Survey and alignment from LEP and LHC, expectation from FCC

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Summary

Before starting

LEP:

- A few data
- Survey & alignment methods
- Lessons learnt

LHC:

- A few data
- Survey & alignment methods
- Lessons learnt

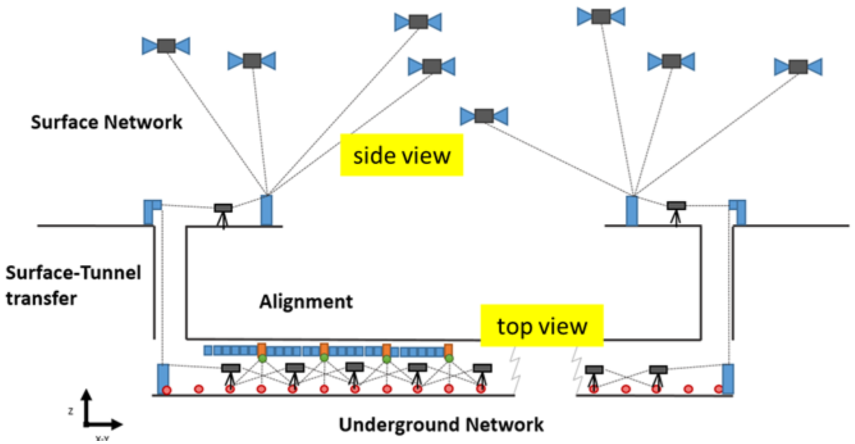
CLIC:

A few conclusions after 20 years of R&D

Expectation for FCC

Dynamic aspects (covered by Laurent Brunetti)

Before starting…



Geodetic aspects will not be addressed in this presentation, by lack of time

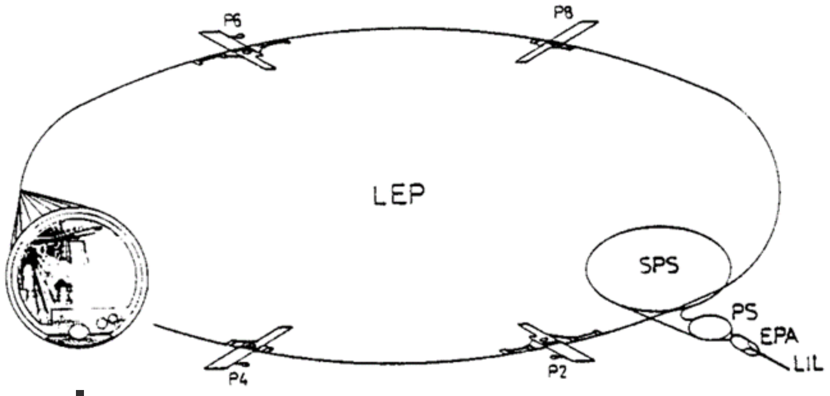
Dynamic alignment "defined as an active and remote position control of accelerator components". In order to be called dynamic, the position control should be possible **(1) at high frequencies,** certainly on time scales below a few hours but most typically below minutes; **(2) during the beam operation**, i.e. without human intervention in the vicinity of the accelerator **[*Redaelli*].**

Static and dynamic alignment refer to **relative alignment** between several consecutive components.

Absolute alignment *[Mayoud]:*

- In the vertical direction: deviation from the theoretical plane of the collider;
- In the transverse plane: variation of its radius w.r.t. the theoretical value.

LEP: a few data (1)



The chain of CERN accelerators

Circumference = **27 km**, including: **750 quadrupoles** and **3300 dipoles**

First beam in 1989

Requirements:

- **Relative accuracy of 0.1 mm all along the machine**, at the level of the fiducials (not integrating the fiducialisation measurements)
- Radial measurements: said less critical (because of large aperture)
- **Best possible absolute accuracy** w.r.t. the theoretical geometry

Yearly measurements in the 8 LSS (in vertical) and the part under the Jura mountain. ***[Mayoud]***


Focus and bend A quadrupole stands next to one of the long dipole magnets that curved electrons and positrons around LEP's 27 km-long ring. Credit: CERN

LEP: methods & instrumentation

Measurements according to a **2D+1 strategy**:

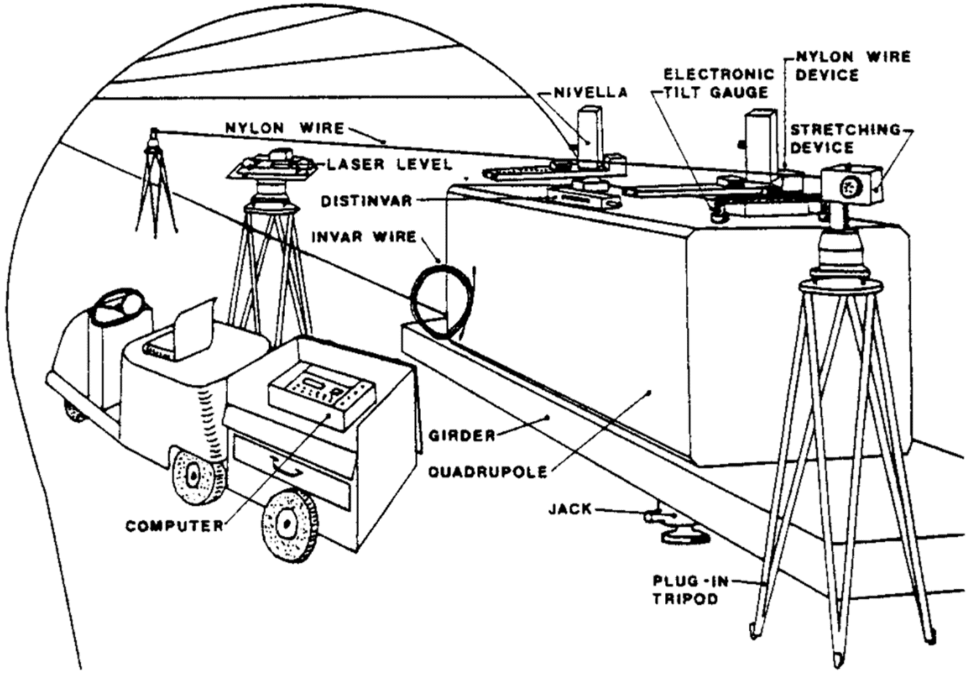
- Roll measurements & correction
- Vertical measurements
- Radial measurements

Levelling:

- performed using fully high precision level
- 1600 points measured twice at each complete loop
- 4 weeks – 2 teams.

Radial:

- Wire offset measurements (Kevlar wire) over 120 m.



Quadrupole alignment arrangement

[Hublin2]

