Alignment options for the FCC-ee

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06 December 2022, FCCIS Workshop

Summary

A short reminder

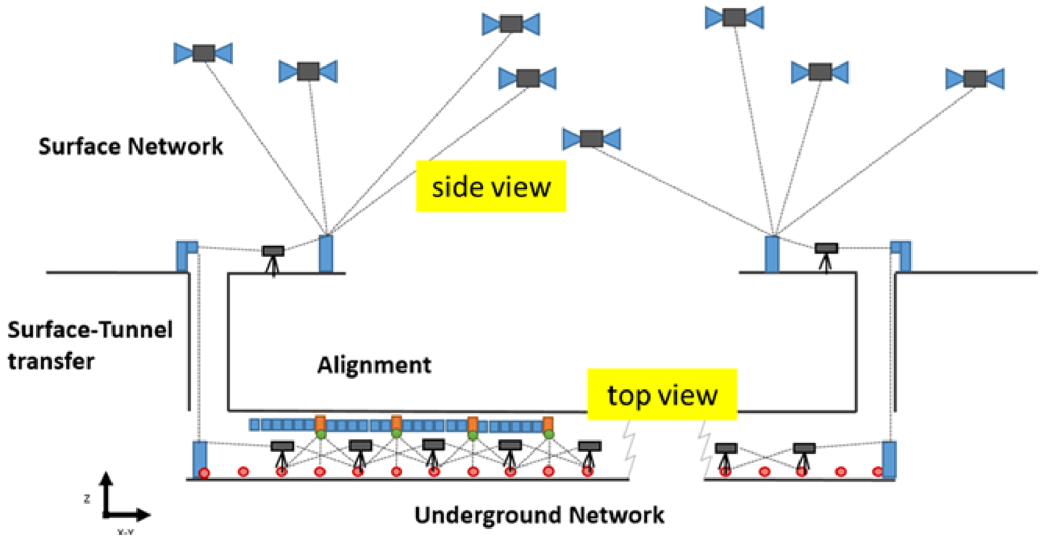
Lessons learnt – state of the art at CERN

- Case of LHC
- Case of CLIC

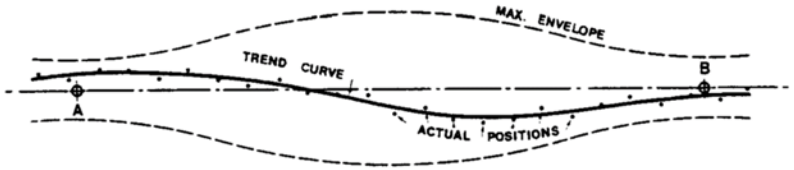
Alignment options for the FCC-ee

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

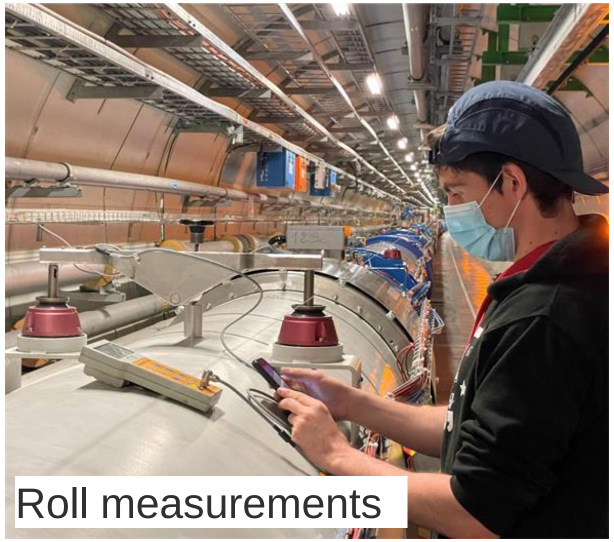
- Takes several years!!!
- Different methods and solutions needed according to the area

