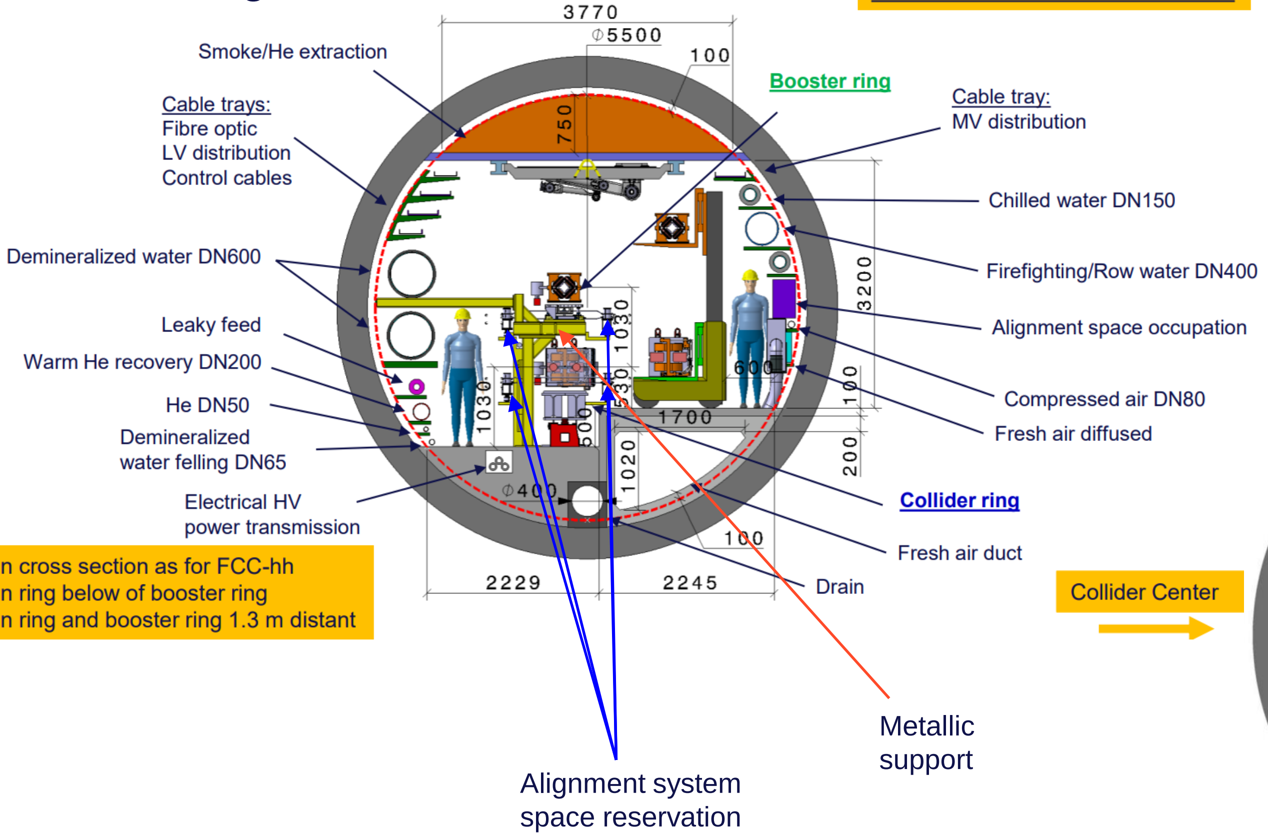
Courtesy A. Navascues Cornago



FCC-ee layout, FCC-ee CDR

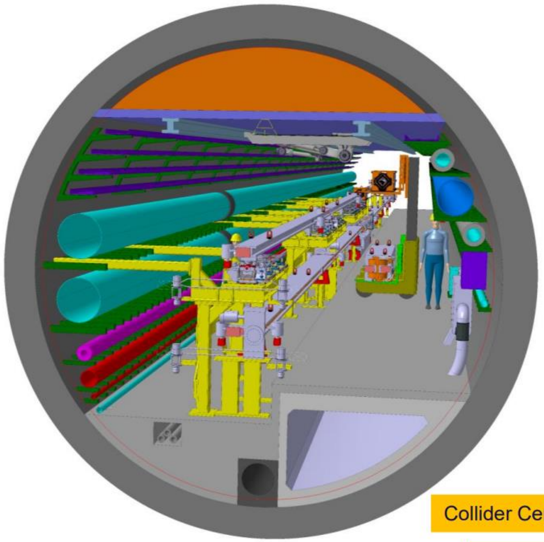
FCC-ee design

Machine tunnel 5.5m in diameter



Main cross section as for FCC-hh
Main ring below of booster ring
Main ring and booster ring 1.3 m distant