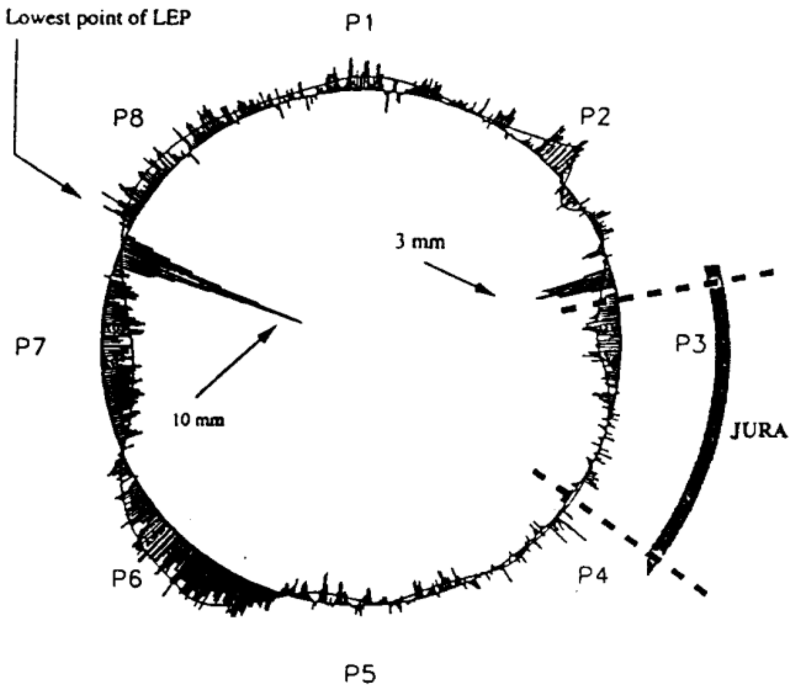
LEP: Survey & alignment

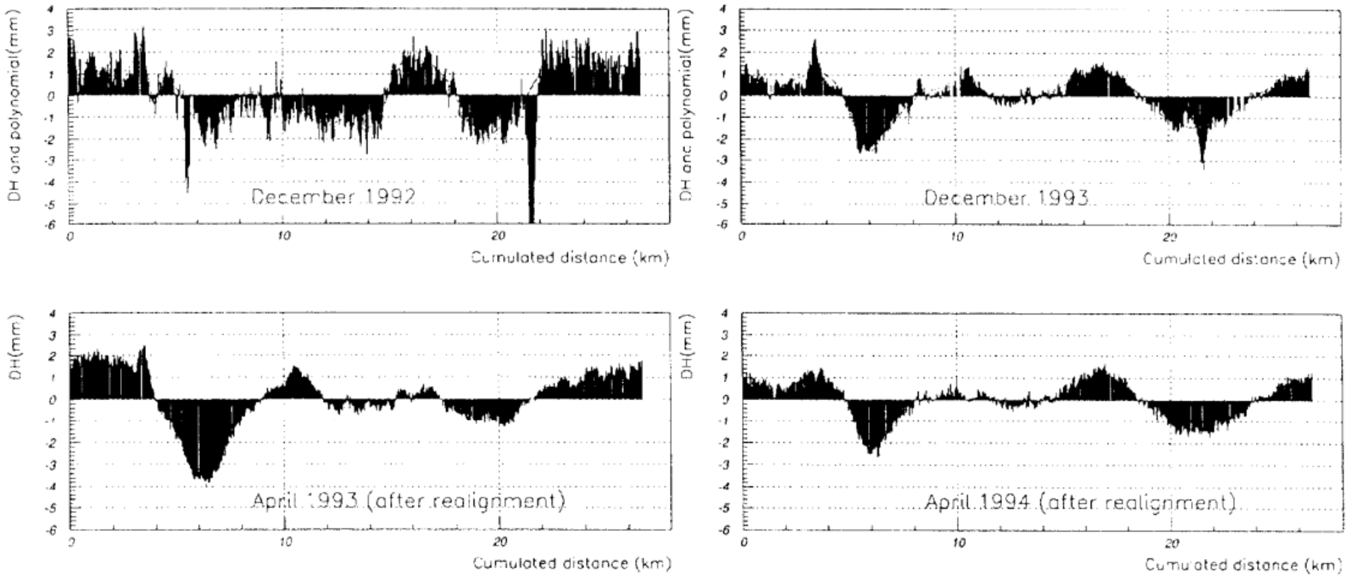
1989-1992	Yearly vertical measurements of the 8 LSS + part under the Jura mountain	
1992		Large subsidence observed: 10 mm in an arc
April 1993	Whole ring measured in vertical	Displacement of 450 quadrupoles Control of rolls on quadrupoles & dipoles
Nov. 1993	Remeasure of the whole ring in vertical	
April 1994		120 quadrupoles re-aligned
End 1994	New measurement campaign	70 quadrupoles re-aligned
	Radial measurements «much more complicated to collect, process and analyzed»	Dispersion over a triplet or quadruplet tends to 0.5 mm and 0.7 mm r.m.s (instead of 0.1 mm)

Monitoring of the low beta quadrupoles using HLS sensors

[Hublin]

LEP: Survey & alignment





Vertical position of the LEP quadrupoles at the end of 92 measured with respect to the best reference plane

Vertical alignment of LEP quadrupoles

[Hublin]

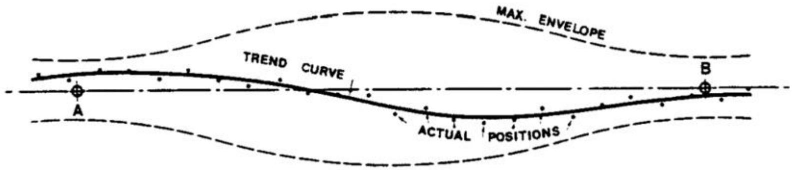
LEP: lessons learnt

- Deformations result from the geo-mechanical forces and strains which apply to the concrete structure of the tunnel: decompression effects, thermal constraints, hydro-static changes, micro-tectonic moves, cracks and moves of the floor.

- No sign of random movements of the ATL-type of the LEP tunnel floors were found in yearly vertical surveys over 10 years. It is possible that below the concrete floor the mountain does “space time ground diffusion” but these movements have not been able to penetrate through the concrete floor in any observable way. **Measurements on tunnel floor ≠ on the component.**

- Trajectory of a beam is mainly sensitive to short range errors → smoothing

- Development of a realignment strategy: measurements fitted with a smooth curve consisting of overlapping polynomials.
  - “Ad-hoc” analysis tools of movement and deformation patterns
  - Analysis through a sliding window for locating singularities
  - Correction of the alignment = displacements when out of the acceptance corridor”



Position of magnets with respect to theoretical orbit

[Pitthan] [Mayoud2]

LEP: lessons learnt

- Survey group must be involved ASAP: be part of the tolerances & accuracy definition; in the design of the supporting system; to develop the required methods and instrumentation.

- Special elements (accelerating cavities, electrostatic separators, collimators and some elements of the straight sections) were aligned w.r.t. to the main quadrupoles. This alignment required a lot of additional resources (8 persons).

- «Thirteen years passed between the installation of the SPS Synchrotron and the LEP collider on the same site. LEP has a length 4 times that of the SPS, with the same required precisions in the alignment of the elements. This meant that there was an increase in the man-working hours, but we were able to profit from the **automatization of the instrumentation**».