State of the art at CERN

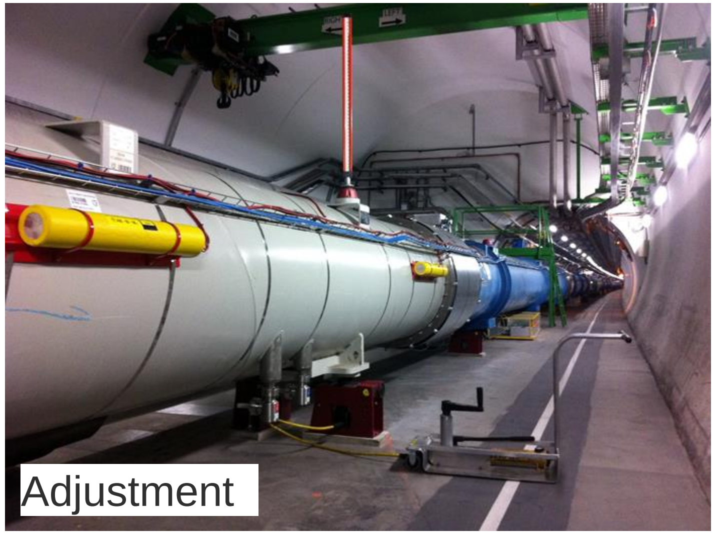
LHC: methods

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

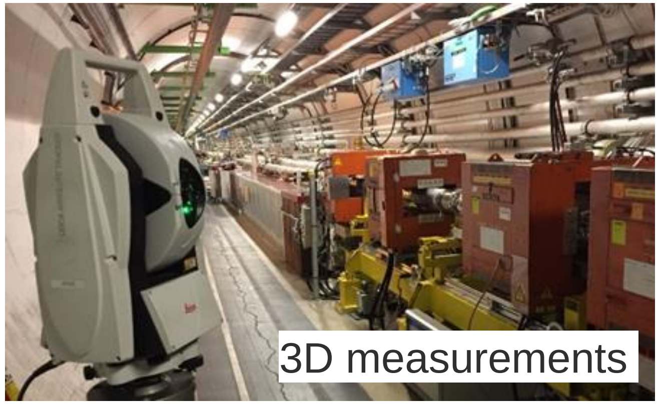
- Measurements
- Analysis
- Displacements


