

OVERVIEW OF THE FCC-EE ALIGNMENT AND MONITORING STUDY

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Many thanks to :

Manuela Boscolo, Francesco Franesini, Hélène Mainaud Durand, Mateusz Sosin, Michel Noir, Bartlomiej Pudlo, Jürgen Gutekunst, Guillaume Kautzmann, Okan Dag

Overview

- Disclaimers
- Update on the work done for the alignment and alignment monitoring in the arcs
- Update on the situation in the MDI
- Conclusion



Disclaimer 1

This presentation will cover the work performed toward the alignment in the tunnel (both arc and the MDI).

But the alignment process starts from the surface, with GNSS, levelling, gravity measurements ...

These aspect have been covered by Benjamin Weyer's presentation, on Tuesday morning.

Geodesy

Implementation of the primary surface geodetic network⁽¹⁾

- IGN and Swisstopo are densifying their national geodetic network in the vicinity of the FCC surface sites

Test on coordinate transfer methodology⁽²⁾

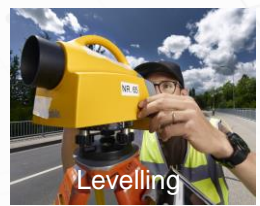
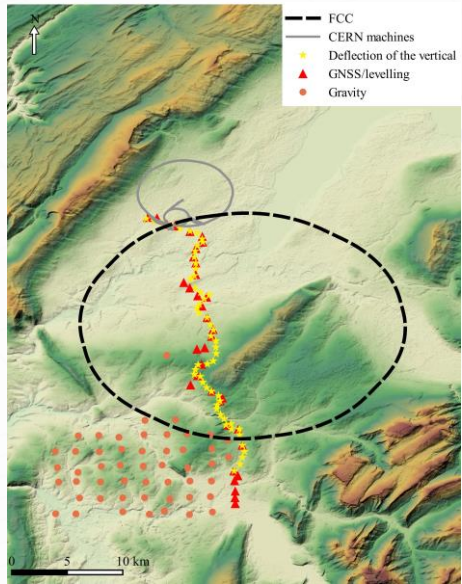
- Plumbing measurement through LHC shafts

Progress made in collaboration with ETHZ

- Concept for calibration, checking and testing of the geodetic equipment for the FCC⁽³⁾
- Computation of a local geoid model using Groops toolkit⁽⁴⁾

The block contains four sub-diagrams: (1) A map showing the FCC surface geodetic network with various station types marked. (2) A schematic of plumbing measurement through a shaft, showing the ground surface and underground tunnel. (3) A pyramid diagram representing the calibration and testing process, with levels: Inspection and check of instruments, In-house competency facilities, Lab-based calibration, Laboratory calibration, and Reference calibration. (4) A line graph comparing observed and calculated height anomalies, with a table below it.

Comparison with IFC validation profile	Mean [m]	Standard Dev. [m]	RMSE [m]	RMSE [m]
Observed	0.0	0.4	0.4	0.4
Modelled	-0.3	0.7	0.8	0.4



Disclaimer 2

This presentation will cover only the work done so far, which is only a fraction of what's needed for such project. For a more complete overview, please see Helene Mainaud Durand's presentation [here](#) (Geodetic Metrology group leader at CERN) :

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 of a component inside a tunnel

Alignment methods & instrumentation available

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

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Hypotheses considered

Tolerances

Layout:

For coherency through the project, it would be great to use the same number of components and length of tunnel area, provided and validated by the project.

From Tessa Charon (FCC week, June 2022)
 At the level of the reference axis (including fiducialisation)

- Number of components:**
 - In the arcs (Main Ring):
 - 2944 girders: 5888 dipoles
 - 2944 quadrupoles
 - 2944x2 sextupoles
 - In the arcs (booster):
 - 2944 girders: 5888 dipoles
 - 2944 quadrupoles
 - 2944 sextupoles
 - In the LSS (???)
 - 2240 components booster
 - 2240 components (main ring)
 - Injectors: 500 components ???
 - Other components ???

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What is done in the LHC

Alignment tolerances

The smoothing activity is performed to minimize offsets between adjacent components in the vertical and radial directions within ± 0.2 mm (1 σ inside a sliding window of 150 m).