Collider Center



Collider Center

F. Valchkova-Georgieva

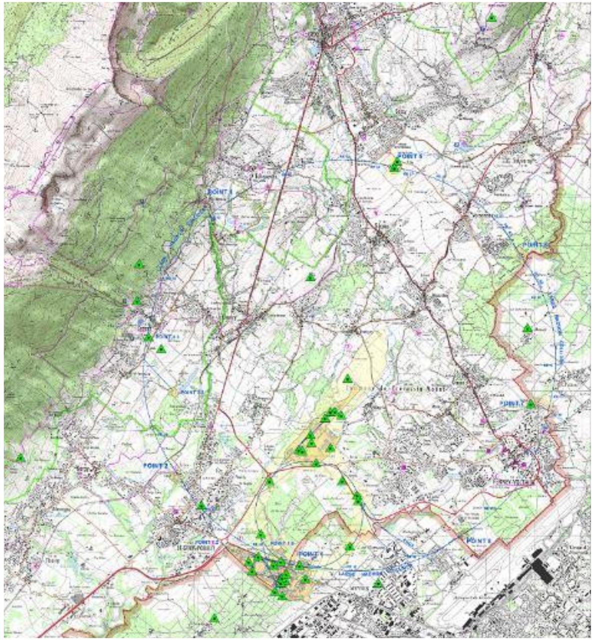
Situation at the LHC

(And comparison to the FCC)

Process for the alignment : surface geodesy and transfer to the tunnel

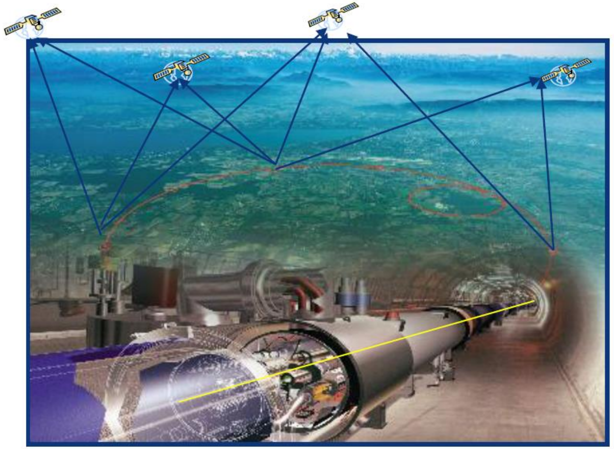
Alignment starts always from the surface …

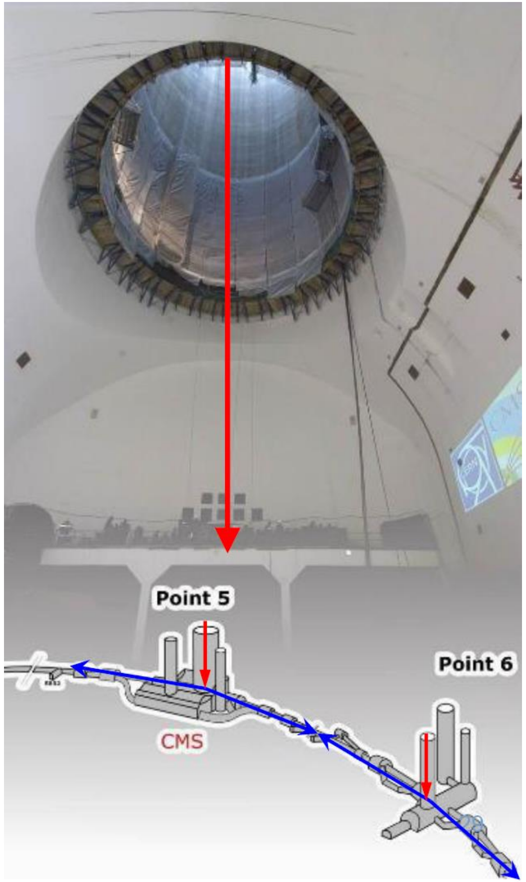
FCC -> See Benjamin Weyer’s presentation



… and then is transfered to the tunnel through the pits.