Roll measurements

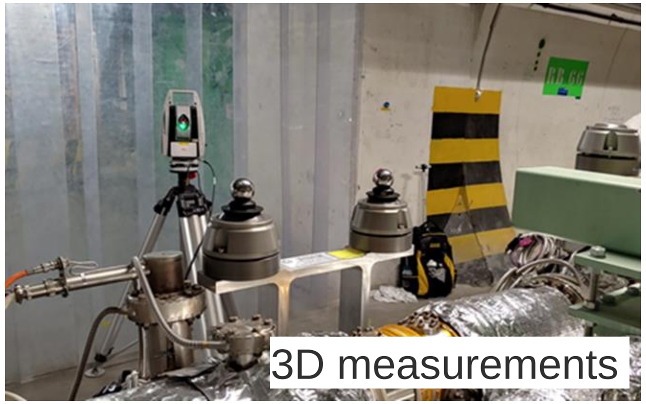

Levelling measurements


Adjustment


Wire offset measurements


3D measurements

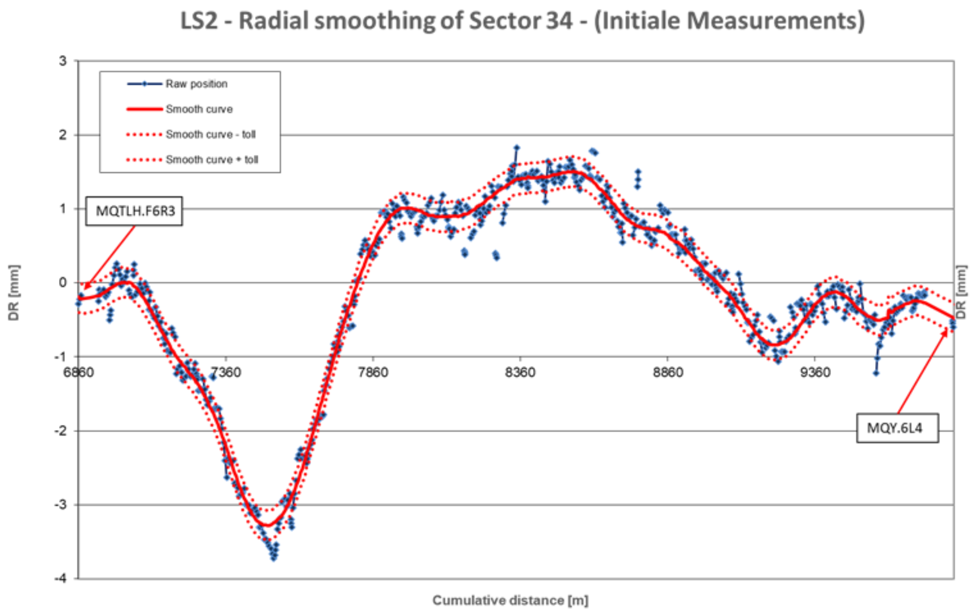

Adjustment


3D measurements

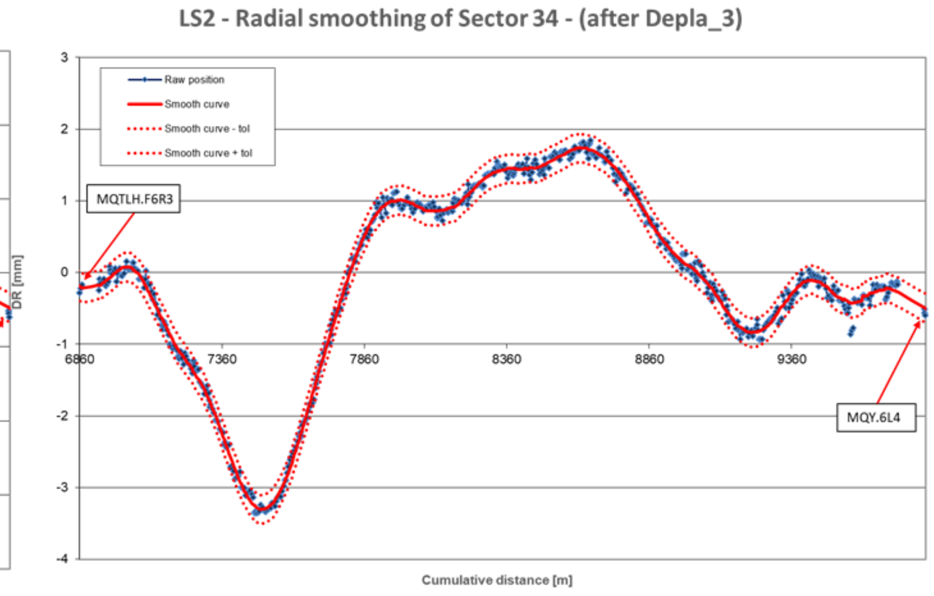
LHC: methods and rate

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 of 2 persons in 4 weeks or 25 teams in 4 months (main components only!)

Laser tracker measurements can't be applied for FCC-ee

Considering the case of ESRF (data from David Martin):

- Update of the full network
  - 5 times a year:
  - 4 teams, 8 hours, half of the machine per team, overlapping
  - ~ 130 girders over 830 m
- Extrapolation to FCC-ee:~ 250 days with minimum overlapps and an important error propagation

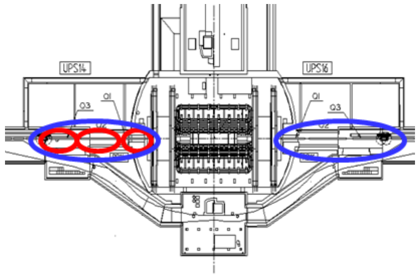
- Considering the number of components, the unknown ground motion during the first years, one option would be to automatize laser tracker measurements and perform these measurements w.r.t. a permanent metrologic network in the tunnel.

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 between the different parties concerned (magnetic measurements, etc.)

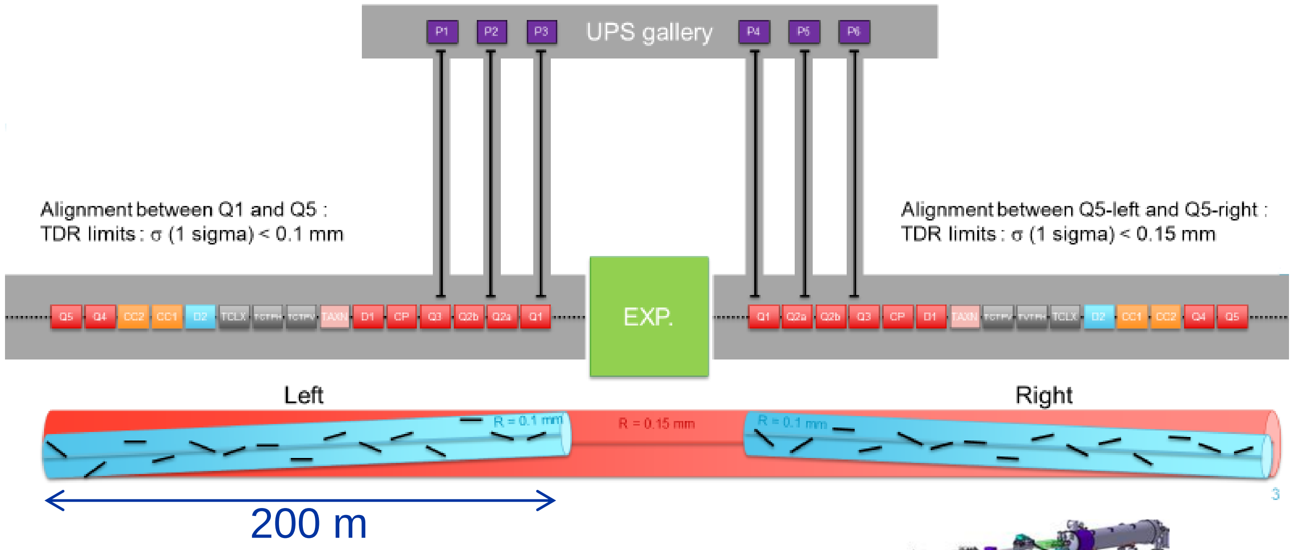
→ **glossary & tolerance definitions needed for FCC-ee (GUM approach).**

