Alignment prospects for the FCC-ee

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21 September 2022, FCC EPOL Workshop

Summary

A short reminder

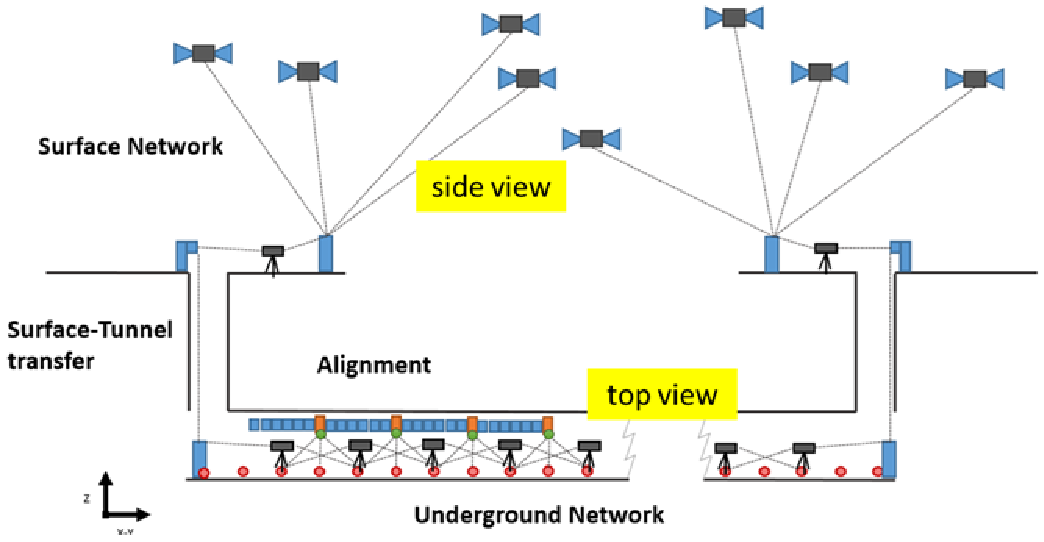
Lessons learnt – state of the art at CERN

- Case of LHC
- Case of CLIC

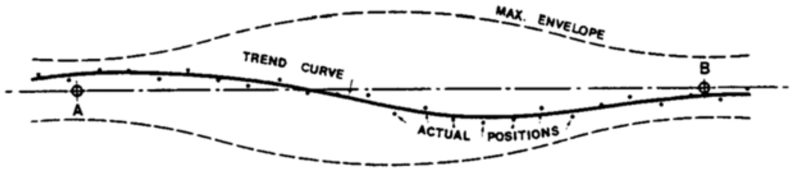
Alignment prospects for the FCC-ee

A short reminder… Steps of alignment

- Definition of alignment tolerances
- Definition of alignment strategy



- Installation & determination of a surface and underground geodetic network
- Preparation of the components: fiducialisation and assembly measurements
- Absolute alignment of each component w.r.t. underground geodetic network
- Relative alignment: smoothing



