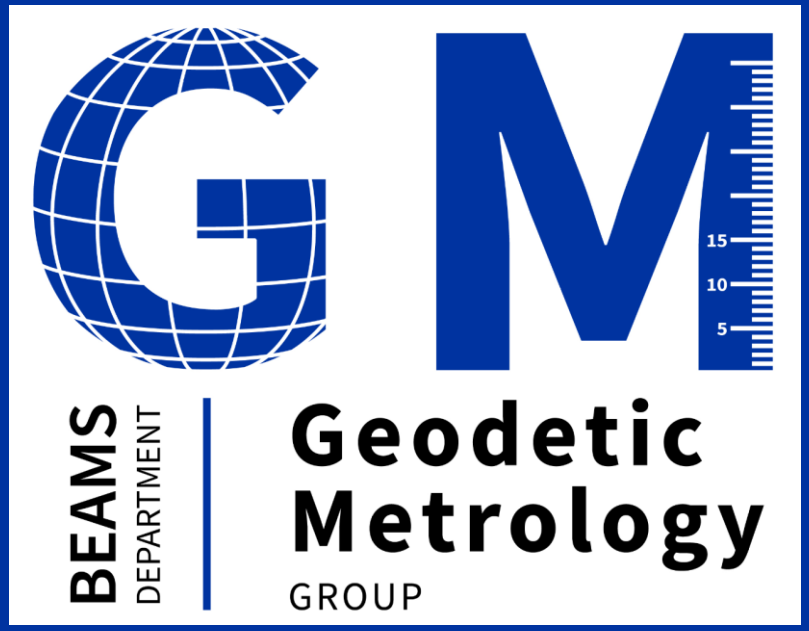


Plans for FCC alignment

H. Mainaud Durand

10 February 2022

Introduction: steps of alignment

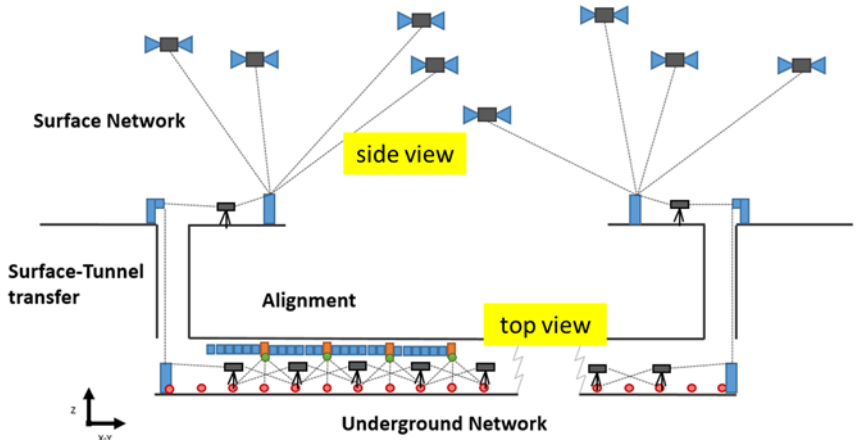
On the surface

- Definition of alignment tolerances
- Definition of alignment strategy
- Installation and determination of surface geodetic network

Inside the tunnel

- Transfer of reference in the tunnel
- Installation and determination of an underground geodetic network
  - Fiducialisation of the components
  - Definition of their theoretical trajectory
- Absolute alignment of the components
- Relative alignment of the components
- Maintenance of the alignment