LHC: lessons learnt



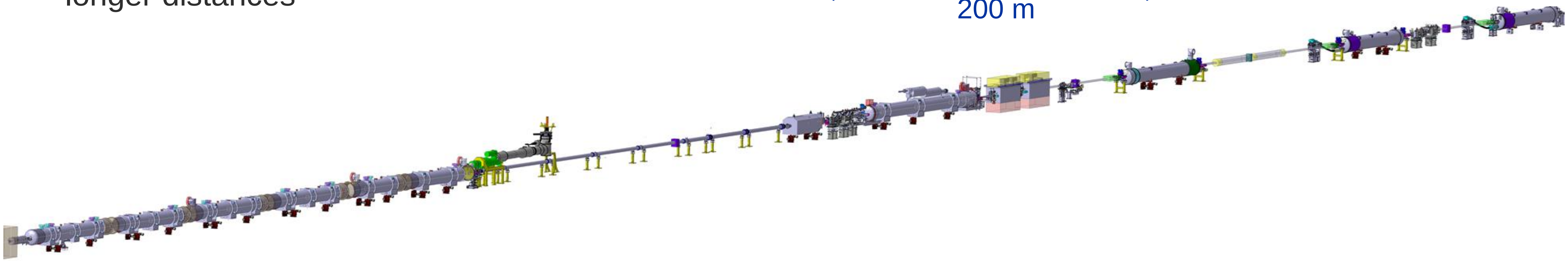
- MDI area: all **low beta triplets** equipped with alignment sensors and supported by motorized jacks.
  - Machine reference available in the 4 experimental area
  - Position determination of the left triplet w.r.t. right triplet within ± 50 µm (1σ) in vertical and within ± 100 µm (1σ) in radial
  - 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.

Use of movers // risk & safety assessment

Lessons learnt from the implementation of FRAS and discussions with other labs:

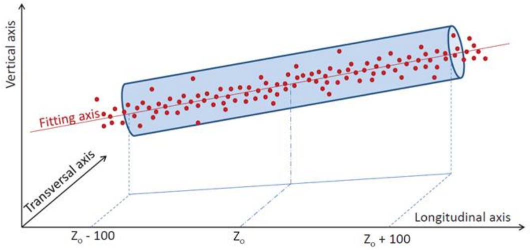
- The HL-LHC Full Remote Alignment System will have to be **operated and maintained without putting the LHC components or the persons** intervening in the tunnel at risk.

- An **identification of the main failure modes and their consequences** have been performed using the Failure Mode And Effect Analysis (FMECA), highlighting a higher risk of **damage at an interconnection below**, of the HL-LHC components.

- Control measures to reduce the risks to an acceptable level are being developed (according to Standard: IEC 61511.3), applying protection layers to mitigate the risk of bellow damage during the displacements of 2 adjacent components: use of **independent solutions** based on different technologies to determine the **3D position** of components and bellows.

- If you foresee to use movers, you will have to associate alignment sensors to follow their displacements.

CLIC: a few conclusions

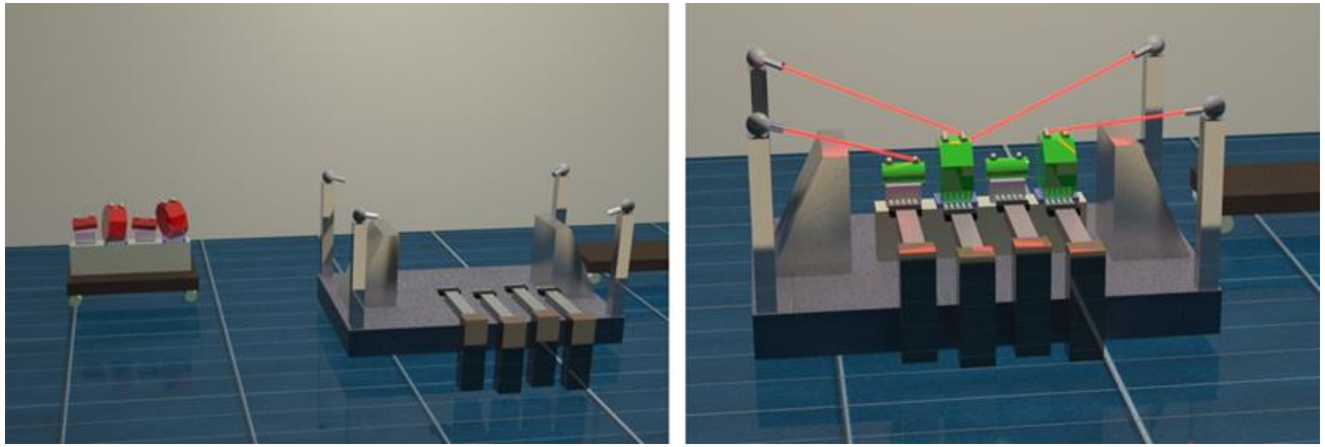


Along Main Linac: over sliding windows of 200 m:

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)

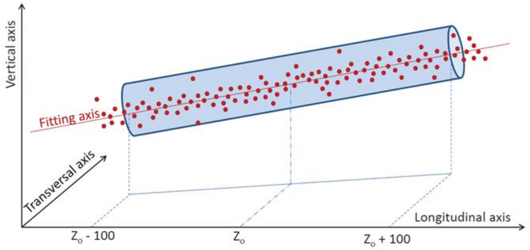
- New solution to perform a **more flexible and accurate fiducialisation** («**PACMAN**»)



- 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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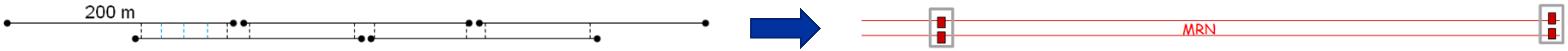
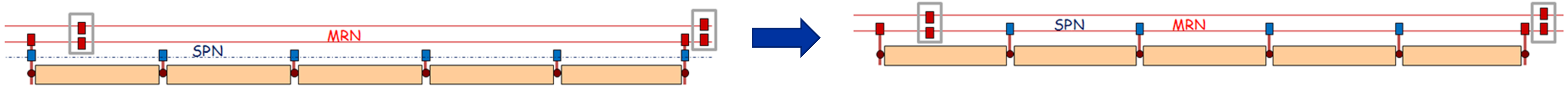
At the level of the reference axis (including fiducialisation)

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

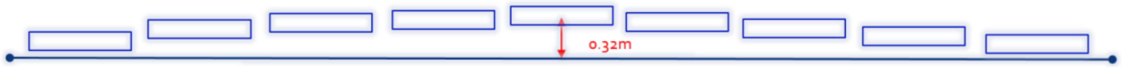
Long range alignment method (Metrological Reference Network)



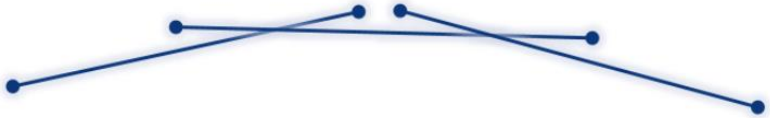
Short range alignment method (Support Pre-alignment Network)



- 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 directly 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

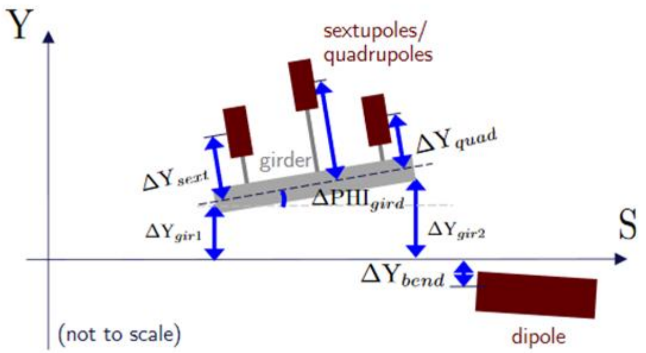
* misalignments relative to girder placement

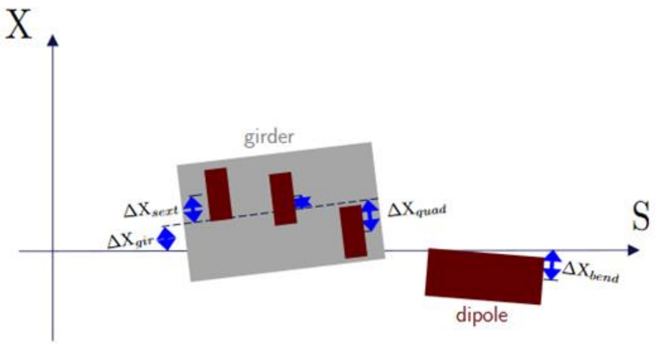
Type	Field Errors
Arc quadrupole*	$\Delta k/k = 2 \times 10^{-4}$
Arc sextupoles*	$\Delta k/k = 2 \times 10^{-4}$
Dipoles	$\Delta B/B = 1 \times 10^{-4}$
Girders	-
IR quadrupole	$\Delta k/k = 2 \times 10^{-4}$
IR sextupoles	$\Delta k/k = 2 \times 10^{-4}$