FCC: the size of the tunnel and the distance between pits may require a more precise process



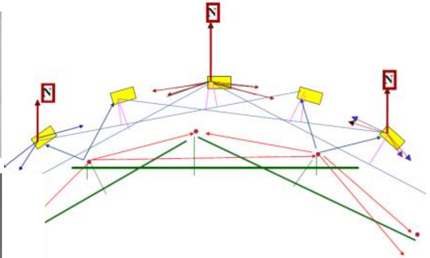


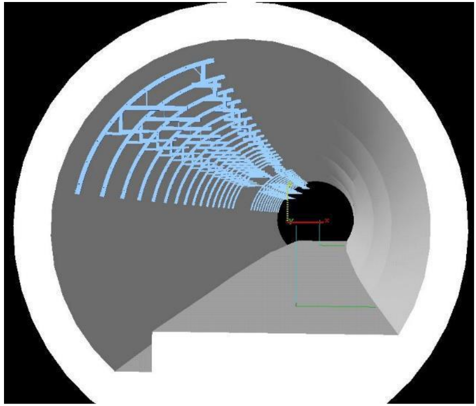
Process for the alignment : installation and measurement of the underground network

Intervention while the tunnel is still empty, installation of the reference network.

FCC: The size will make this operation repetitive and heavily time consuming

CERN photo



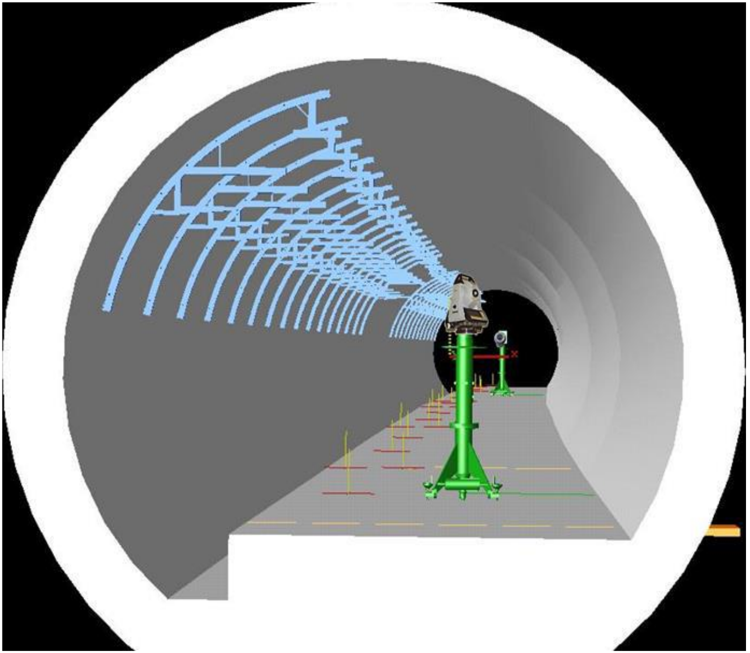


Measurement of the network, combination of multiple measurement techniques :

Azimuth	s = 1 mgon
Angles	s = 0.5 mgons
Distances	s = 0.15 mm
Wire offset	s = 0.1 mm over 120m
Levelling	s = 0.05 mm

FCC: The size will make this operation repetitive, heavily time consuming and may require more precise measurements + movements during the installation

Process for the alignment : Ground marking

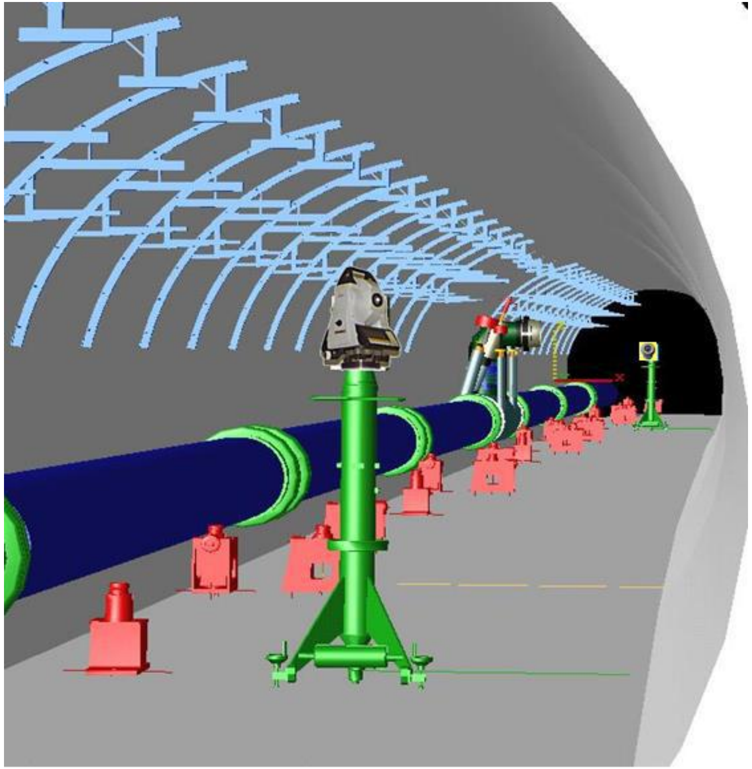


While the tunnel is still empty:

- marking for all the jacks
- +/- 2 mm (1σ)
- Wedge or digging to foresee

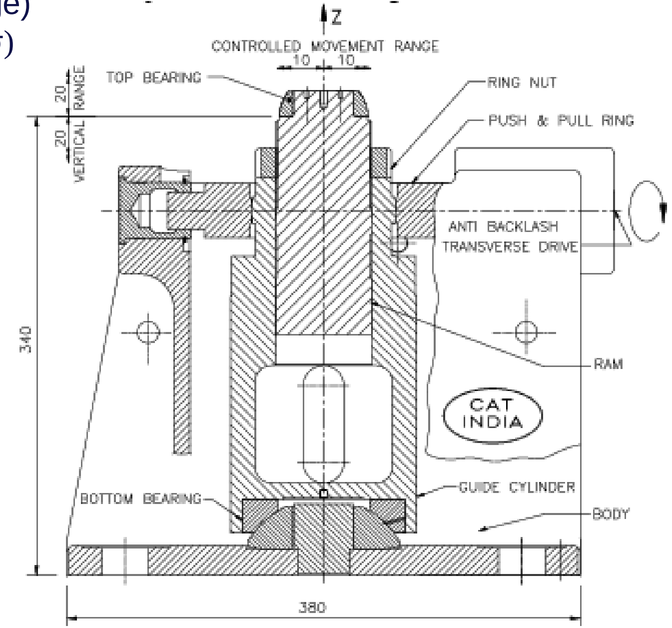
FCC: The size will make this operation heavily time consuming and may require more precise measurements

Process for the alignment : Jack alignment



Data for the LHC

- the head of the jack (mid-range) must be aligned at +/- 2 mm (1σ)
- middle jack is not aligned



FCC: The size will make this operation repetitive, heavily time consuming and may require more precise alignment

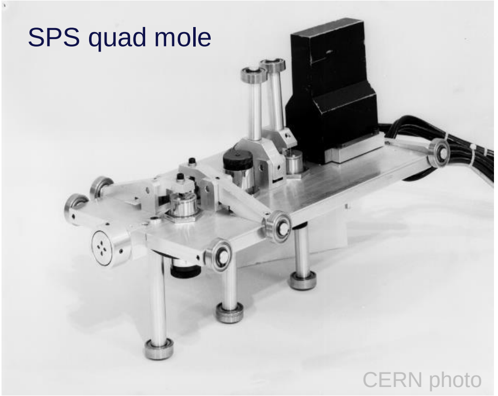
Process for the alignment : fiducialisation

Transfer of the reference axis on fiducials (= point references on the object).
But which axis ? Mechanical axis or magnetic axis ?
- Quads : mostly magnetic axis
- Dipoles : mostly mechanical

Small objects are done by the metrology service, but bigger ones are done by BE-GM.

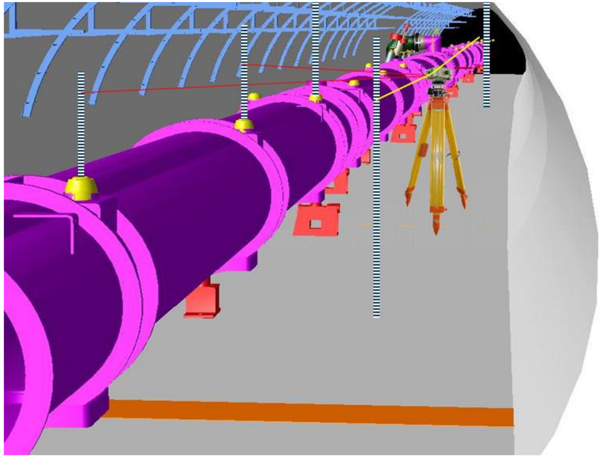
Must be performed for every components.

Multiple technics are existing :
- conductive wire
- mole
- palping
- direct measurement
- …

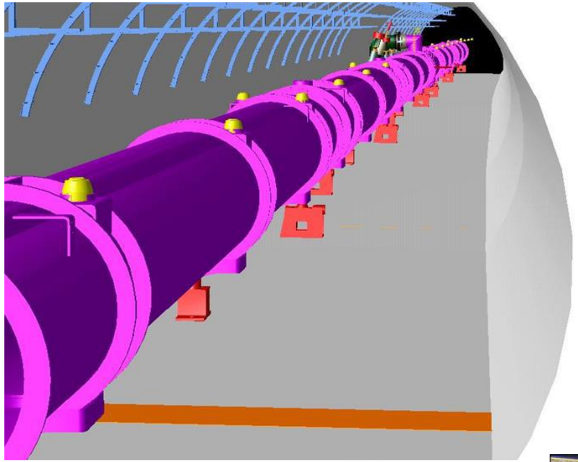


FCC: The size will make this operation repetitive, heavily time consuming and may require more precise alignment