[Quesnel]

LEP: lessons learnt

Inner triplets: “0.08 mm r.m.s. were requested but the working conditions did not allow to reach this accuracy”.

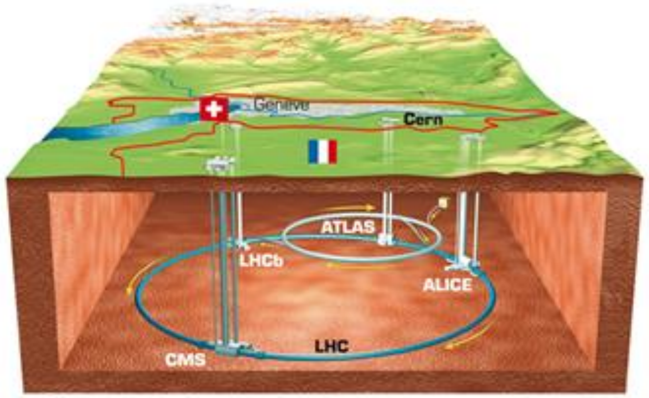
The alignment of the inner triplets was based on the experience gained from the previous machines at CERN: the ISR, the SPS and the LEP. In particular in the LEP, the repeated surveys of the underground reference networks, in a recent and consequently not yet stable tunnel, with no link to the experiments, made difficult to have a good geometrical relationship.

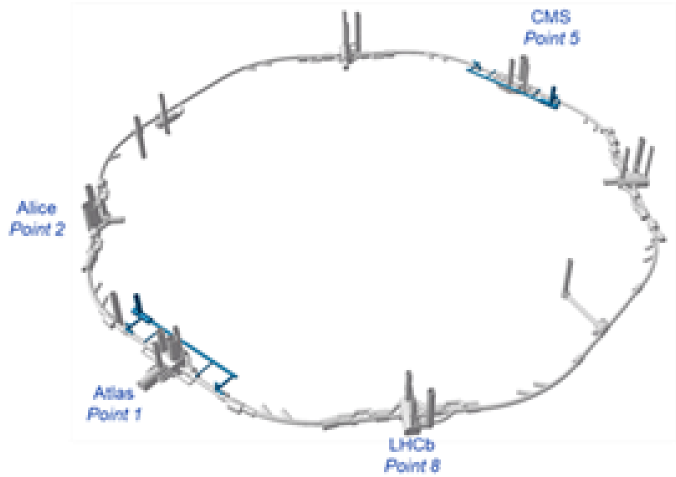
From LEP to LHC:

“The survey data of LEP ring show in a clear manner that the ground of the tunnel is slowly moving with time. This phenomenon will be eventually enhanced by the on-going construction of 2 experimental caverns for ATLAS and CMS and for 2 tunnels for the injection lines from the SPS to the LHC” → Permanent monitoring of the tunnel floor put in place in specific area during CE works.

[Quesnel]

LHC: a few data





The LHC in figures:

- Total length: 26 650 m
- 8 LSSs (Long Straight Section) ➔ ~530 m
  - Main magnets and secondary components:
- 8 ARCs (curved sections) ➔ ~2 800 m
  - 154 dipoles
  - 53 quadrupoles

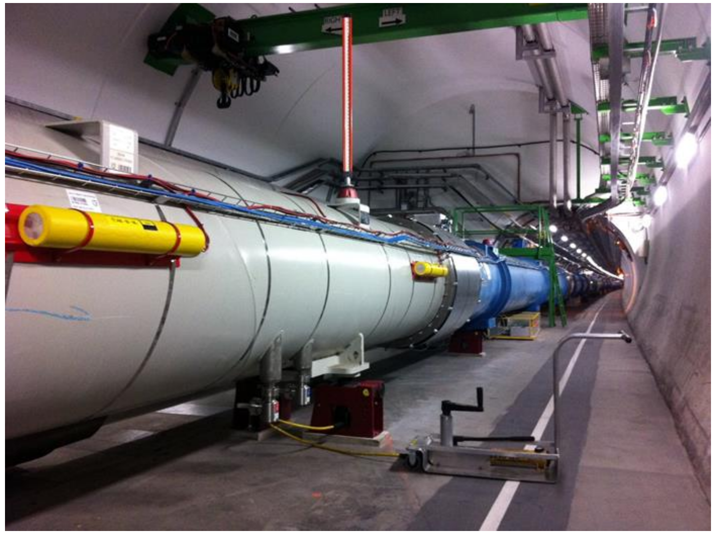
Alignment tolerances:

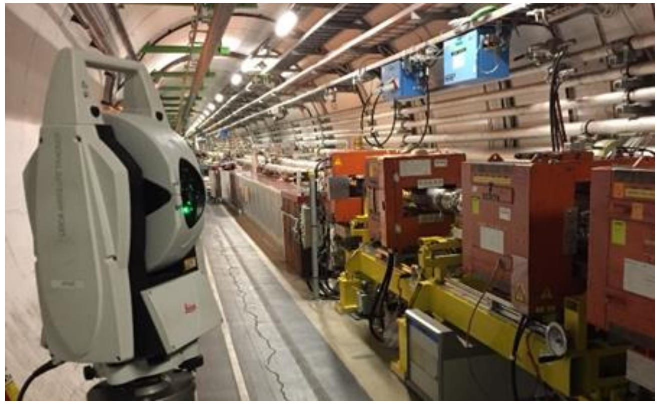
- All components pre-aligned w.r.t. geodetic network to achieve a relative accuracy of 0.2 mm at 1σ, at the level of the fiducials (not integrating the fiducialisation)
- Smoothing: deviation w.r.t a smooth line: 0.20 mm at 1σ in a 150 m long sliding window (main components)

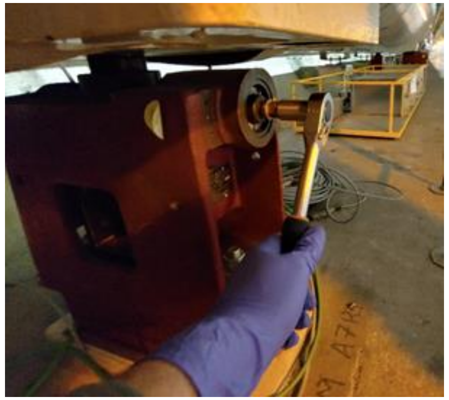
LHC: methods

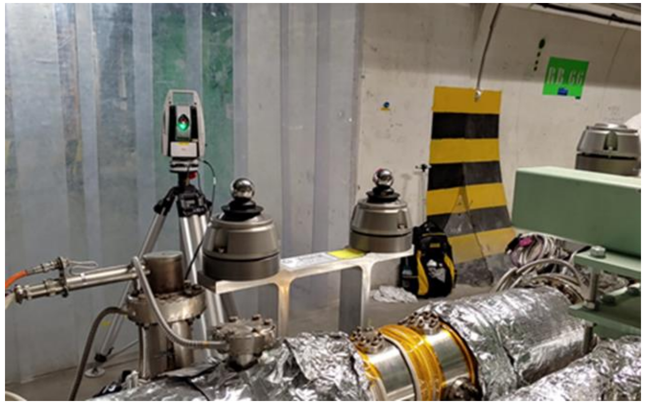
- 2D + 1 measurements for main components
- 3D measurements for some secondary components