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:

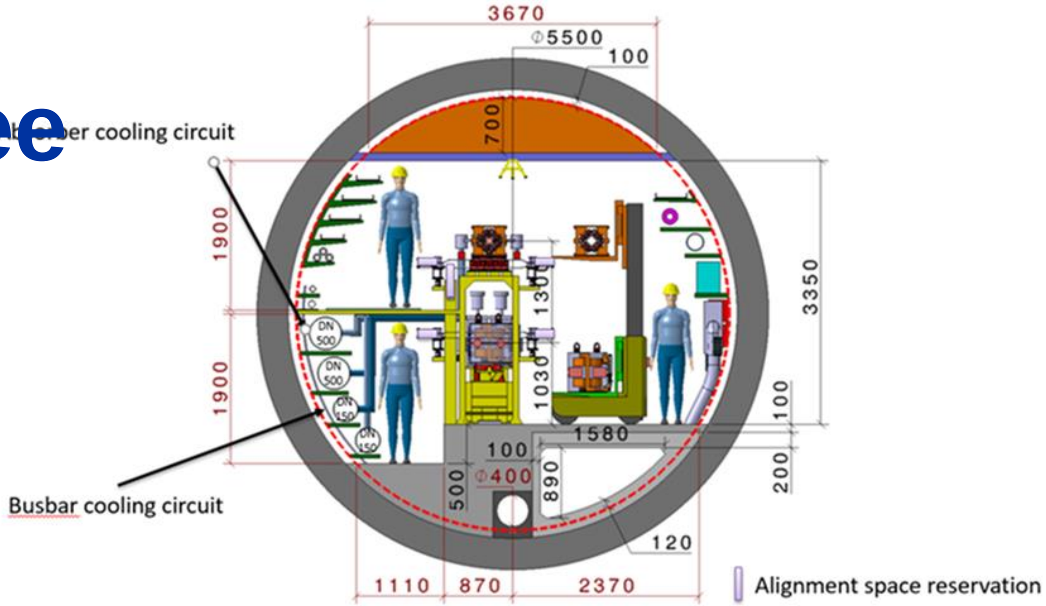
Studies have started → 1 doctorate student: Leonard Watrelot developing alignment solutions since 2020

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

Focus on alignment options (with no further study)

Option 1: Combination of automated laser tracker measurements + permanent metrological network

Concept:

- A metrological network consisting of overlapping references (stretched wire or Structured Laser Beam) will be installed along the tunnel walls/ceiling, with regular external references, to:
  - Limit the error propagation
  - Provide a permanent accurate reference of alignment, from the installation (the metrological network will be installed asap) to the maintenance periods
- Laser tracker measurements performed from a robot/train w.r.t. targets installed permanently on the components; laser tracker measurements could be replaced by absolute distance measurements (trilateration measurements)

Pros:

- Could provide a fast way for re-adjustment: measuring locally w.r.t. permanent references

Focus on alignment options (with no further study)

Option 2: permanent alignment sensors

Concept:

- A permanent reference network is installed between the booster and the main ring, consisting of overlapping references (either a stretched wire or Structured Laser Beam)
- Low-cost alignment sensors attached to the girders measuring w.r.t. these references

Pros:

- Such a configuration would allow a permanent monitoring of the girder position and as a consequence of the quadrupoles / sextupoles alignment, integrating temperature gradient, etc.
- Very low propagation of error

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.

From J. Gervaise: «Geodesy and metrology at CERN: a source of economy for the SPS programme. 17 nov. 1976, CDS Link

I. INTRODUCTION

It would seem important, when discussing the high-precision geodetic and metrological survey techniques used in the construction of large particle accelerators, to emphasize the extensive savings which can be gained by any laboratory which undertakes the construction of the second-generation giant proton synchrotrons (400 - 500 GeV).

As a first approximation, it is generally believed that accuracy is costly in terms of time, money and staff. The term "costly" is misleading and only used for budget purposes. The speed and accuracy with which the CERN Survey Group installed the quadrupole and dipole magnets in the Super Proton Synchrotron (SPS) tunnel resulted in substantial savings. Only two months elapsed between the moment when protons were first injected into the accelerator and when they reached the design energy of 400 GeV at an intensity of 3.10^{12} protons per pulse. This time would certainly have been greater if the elements in the ring had not been installed within the prescribed tolerances. Although it is impossible to place a monetary figure on the time saved by CERN, it is likely to have been considerably greater than the budget of the Survey Group.

Having drawn attention to this point, the purpose of this paper is to explain how the Survey Group achieved these results.