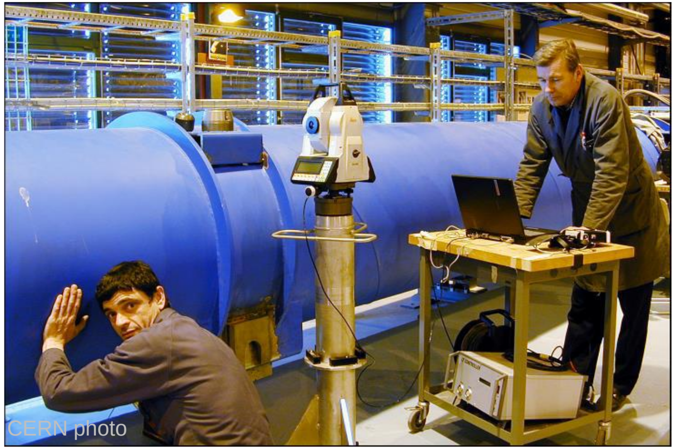
Process for the alignment : first alignment



Optical level NA2
+/- 0.2 mm wrt the network

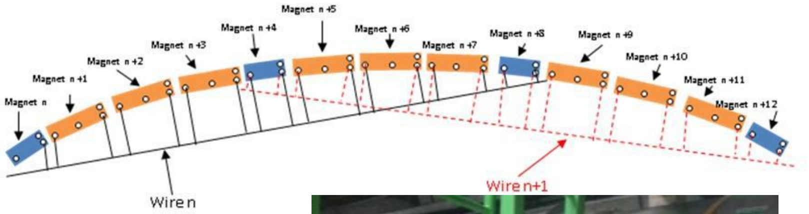


TDA 5005 for distances and angles
+/- 0.3 mm wrt the network



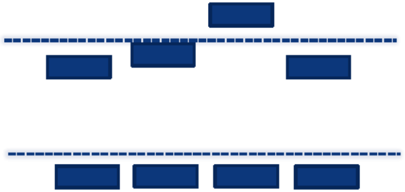
FCC: The size will make this operation repetitive, heavily time consuming and may require more precise alignment + big movements expected during the settlement of the tunnel.

Process for the alignment : Smoothing



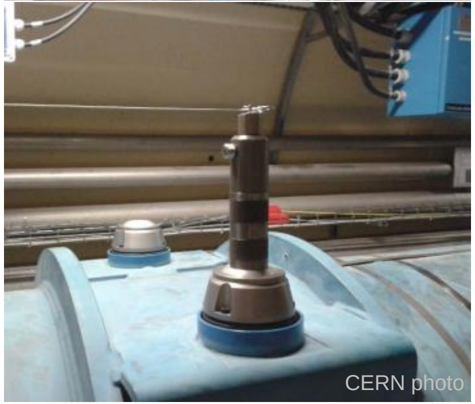
- Alignment has been done thanks to the geodetic network (+/- 0.2 mm)
- But then, “steps” in the alignment need to be smoothed
- Measurement is done directly on the magnet and not the network thanks to digital leveling and wire offset measurement

CERN photo



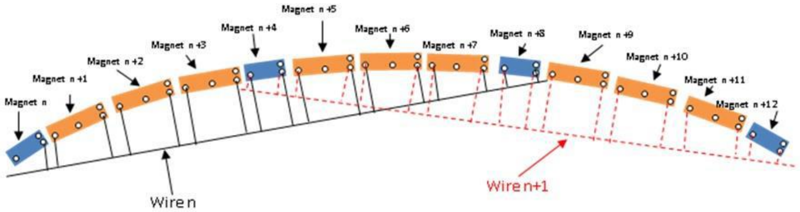
LHC data:
- 120 m long wire, redundancy of 2 dipoles or 3 quads
- ~ 550 measured points per sector
- Uncertainty of 0.04 mm (1σ)
- ~ 400m-80points per day for a team of 2 surveyors (one pass, everything goes well)


CERN photo


CERN photo

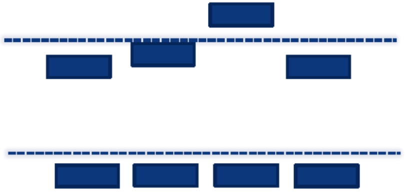
FCC: The size will make this operation repetitive, heavily time consuming and may require more precise alignment + big movement of the tunnel expected

Maintenance of the alignment



- Alignment and smoothing may need to be performed locally or globally during different stops (YETS and LS).
- During these stops, the duration of the alignment is very limited.