- Measurements
- Analysis
- Displacements



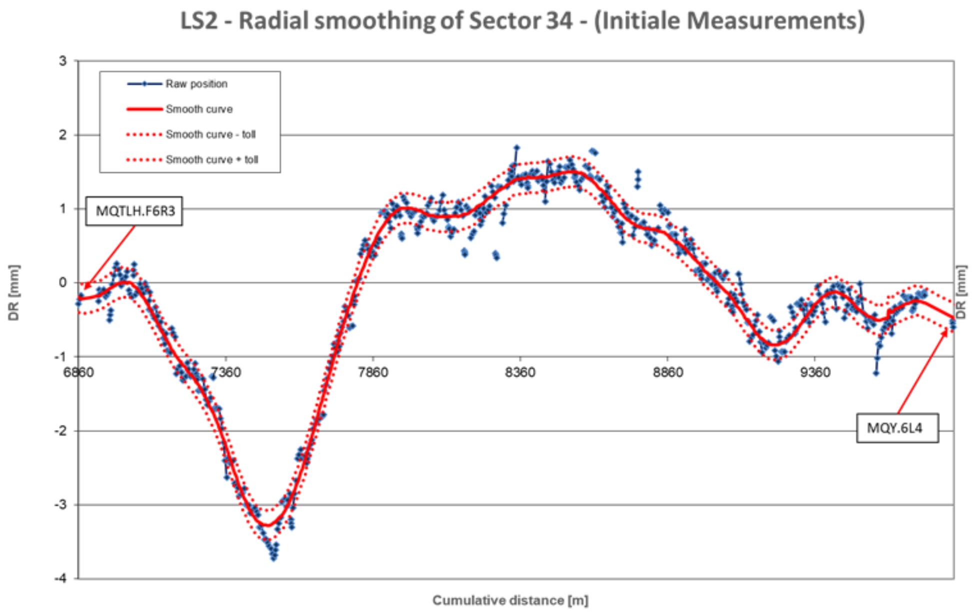




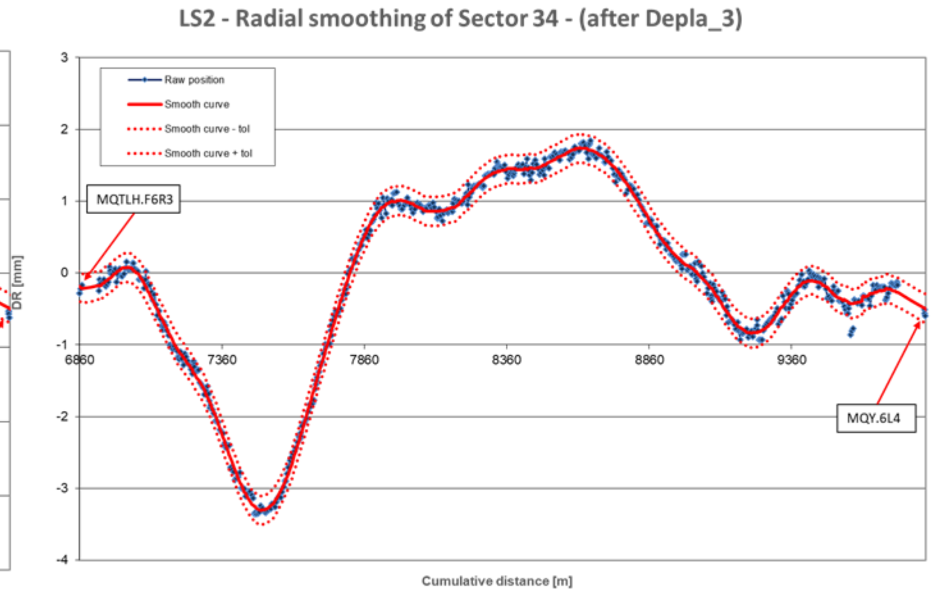


LHC: methods and rate

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*]:

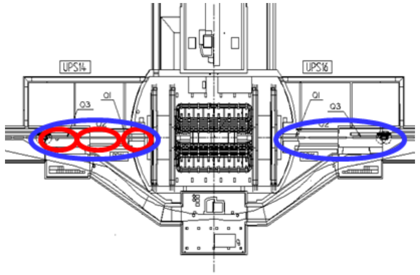
- Tilt measurement and correction: 15 weeks.
- Vertical and radial smoothing: 338 weeks.

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

LHC: lessons learnt

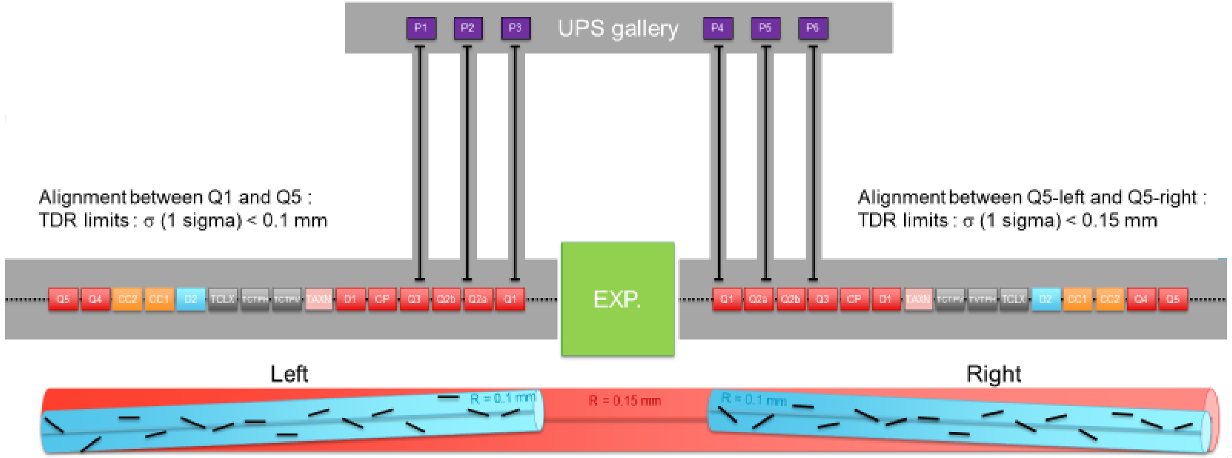
- **Contract management during YETS and LS: up to 13 additional persons:**
  - Very difficult to find trained surveyors
  - Very difficult to keep the motivation of the persons on such repetitive tasks.
  - All particular cases and «exotic» components managed by CERN staff
- **A rigorous approach** was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