Time scale

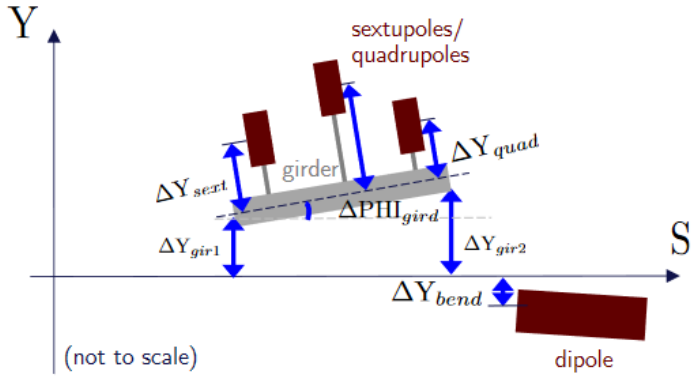


Alignment requirements for the FCC-ee

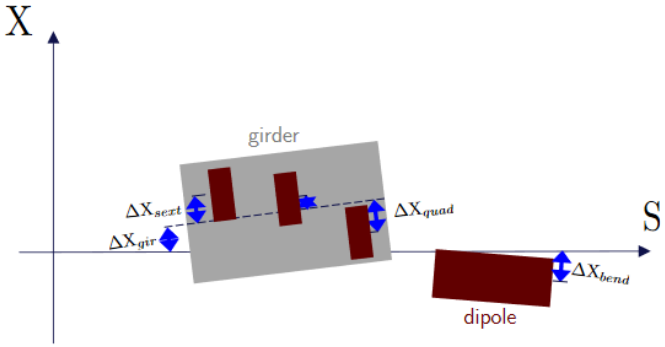
Type	ΔX (μm)	ΔY (μm)	ΔPSI (μrad)	ΔS (μm)	ΔTHETA (μrad)	ΔPHI (μrad)	Field Errors
Arc quadrupole*	50	50	300	150	100	100	$\Delta k/k = 2 \times 10^{-4}$
Arc sextupoles*	50	50	300	150	100	100	$\Delta k/k = 2 \times 10^{-4}$
Dipoles	1000	1000	300	1000	-	-	$\Delta B/B = 1 \times 10^{-4}$
Girders	150	150	-	1000	-	-	
IR quadrupole	100	100	250	50	100	100	$\Delta k/k = 2 \times 10^{-4}$
IR sextupoles	100	100	250	50	100	100	$\Delta k/k = 2 \times 10^{-4}$
BPM**	-	-	100	-	-	-	-

* misalignment relative to girder placement
** misalignment relative to quadrupole placement

Misalignments are randomly distributed via Gaussian distribution, truncated at 2.5 sigma.



From Tessa Charles (FCCIS WP2 workshop 2021 (29/11/21)



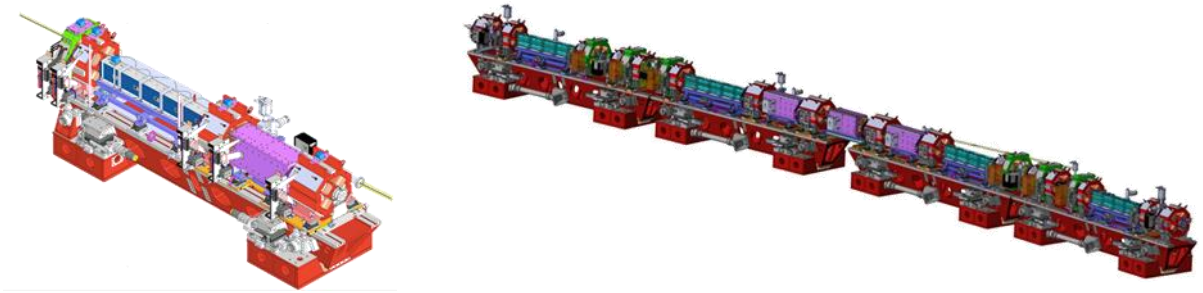
State of the art

In the LHC:

Would require too many Survey teams in parallel. Has to be automated.

- Smoothing of the fiducials: deviation w.r.t. a smooth curve of 0.15 mm at 1σ in a 150 m long sliding window
- Frequency of realignment depending on the stability of the tunnel: S78 remeasured every year; some LSS as well; for the other sectors: realignment every Long Shutdown

In Synchrotrons: example of EBS at ESRF



From David Martin, Virtual Mini-workshop on girders and alignment – ESRF EBS alignment 10-11 May 2021

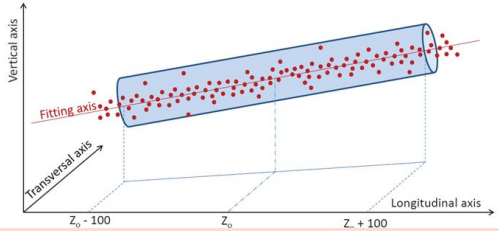
	Ux [µm]	Uy [µm]	Uz [µm]
Fiducialisation		19	34
Girder Rectitude		8	8
Magnet Opening/Closing	8	5	7
Alignment on girder	126	30	31
Transport	*20*	*20*	*20*
Alignment in tunnel	435	53	30
Total	**435**	**67**	**59**

Final magnet alignment uncertainties for the EBS machine (estimation)

Methods developed adapted to Synchrotrons, for only 131 girders, stable temperature, limited transport.