Number of components:

- 154 dipoles per arc (1232 in total)
- 55 quadrupoles per arc (440 in total)

In the LSS (in total):

- 263 heavy components (magnets, RF components)
- 372 light components (beam instrumentation + collimators)

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FCC vs LHC: facts and lessons learnt

- Far more components :**
 - arcs – dipoles: 5888 vs 1232 (not counting the booster ones)
 - ArCs – quadrupoles: 2944 girders (2944 quadrupoles + 5888 sextupoles) vs 440 (not counting the booster ones)
- In a brand-new tunnel (w.r.t. a 40 years old tunnel)**
 - Unstable area not known → regular measurements needed
- High level of radiations in the arcs**
- No applicable solution for the MDI area**
- We need to have first measurement concepts validated before trying to automate them**
- Very important to have clearly defined alignment tolerances for all area.**

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Alignment concept proposed

Standard steps shall be automated

- As-built measurements
- Marking on the floor
- Measurement of jacks' head
- Initial alignment (determination + adjustment) of the components

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Conclusions

Recall, what need to be done to complete the feasibility study

- Impact of alignment requirement
 - Can change the design of accelerator supports
 - Can bring additional equipment to be installed in the tunnel (motorized jack...)
 - Can add set of cables
 - Can increase the cost

Still a lot of unknowns: the alignment tolerances of the booster, confirmation of the main ring alignment tolerances, alignment tolerances of the injectors, access to the components, radiation level, thermal stability, etc. and on top of this we have currently no solutions available (studied and qualified) for the position determination in the MDI and in the arcs.

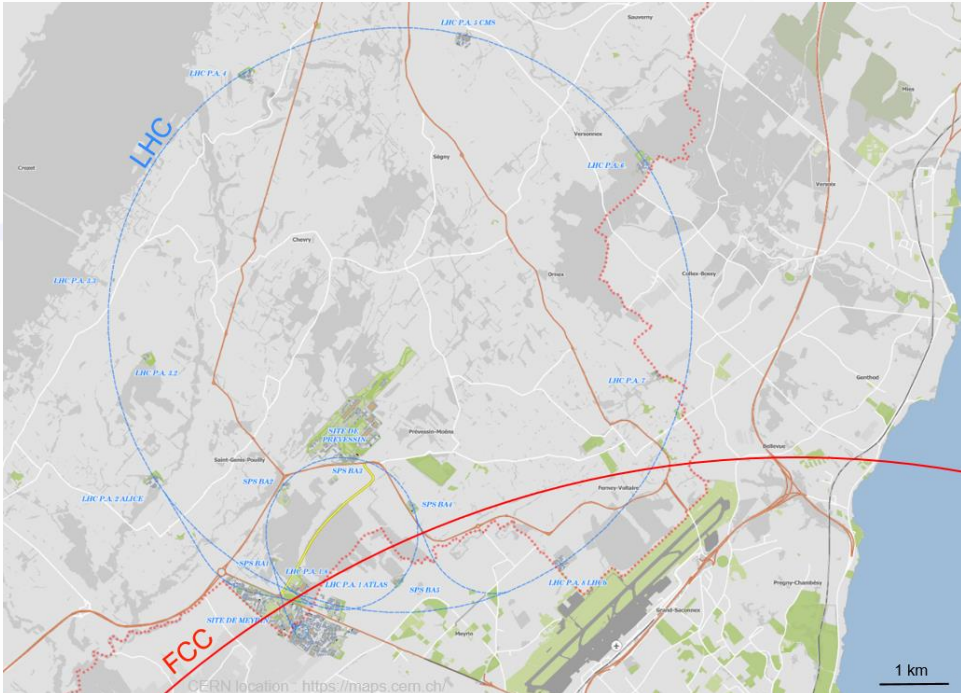
We have to start ASAP the R&D on this very preliminary concept and develop alternatives. The feasibility studies on alignment will not be finalized before the end of the year, as they have just started with a very limited workforce. **Additional resources are needed** to conclude on the most urgent items. **The development of a chained FSI technology is key** to decrease the number of cables but is currently at its premises.

We have to perform the studies in the right order: we have first to develop and qualify the concepts, before looking at their automation (robot or train solution) or at their low-cost industrialization (jacks). Relaxing the alignment requirements should not be the only target; given the number of components and the brand-new deforming tunnel, we will need anyway alignment sensors. **We should focus our energy on finding sustainable and affordable solutions.**

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Focus of the work done

FCC and LEP/LHC are very similar, the main difference (regarding alignment) is the size and all that results from this (even though alignment requirements, component shape, support, stability and many others deriving from these are non-negligible).