CERN photo



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CERN photo

In the LHC, some sector need an alignment every year because of tunnel movement, while some other require an intervention only every 5 years.

FCC: The size will make this operation impossible (not enough available trained workforce)
Moreover, it is repetitive, heavily time consuming and may require more precise alignment + big movement of the tunnel expected

Need for automatization

Each step is made extremely repetitive by the size of the machine:

- Fiducialisation (> 8000 dipoles, > 3000 quadrupoles and > 800 sextupoles + installation on girders+booster+LSS)
- Installation and measurement of the underground network
- Ground marking
- Jack alignment
- First alignment
- Smoothing
- Maintenance of the alignment

And it will be the case for the entire use of the machine (not only during the installation)
Repetitive tasks and the risk of mistakes it induces
Automatization is required for each stage, but the most demanding is the maintenance of the alignment.
Automatization methods interfaces have to be included in study on FCC design

Why is that the most complex for the maintenance of the alignment ?

- ➢ Big and continuous movements expected (especially near after the construction of the tunnel)
- ➢ Required for the whole ring
- ➢ Most complex physical operation in the alignment chain (measurement + eventual physical intervention on the component)
- ➢ Most demanding in terms of uncertainty and time available
- ➢ Must deal with everything installed in the tunnel and must therefore deal with physical limitation (including security)
- ➢ Must be performed multiple times

And alignment of the secondary components is more time consuming than the main components (Dipoles, quadrupoles …)

Need for automatization

Two main solutions could be implemented:

Implement supports and sensors able to continuously measure the alignment and realign if required

Advantages:

- Extremely practical
- Some solution are already existing
- Alignment of the entire ring known in real time
- Remote adjustement could be done simultaneously on almost all the ring if needed, but also on specific components (for the beam based alignment for example)
- Instantaneous reaction time

Disadvantages:

- On the costy side for now (could be lowered by industrialisation justified by the size of the project)
- R&D required to take less space
- Longer to implement

Install robot able to navigate, measure and perform the alignment remotely

Advantages:

- Apparently cheaper
- More versatile (survey gear could be implemented with other tools on the same support)

Disadvantages:

- Not instantaneous (can be fast if enough robots)
- No continuous knowledge of the alignment (but can be done on demand)
- Very complex system for the wanted uncertainty (need to move, measure and act on the components to readjust them)
- Lot of R&D required
- May require a lot of clearance for the lines of sight

Extremely high chance that the system resulting is a combination of the two.

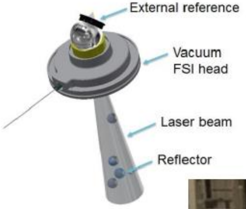
Technology evolves

Full Remote Alignment

Permanently installed sensors and their infrastructure

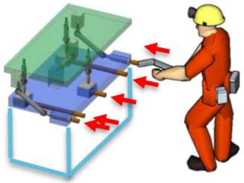
Remote controllable actuators

Cold mass monitoring in HL-LHC



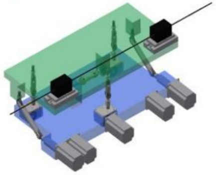
Sosin, M., et al. "Frequency sweeping interferometry for robust and reliable distance measurements in harsh accelerator environment." *Applied Optical Metrology III*. Vol. 11102. SPIE, 2019.