VIII. CONCLUSION

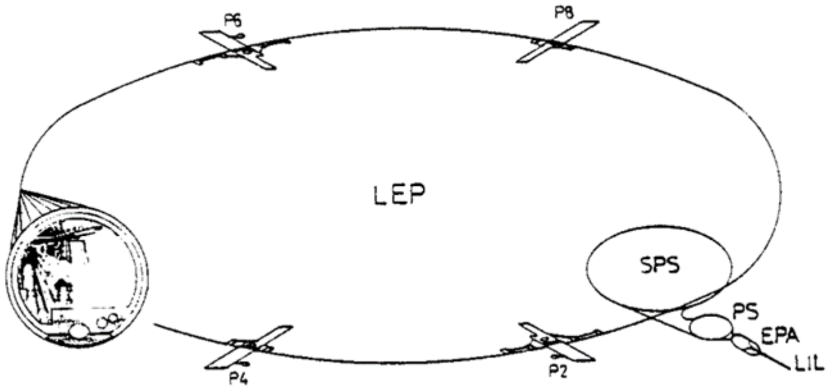
Although it was not possible here to go beyond a general description, this paper has shown how the Survey Group took up the three challenges to their technical skill during the construction of the 400 GeV proton synchrotron.

From the budget standpoint, it is very difficult to place a figure on the savings made owing to the successful outcome of the Group's activities. On looking back, it is hardly conceivable that the boring machine would not return to its starting point with acceptable tolerances. On the other hand, it is quite understandable that, because of the early start of the provisional installation work, it might have been necessary, during final installation, to remove all the magnets which were first installed in sextants 3 and 4, shift the supports and reinstall the magnets and beam control equipment, with all the consequent disturbances to the vacuum and busbar systems.

The excitement of the engineers and physicists responsible for the construction of the accelerator on learning that protons had orbited the ring for the first time clearly illustrates the relief felt when such a complex machine as an accelerator operates correctly from the very first moment. The first photographs of the closed orbit gave the Survey team concrete proof of the success of their work. Here too, if it had been necessary to align the machine by moving quadrupoles as a result of beam measurements and repeat this a number of times, this would have proved an extremely time-consuming task taking many months. Furthermore, it would no doubt have had serious repercussions on CERN's personnel budget and necessitated considerable capital investment.

home.cern

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**:

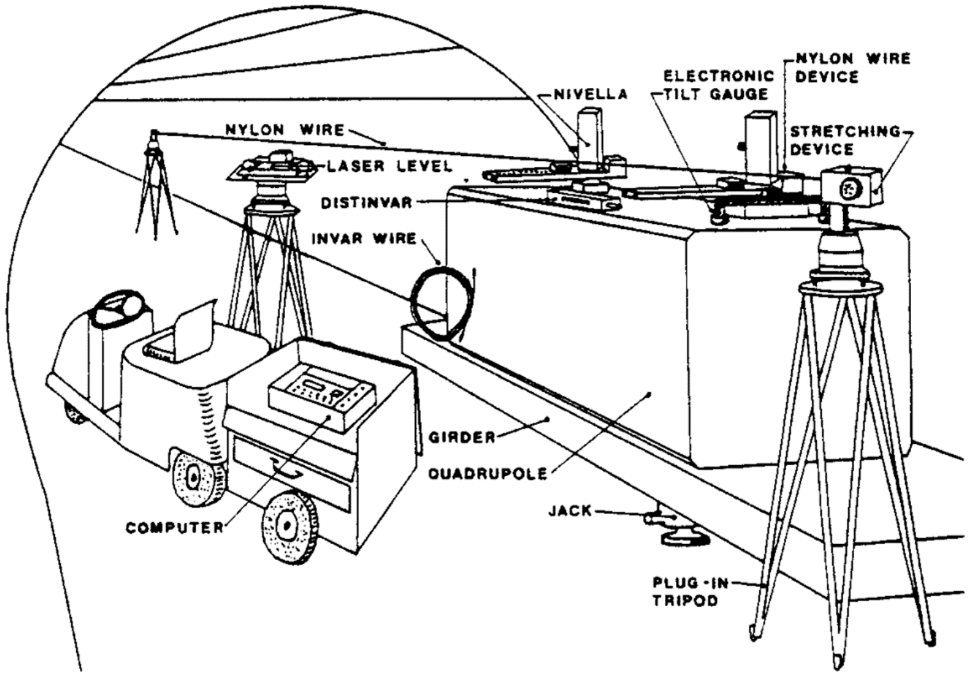
- Roll measurements & correction
- Vertical measurements
- Radial measurements