Position of magnets with respect to theoretical orbit

- 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

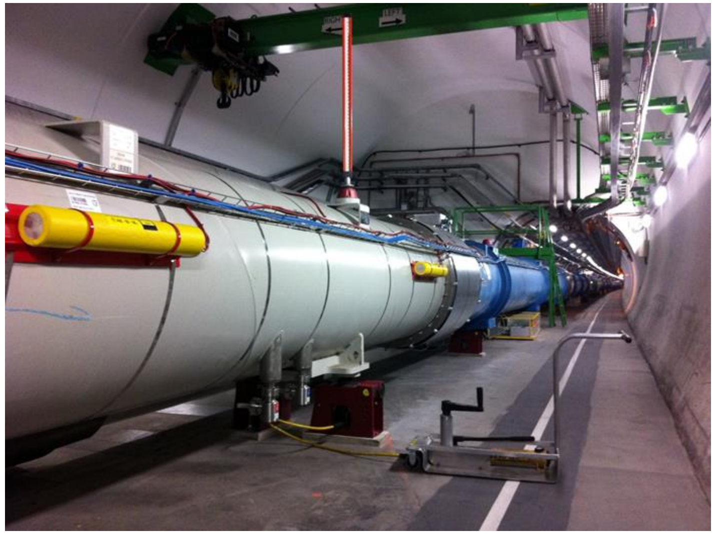
State of the art at CERN

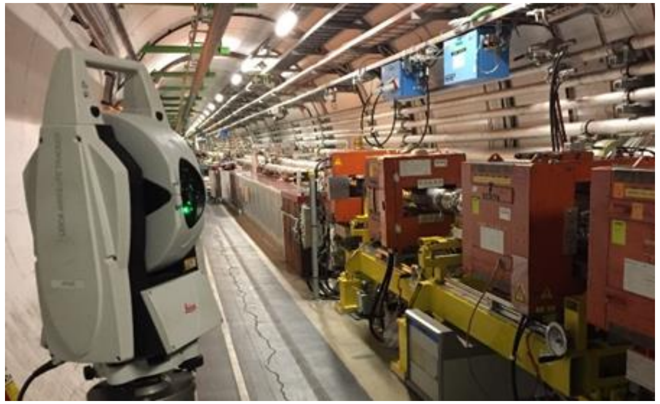
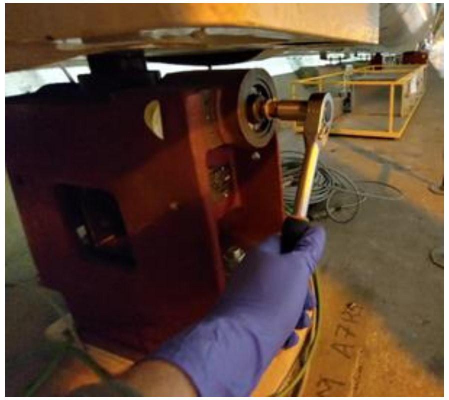
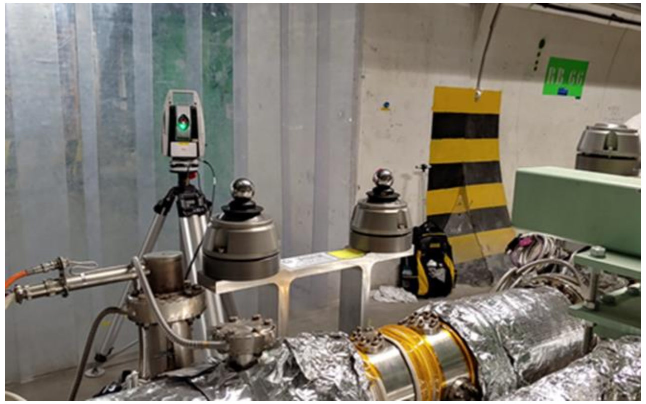
LHC: methods

- 2D + 1 measurements for main components
- 3D measurements for some secondary components