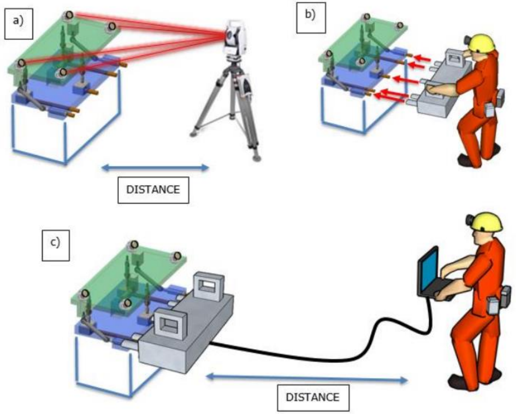
Full Remote Alignment



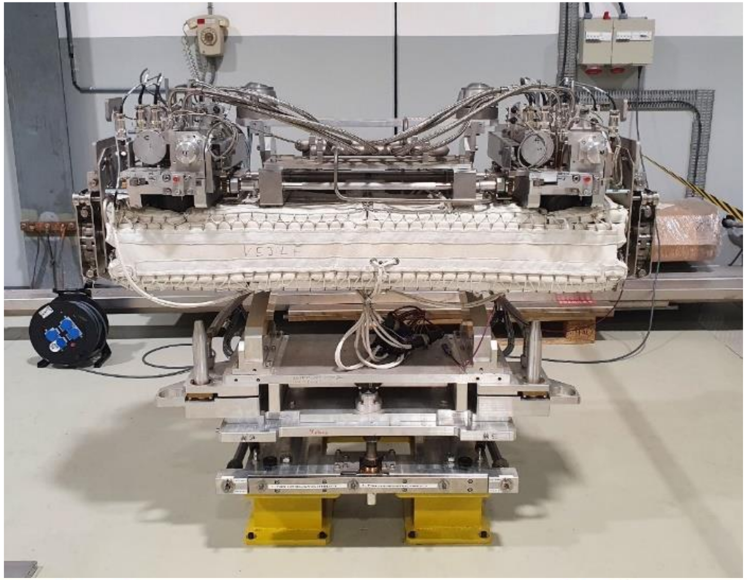
Universal adjustment platform – manual operation concept

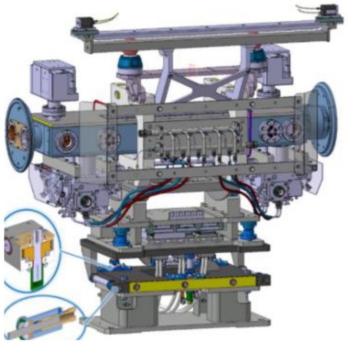
Universal adjustment solution - permanent motors version concept. Platform equipped with WPS sensors

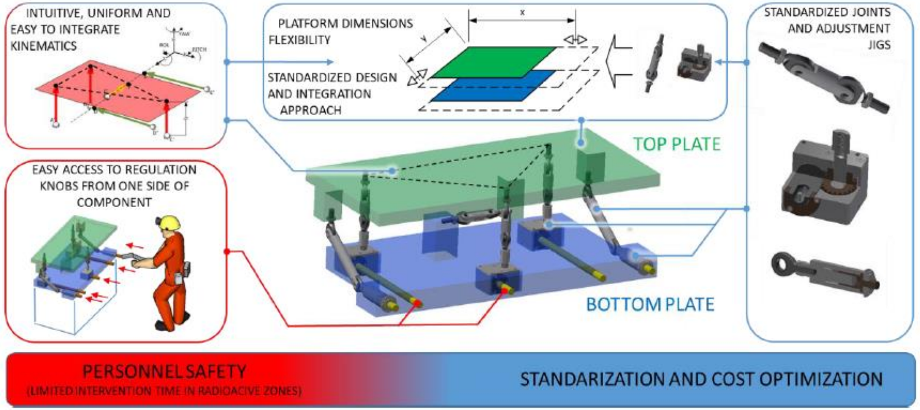




Universal adjustment solution – concept of use plug-in motors:
a) Platform measurement from distance using a laser tracker;
b) Installation of plug-in motors in less than one minute;
c) Remote adjustment from distance.

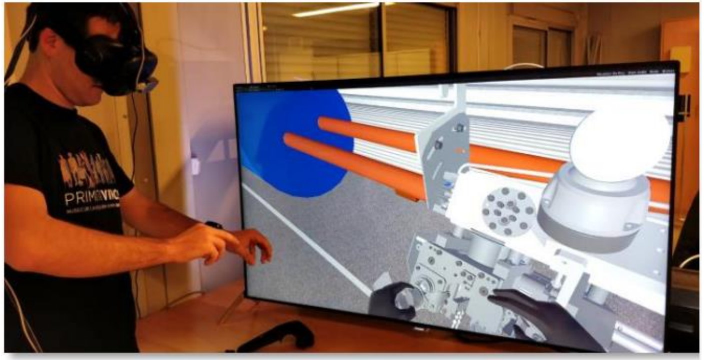


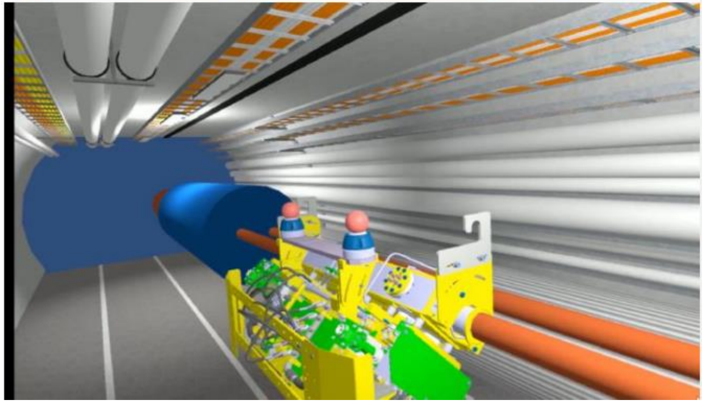




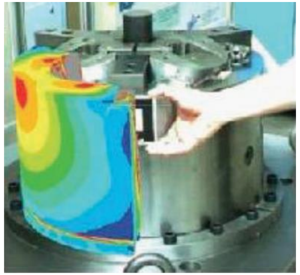
https://www.euspen.eu/resource/universal-adjustment-platform-standardization-of-6-degrees-of-freedom-adjustment-systems-design-and-integration/