LHC: lessons learnt



- MDI area: all low beta triplets equipped with HLS and WPS sensors
- Machine reference available in the 4 experimental area
- Triplets consolidated during LS2 to get “pseudo-absolute” position of triplets:
  - Position determination of the left triplet w.r.t. right triplet within 50 µm in vertical and within 100 µm in radial
  - Position determination of one quadrupole inside a triplet within 70 µm
- 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

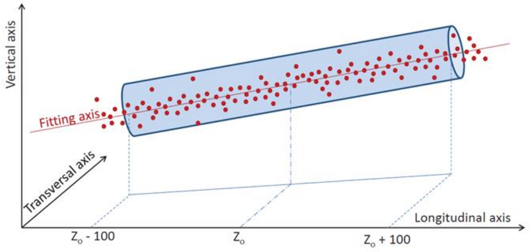
- Major upgrade program for LHC
- 1.2 km of beamline will be exchanged
- Provide same alignment precision as for LHC over longer distances

Thanks to the implementation of FRAS, we could make some savings at the level of the HL-LHC (optimization of correctors and cryo-capacity) of more than 5 MCHF.

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

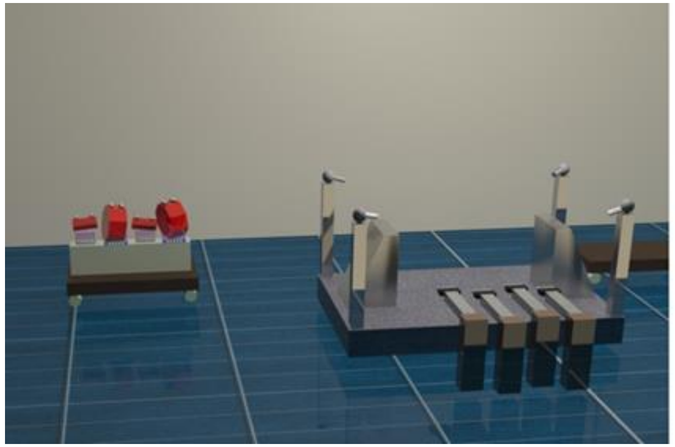


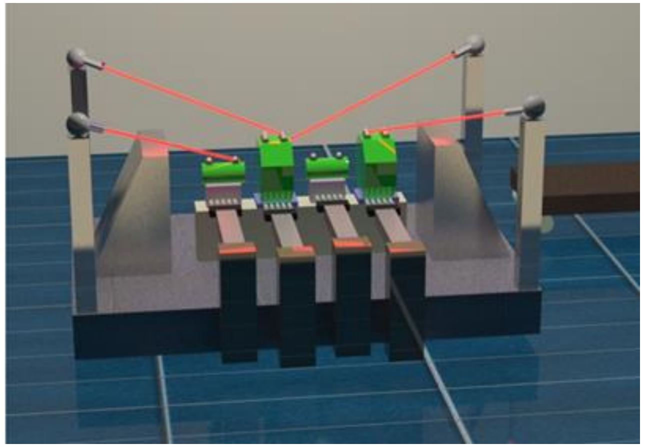
Along Main Linac: over sliding windows of 200 m:

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
- Redundancy of measurements is crucial
- No solutions found at the level of the MDI area
- Feasibility of the proposed solution (alignment sensors + actuators) **validated only at 20°C**
- **Temperature impact is crucial** and very complicated to model at a micrometric accuracy

Expectations for FCC-ee

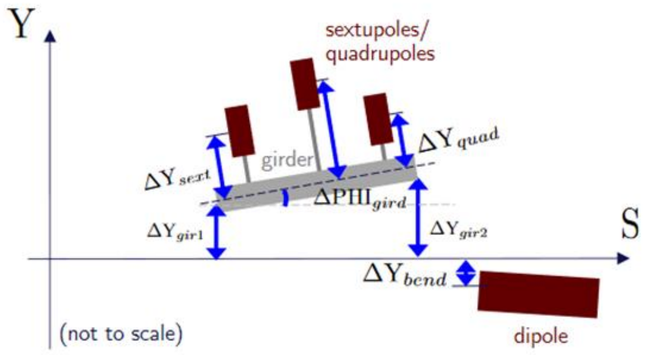
Requirements:

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	-	-	-	-

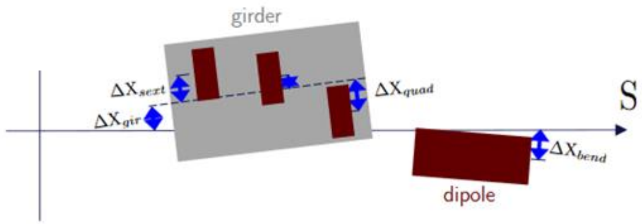
* misalignment relative to girder placement
** misalignment relative to quadrupole placement