- Measurements
- Analysis
- Displacements



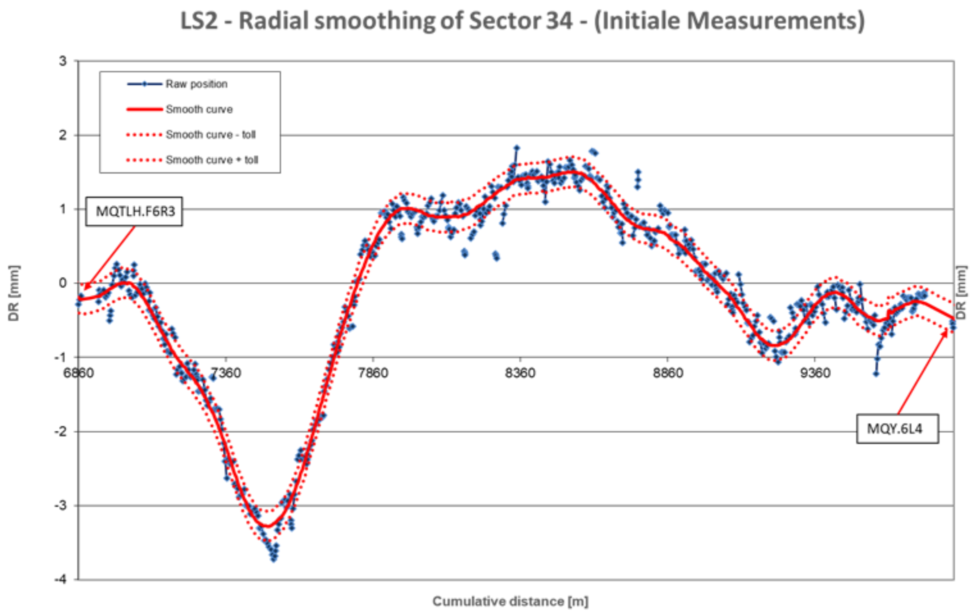


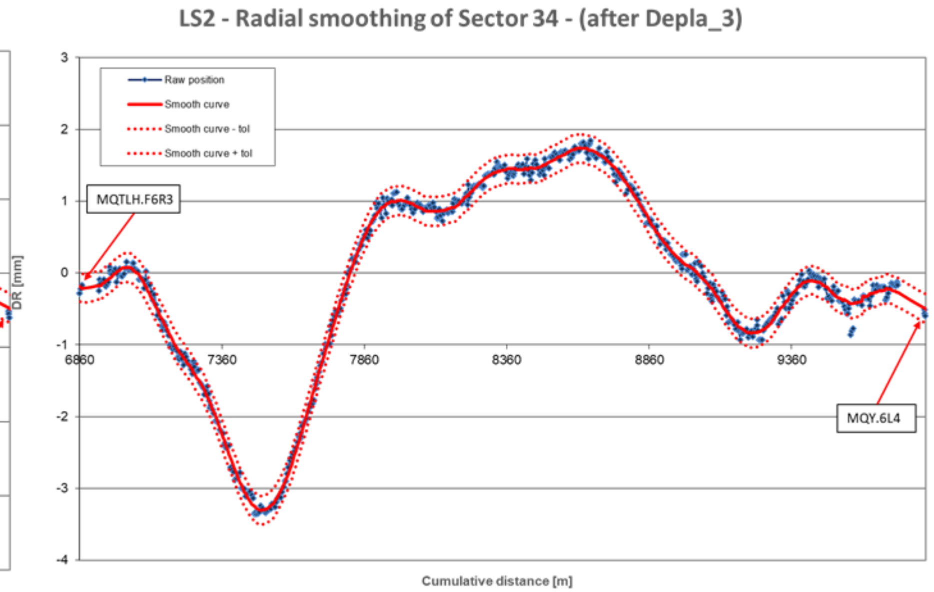
LHC: methods and rate

Standard (LHC) methods can't be applied for the FCC-ee

After measurements



After displacements / smoothing



A few (approximative) rates in the LHC:

- LSSs (main components): measurements [*1 team, 3 weeks*] – 2 weeks analysis – smoothing [*1 team, 4 weeks*]
- ARCs : measurements [*2 teams, 2 weeks*], smoothing [*2 teams, 3 weeks*]

By extrapolation to the FCC-ee [*data from Mark Jones*]:

- Tilt measurement and correction: 15 weeks.
- Vertical and radial smoothing: 338 weeks.

} 100 teams in 4 weeks or 25 teams in 4 months (main components only!)