Augmented reality





Overview of the Robotic Service at CERN for accelerator maintenance
https://indico.cern.ch/event/999825/contributions/4251111/attachments/2218904/3757125/2021.03.31%20-%20Robotics%20Service%20At%20CERN.pdf

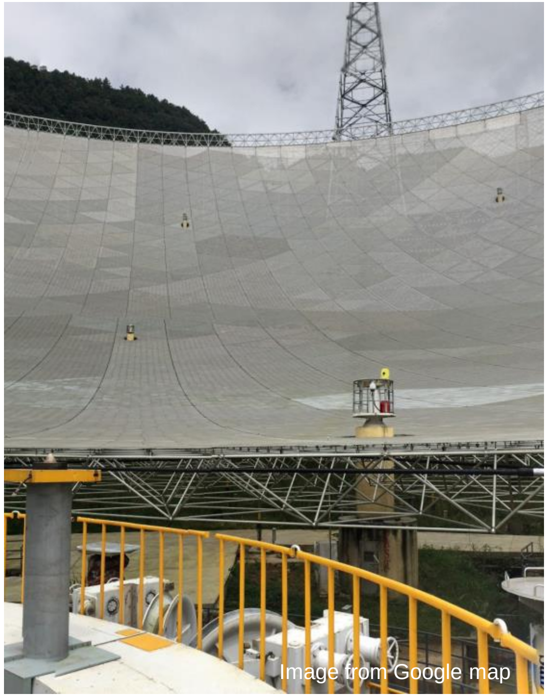


- Integration visualization
- Training
- Component visualization on site
- Additional information visualization (misalignment, vibration, temperature, radiations ?)
- Advanced diagnostics
- …

Pejić, P., Rizov, T., Krasić, S., & Stajić, B. (2014, October). Augmented reality application in engineering. In *3rd international congress, SMAT* (pp. 39-44).

Robots

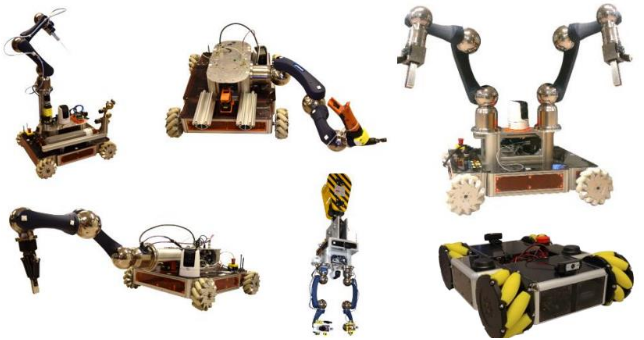
(Cf. Dr Mario Di Castro's presentation : Robotics for Accelerator Maintenance, later this afternoon)



Permanent network of robotic total stations in the Five-Hundred-meter Aperture Spherical Telescope in China

- Simulation of robotic interventions
  - ✓ Integration of robots in the environment and choice of robots
  - ✓ Intervention procedures
  - ✓ Tools design and test
  - ✓ Machines risk assessment
  - ✓ Robots training by demonstration
  - ✓ Operators training and teleoperations
  - ✓ Risk analysis
  - ✓ Recovery procedures
- Simulation of human intervention
  - ✓ Human intervention procedures
  - ✓ Live radiation levels and cumulated dose while training in VR (Augmented reality in virtual reality)
  - ✓ Intervention training
  - ✓ Risk analysis
  - ✓ Feedbacks for future remote-handling-friendly machines

Di Castro, M., Tambutti, M. B., Ferre, M., Losito, R., Lunghi, G., & Masi, A. (2018, August). i-TIM: A robotic system for safety, measurements, inspection and maintenance in harsh environments. In 2018 IEEE International Symposium on Safety, Security, and Rescue Robotics (SSRR) (pp. 1-6). IEEE



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https://aecmag.com/reality-capture-modelling/trimble-releases-autonomous-robotic-scanning-solution/

Permanent references are required for robots, installation and maintenance of those must be foreseen.

Thank you for your attention