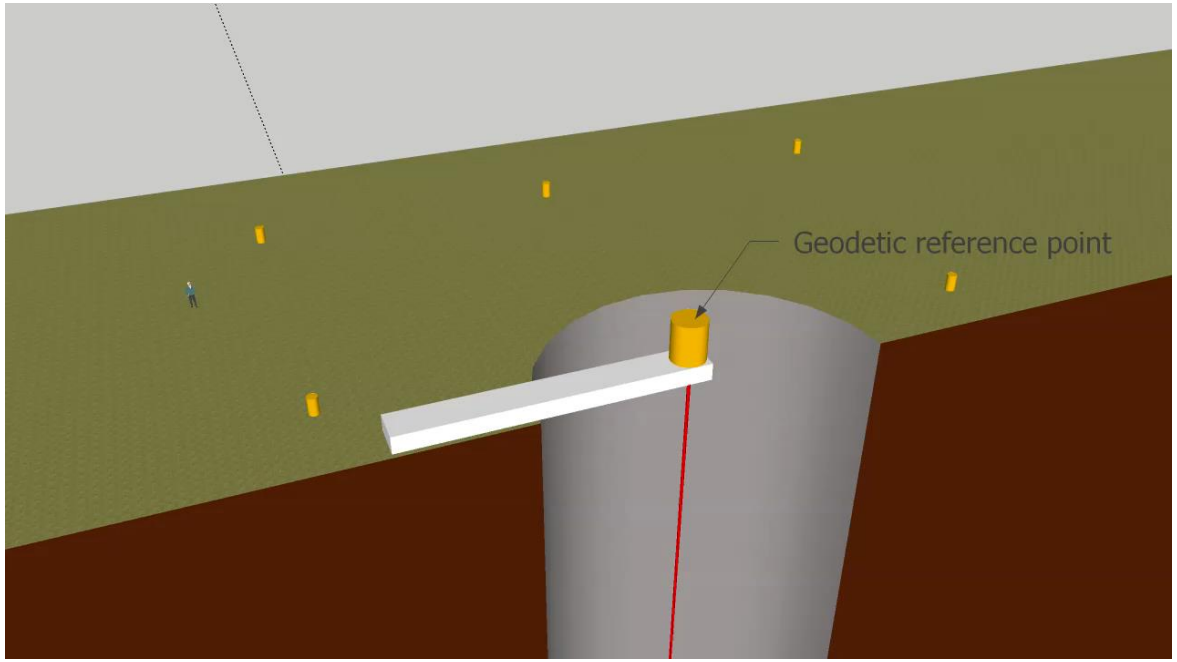
State of the art

Component type	AS	BPM	MB Quad	DB quad
Radius (µm)	14	14	17	20



CLIC active pre-alignment (PACMAN strategy)

Developed for linear colliders, integration impossible in the FCC-ee. Only demonstrated at 20°C.



Feasibility demonstrated at 20°C, in radial, for a linear collider. R&D stopped since 2017.

State of the art

Too expansive solution if extrapolated as it is to FCC-ee.
Only applicable along straight lines

FRAS = Full Remote Alignment System for HL-LHC

Alignment strategy:

- Remote alignment system installed along 200 m on each side of the experiment
- Continuous position determination systems
- Additional measurement systems will be put in place: longitudinal measurements, **permanent measurements** inside the cryostats

Challenges:

- Operation and maintenance in highly radioactive areas
- Manufacturing, calibration and exploitation of more than **700 sensors** in total
- Remote alignment of components in a range of ±2 mm with micrometric precision
- Determination of the relative position of the cryostats within a few µm
- Determination of the absolute position of the cryostats within ± 150 µm

Challenges

For the assembly/fiducialisation process:

- Quite standard tolerances for Synchrotron's components, but the number of components is not at all the same, as the transport conditions and the stability of the environment
- Trade-off to make between the rigidity of the girder, the adjustment systems, the cost, the time needed for the assembly and measurements
- Dedicated method to be developed for the FCC-ee components: high-accuracy automated process

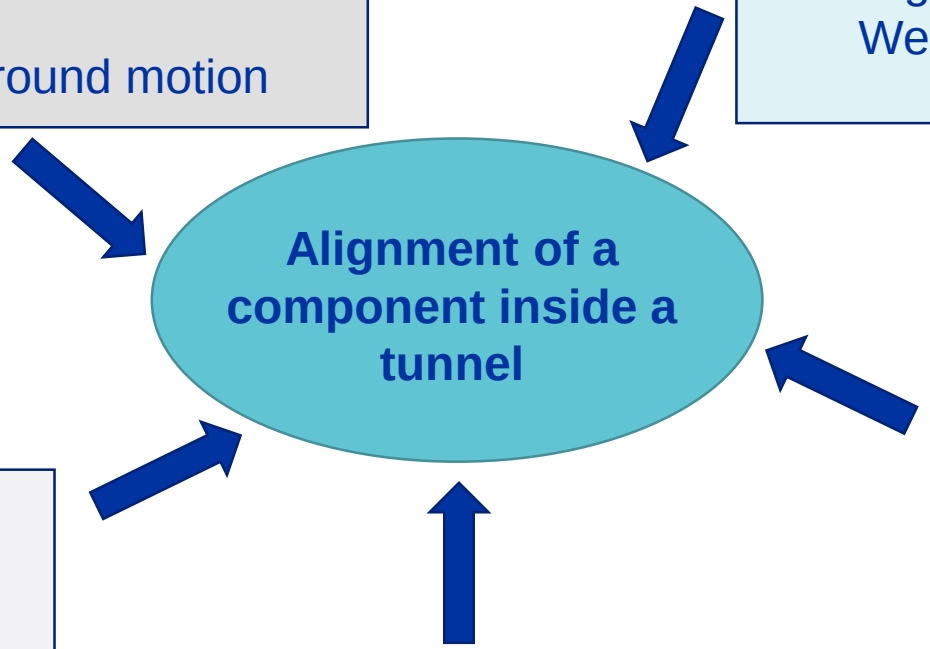
For the relative alignment:

- The alignment tolerances requested for the FCC-ee are quite similar than those of the LHC, but there will be a far higher number of components to align, in a brand-new tunnel that might not be stable; the temperature variations (as this will be a warm machine) might have a great impact on the alignment.
- Standard methods of alignment will not be used: 2 other solutions must be studied to determine in an automatized way the position of the components:
- The use of measurements trains
- The development and implementation of low-cost alignment sensors

Definition of an 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



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**

Towards solutions for the FCC-ee alignment

- We will have to perform at a given time a trade-off between the alignment solutions we can propose, their cost and their benefit on the optics.
- Currently no available solution
- We have to develop affordable and sustainable solutions for both the initial alignment of components and the alignment of their girder support in the tunnel
- Strategy proposed to develop solutions for the initial alignment of components on girder:
  - State of the art of the solutions developed in the Synchrotrons
  - Definition of the requirements for the FCC-ee (eigen modes, static rigidity, temperature gradients, etc.)
  - Study of different concepts (flexible vs rigid girders)
  - Proposal of an R&D plan after 2025

Towards solutions for the FCC-ee alignment

Strategy proposed to develop solutions for the relative alignment of girders in the tunnel:

- Study of different solutions:
  - Automated solutions based photogrammetric measurements combined with permanent reference systems and underground networks
  - Solutions of low-cost alignment sensors (based on the Frequency Scanning Interferometry in a “chained” format) for a permanent monitoring of the position of the girder, applied to a circular collider (with a wire used as a broken line)
  - Solutions based on the Structured Laser Beam (SLB)
- In all cases, development of instrumentation, methods, first qualification on prototypes, to have a better idea of the potential, R&D path needed and cost
- Solutions for the MDI area already under study by Léonard Watrelot in the frame of his PhD

Work plan 2022-2026 for survey & alignment studies

Deliverables

- Targeted R&D to develop the needed key technologies:
  - Development of an affordable (and sustainable) solution to perform the remote alignment of components in a circular collider: study of an alternative based on the Structure Laser Beam (SLB), study of a solution based on a broken line using a stretched wire, dedicated adjustment solutions [2025]
  - Development of a train-based solution to determine the position of components in an automated way [2025]
  - Development of an affordable solution for the short-range alignment of components on girders [2025]
- Identification of resources from outside CERN's budget [2025]
- Preparation of a consolidated cost estimate, with concepts for alignment and an optimization of space. [2025]
- FCC key deliverable: a FCC-ee complete arc half-cell mock-up including alignment systems

Resources: Current situation

- Scenario 1: no additional staff resources
  - No participation to the FCC studies
  - Non optimization of an alignment solution
  - Very limited study of the cost estimate
  - No participation to the FCC-ee complete arc half-cell: preparation, implementation and alignment.
  - Resources: no manpower, no material budget
- Scenario 2: with 1 additional Survey engineer for 5 years (staff)
  - Limited participation to the FCC studies: integration studies and R&D studies, via the supervision of fellows
  - Limited optimization of an alignment solution, via the supervision of fellows
  - Cost estimate
  - No participation to the FCC-ee complete arc half-cell: preparation, implementation and alignment.
- Scenario 3: possibility to hire additional staffs for R&D studies:
  - Study of all deliverables, including the FCC-ee mock-up

Summary

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.

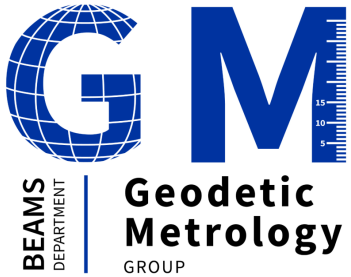
Currently no existing are directly applicable for the alignment of the FCC-ee:

- 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 in 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). We need to develop new concepts that will be at least automated (or permanent)

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

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.



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