LHC: lessons learnt

- **Contract management during YETS and LS: up to 13 additional persons:**
  - Very difficult to find trained surveyors
  - Very difficult to keep the motivation of the persons on such repetitive tasks.
  - All particular cases and «exotic» components managed by CERN staff

- **Automate as much as possible the measurements: development of a Survey wagon**

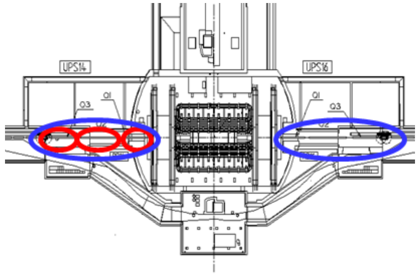
- **Standardize** as much as possible all adjustments and measurement solutions: **Survey guidelines under approval by all equipment owners**

- **The alignment of special elements (secondary components) can be far more time-consuming than the standard ones**

- **A rigorous approach** was put in place **to assess the alignment tolerance (WGA):** the alignment tolerance coming out of the MAD program simulations was considered to be a global alignment error budget (1σ precision), and had to be split betwen the different parties concerned (magnetic measurements, etc.)

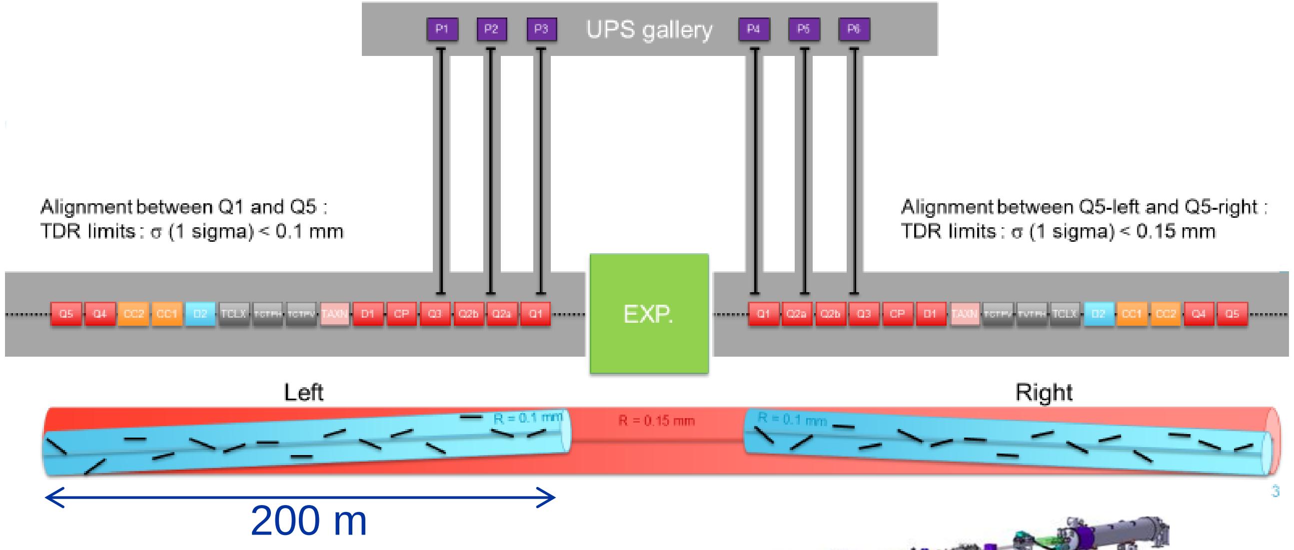
  → **glossary & tolerance definitions needed for FCC-ee.**