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

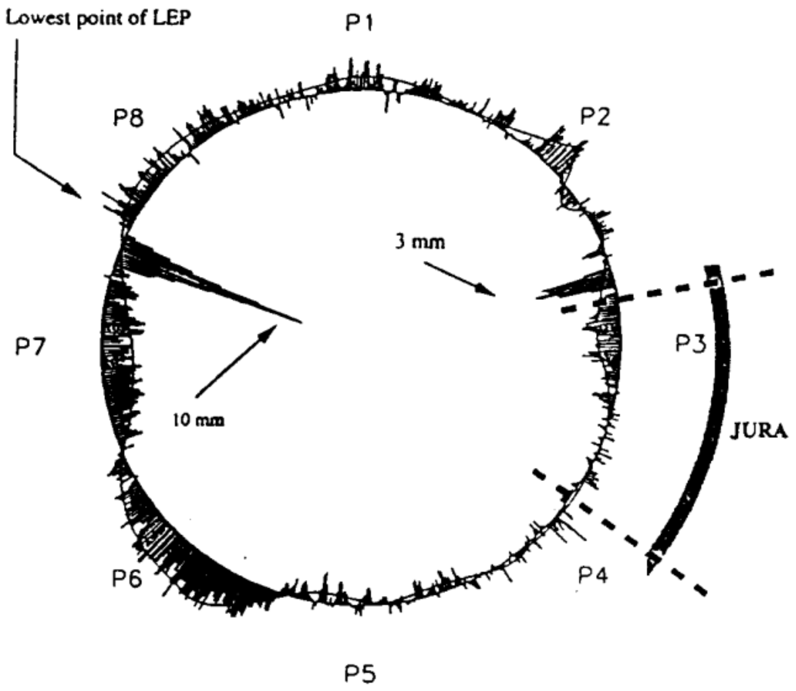
[Hublin2]

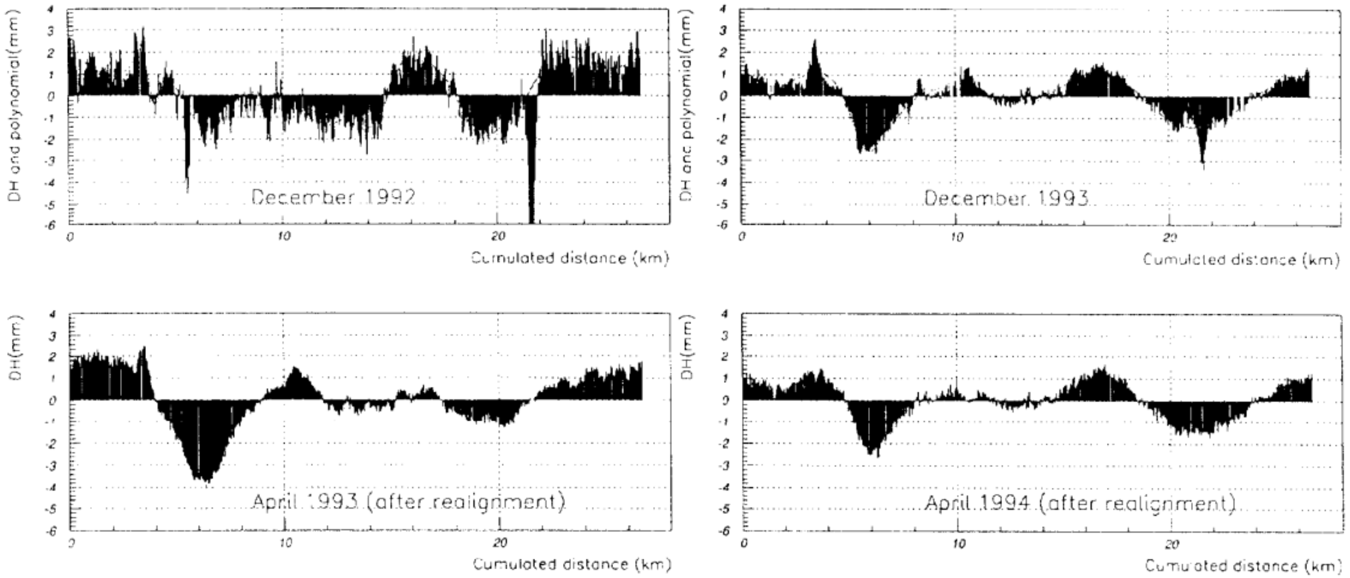
LEP: Survey & alignment

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]

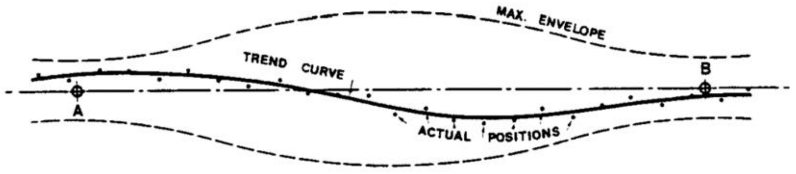
LEP: lessons learnt

- 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]

Ground motion