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

At the level of the reference axis (including fiducialisation)



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



Expectations for FCC

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:

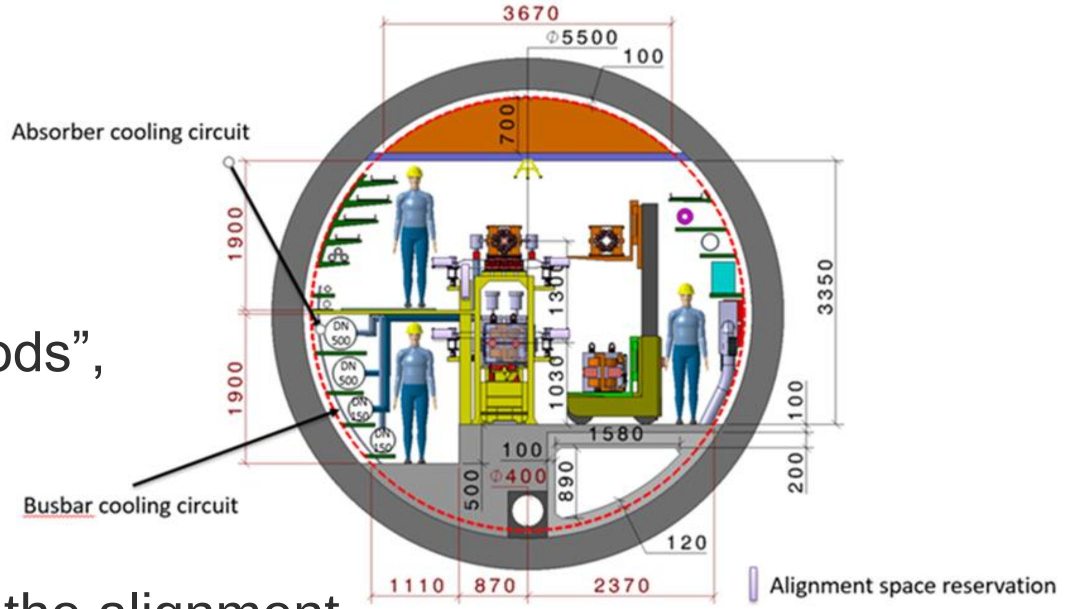
Studies shall start ASAP → 1 doctorate student: Leonard Watrelot investigation solutions since 2020

Expectations for FCC

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.)

Expectations for FCC



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 might 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 will start in July 22)

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

Summary on Survey & alignment for FCC (static part)

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 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). 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.

A few comments from yesterday session

H. Mainaud, 10 Feb:
"The actual value of tolerances will not be the cost driver."

From Rogelio's presentation: thanks for the citation but a bit shortened!

"…being the size of the machine the main one":

Given the size of the FCC-ee, we will not be able to perform standard alignment and to use standard techniques in such a machine: we will need alignment sensors at least for the girders of the arcs quadrupoles and sextupoles. So applying a factor 2 on tolerances should not increase the cost by two. This is of course different for dipoles for which a rather static alignment is foreseen.

		From steerers/orbit data
rms DX DY alignment	Expected magnet-to-magnet 60-70 μm	Achieved magnet-to-magnet 25-55 μm

Be careful when you compare magnet to magnet alignment (from Simone's presentation) w.r.t. magnet alignment over 100m - 150 m (tolerances for the girders given by Tessa). This is not at all the same length, you can't compare!!

You can not extrapolate a smoothing performed 5 times a year (4 teams, 8h) at ESRF (To be confirmed by David Martin) and what will have to be done for the FCC-ee, in a brand new tunnel, with temperature gradients.

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.

References

[Mayoud] M. Mayoud, Geodetic metrology of particle accelerators and physics equipement, IWAA 1999, Annecy, 1999

[Redaelli] S. Redaelli, Dynamic alignment in particle accelerators**,** **CAS lecture**

[Hublin] M. Hublin et al., Maintenance of the geometry of LEP improvement & optimization of the vertical and radial smoothing, IWAA 95, **DOC**

[Mayoud2] Metrology and surveying at CERN: recent news and fact, IWAA 2002, spring 8, Japan, 2002

[Quesnel] A strategy for the alignment of the LHC, IWAA 2004, CERN, 2004

[Hublin2] Computer aided geodesy for LEP installation. Part I: the installation procedure, CAS, **DOC**

[Pitthan] LEP vertical tunnel movements – lessons for future colliders, SLAC-PUB-8286

And a lot of material (pictures, data) from BE-GM members.

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