LHC: lessons learnt



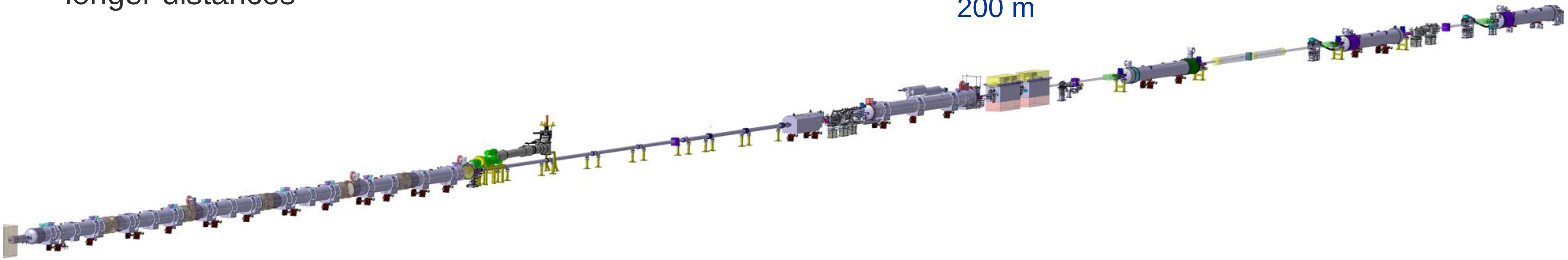
- MDI area: all **low beta triplets** equipped with alignment sensors and supported by motorized jacks.
  - Machine reference available in the 4 experimental area
  - Position determination of the left triplet w.r.t. right triplet within ± 50 µm (1σ) in vertical and within ± 100 µm (1σ) in radial
  - Position determination of one quadrupole inside a triplet within ± 70 µm (1σ)
  - Remote adjustment performed (when needed) during YETS
- Very accurate on top of the cryostat but what happens inside? → **Internal monitoring** for HL-LHC: continuous determination of the position of the cold masses of the inner triplets and the crab cavities w.r.t. their cryostat.

LHC: towards HL-LHC



High Luminosity LHC

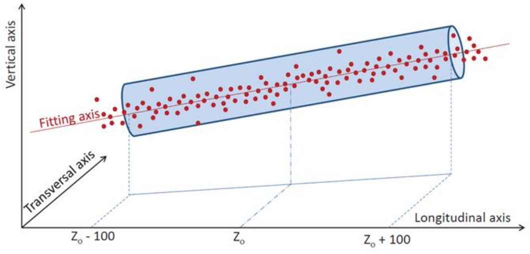
- Major upgrade program for LHC
- 1.2 km of beamline will be exchanged
- Provide same alignment precision as for LHC over longer distances



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.

CLIC: a few conclusions

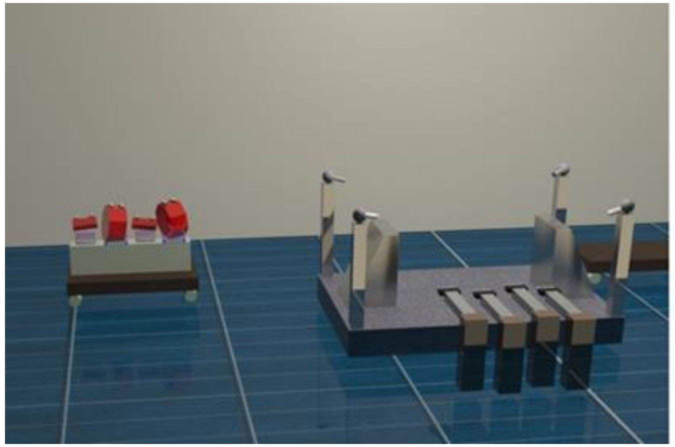


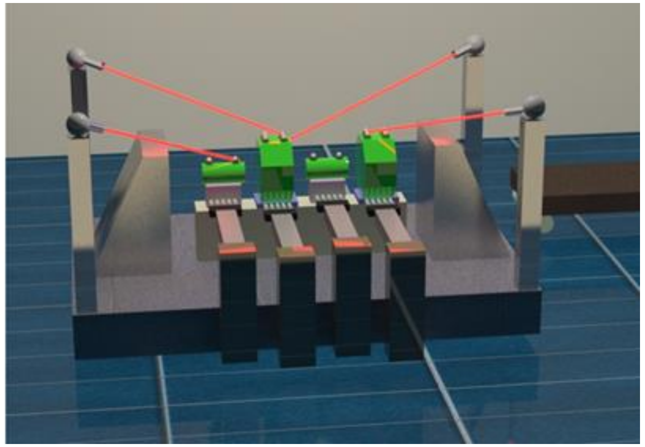
Along Main Linac: over sliding windows of 200 m:

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

At the level of the reference axis
(including fiducialisation)

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

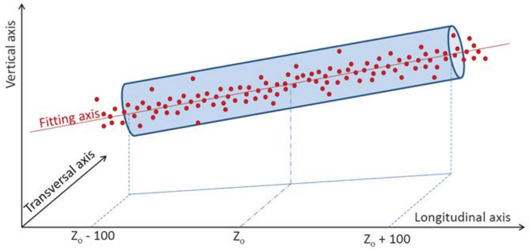




- To relax mechanical tolerances
- To keep the possibility to re-align the components after transport in the tunnel
- More info: PACMAN

- Importance of girder support (rigidity, material), sensor interface and external constraints
- Trade-off to make between the rigidity of the girder, the adjustment systems, the cost, the time needed for the assembly and measurements, the long-term stability, the temperature impact.
- Measurements at 20°C, but the temperature at operation will be quite different!
- **Temperature impact is crucial** and very complicated to model at a micrometric accuracy

CLIC: a few conclusions



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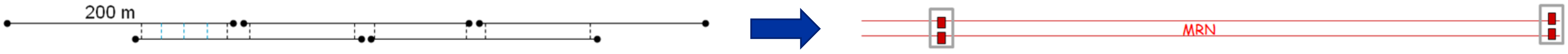
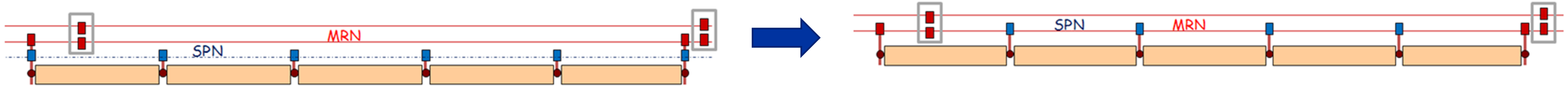
At the level of the reference axis (including fiducialisation)

Specific alignment strategy and methods developed for the tunnel, using a combination of long-range micrometric alignment systems and short-range alignment systems.

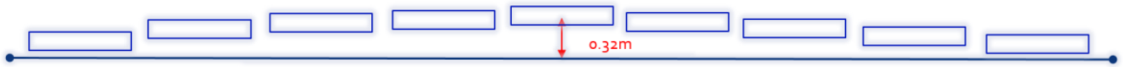
Long range alignment method (MRN)



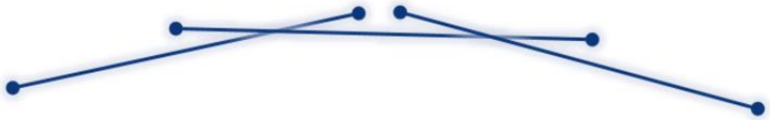
Short range alignment method (SPN)



- We qualified Wire Positioning Sensors (WPS) measuring w.r.t. overlapping wires (200 m long)



- An overall budget of error of ± 17 µm (1σ) for MB quad was demonstrated (simulations, cross-checked on short range / long range facilities, at 20°C). **The methods developed are not transferable to a circular collider.**



Alignment prospects for FCC-ee

Alignment requirements for FCC-ee

FCC-ee emittance tuning results
without BPM errors and without chromaticity correction

RMS misalignment and field errors tolerances:

Type	ΔX (μm)	ΔY (μm)	ΔPSI (μrad)	ΔS (μm)	ΔDTHETA (μrad)	ΔDPHI (μrad)
Arc quadrupole*	50	50	300	150	100	100
Arc sextupoles*	50	50	300	150	100	100
Dipoles	1000	1000	300	1000	-	-
Girders	150	150	-	1000	-	-
IR quadrupole	100	100	250	250	100	100
IR sextupoles	100	100	250	250	100	100

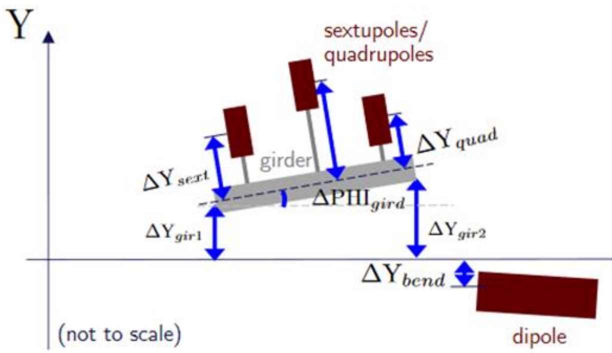
* misalignments relative to girder placement

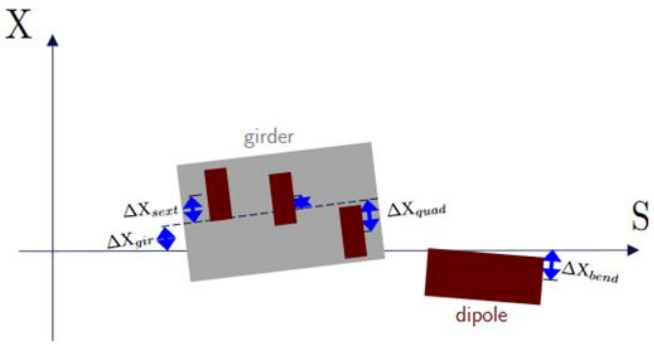
Type	Field Errors
Arc quadrupole*	$\Delta k/k = 2\times10^{-4}$
Arc sextupoles*	$\Delta k/k = 2\times10^{-4}$
Dipoles	$\Delta B/B = 1\times10^{-4}$
Girders	-
IR quadrupole	$\Delta k/k = 2\times10^{-4}$
IR sextupoles	$\Delta k/k = 2\times10^{-4}$

Important to note:
BPM errors not included and chrom correction not included.

Radiation not included in correctors and trim and skew quads.

Also note:
Despite well corrected linear optics, the DA is still greatly reduced.





From Tessa Charles (FCC week, June 2022)

At the level of the reference axis (including fiducialisation)

Alignment prospects for FCC-ee

Stability of the tunnel:

- Further analysis of the stability of the LHC tunnel w.r.t. surface deformation should be performed for a better extrapolation to FCC

  → Geo-monitoring proposal under preparation with ETH Zürich, IGN and Swisstopo

- A permanent monitoring in specific area will have to be put in place **ASAP** in the new tunnel to have a better understanding of the stability of the area. **R&D developments needed!**
- Be flexible in the range/stroke of the supporting systems of the components.

Installation process:

All steps of installation (marking on the tunnel floor, jack heads control, pre-alignment) will have to be automated as much as possible.

MDI area:

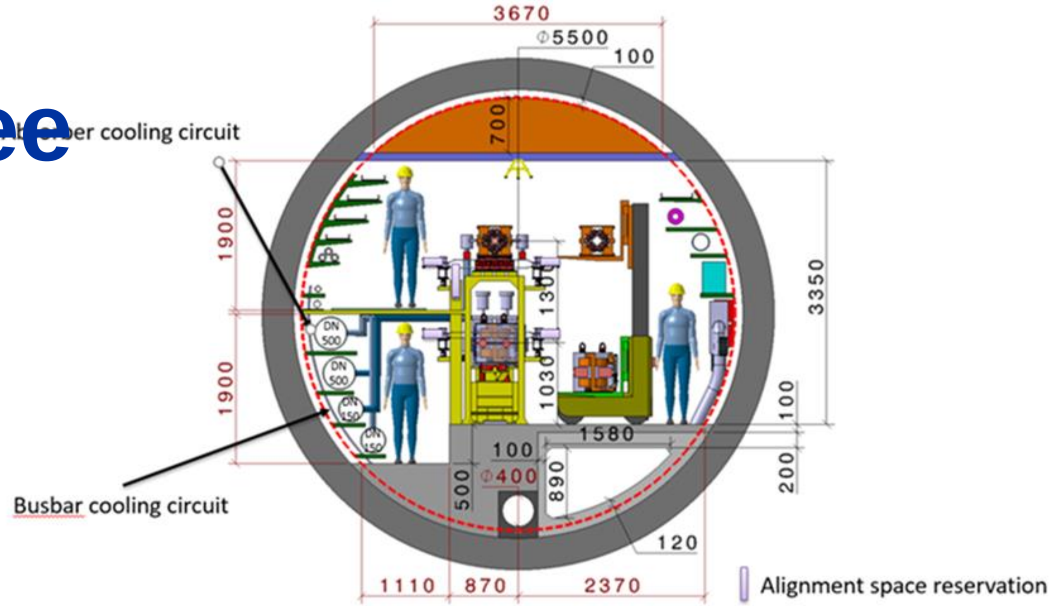
Studies shall start ASAP → 1 doctorate student: Leonard Watrelot investigation solutions since 2020

Alignment prospects for FCC-ee

Fiducialisation process:

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

Alignment prospects for FCC-ee



Smoothing:

- Too long and fastidious in LHC using "standard methods",
- Far higher number of components for FCC-ee
- In a brand-new tunnel, with unknown ground motion
- Temperature variations will have a great impact on the alignment
- The methods developed for CLIC can't be integrated for the FCC; HL-LHC methods too expansive

Two directions of study for the smoothing process:

- **Develop and automate new measurement methods** to optimize the duration of interventions
- **Develop specific alignment sensors** (rad hard, with limited cables → optical fibers, low-cost, robust and less invasive as possible):
  - FSI based alignment sensors: «chained» configuration, compatible with high level of radiations
  - Structured Laser Beam: application of such a beam to alignment (1 PhD student has started in July 22)

Develop new methods of alignment, using alignment sensors, applicable in a circular collider

Summary on Survey & alignment for FCC-ee

End of 2025, we will have to provide a Feasibility Study Report on the alignment solutions for the FCC, proposing at least directions of studies for alignment solutions at an affordable cost.

Currently **no existing solutions are directly applicable** for the alignment of the FCC-ee:

- CLIC solutions were developed for a linear collider, taking too much space in the tunnel
- Alignment systems for FRAS HL-LHC are meant for a very low number of devices and are not optimized from the cost point of view
- The level of radiations in the arcs will be higher than for HL-LHC: innovative alternatives based on optical fibers must be developed **plus** alternatives to a stretched wire based on the Structured Laser Beam.

Standard alignment solutions will not be possible for a collider of the **size** of the FCC (Chinese colleagues concluded the same for the CEPC). Given the number of components, ground motion in a brand-new tunnel, we need to develop new concepts that will be at least automated (or permanent using low-cost alignment sensors)

Alignment tolerances for the assembly/fiducialisation of components are challenging but reachable; but very difficult to extrapolate to the size of the FCC (automation needed).

In order to be able to propose directions of developments in 2025, we have to launch different directions of R&D as soon as possible, to be able to propose a realistic road map after 2025.

IWAA 2022

16th International Workshop on Accelerator Alignment

31 October - 4 November 2022

CERN, Geneva, Switzerland

International Workshops on Accelerator Alignment (IWAA) are normally held every two years at particle accelerator laboratories around the world. They are devoted to large scale and high precision positioning of particle accelerators and photon science experiments, focusing on the exchange of information between geodesists, surveyors, physicists and other specialists. The fields of geodesy, geomatics, metrology, monitoring and traditional surveying will be discussed in this unique gathering.

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