First goal is to study the alignment error propagation as it impacts :

- Marking
- Initial installation
- Monitoring
- Adjustment
- Resources
- Cost
- Time spent

Over the entire lifespan of the machine



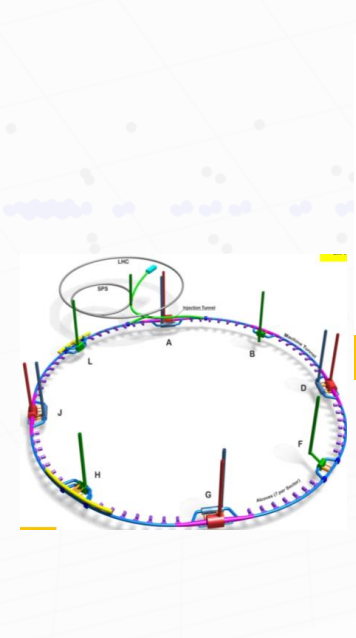
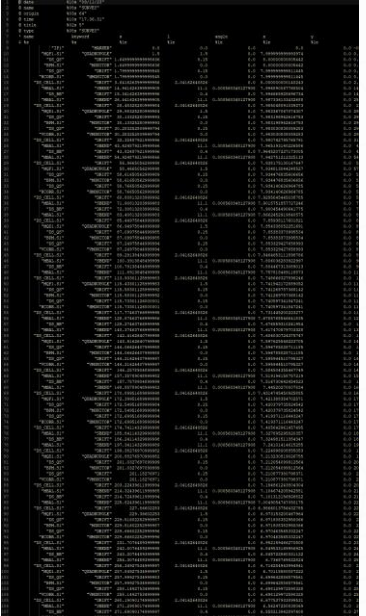
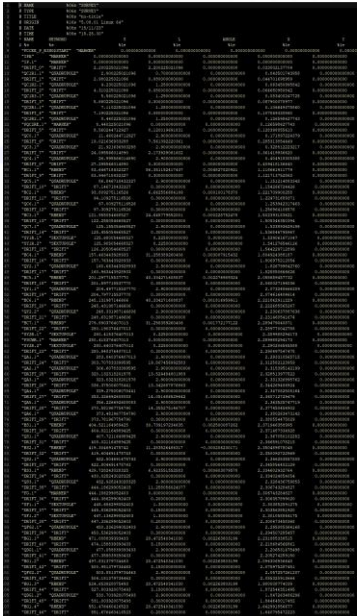
Ongoing simulations

One big challenge : We have two (or even three) objects being increasingly more detailed and mature, but without a clear link between them yet.

But as surveyors we are asked to locate the machine in the tunnel with very demanding precisions.

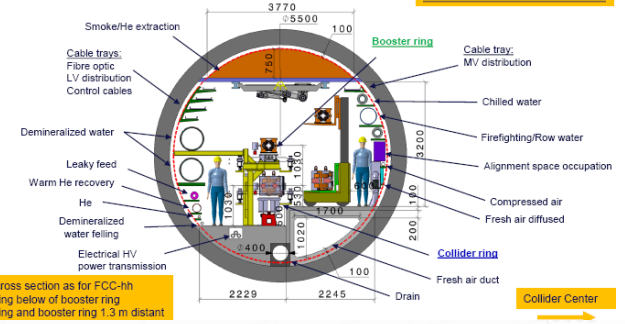
Collider optics layout

Booster optics layout

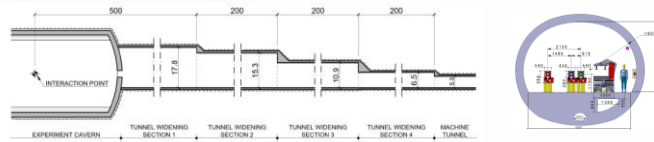
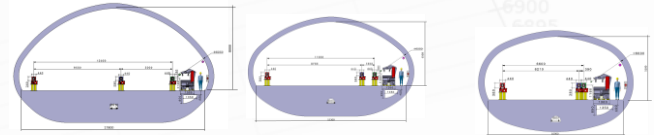


Tunnel integration

Integration of FCC-ee machine elements (regular arc) 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



The current process for the simulations

.tfs file

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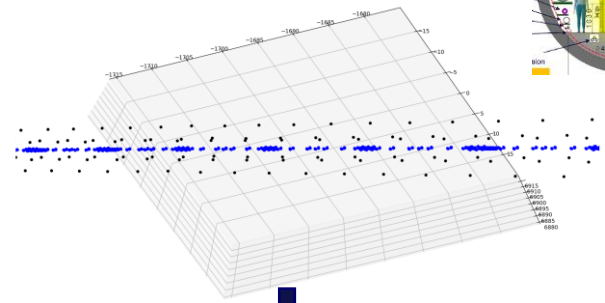
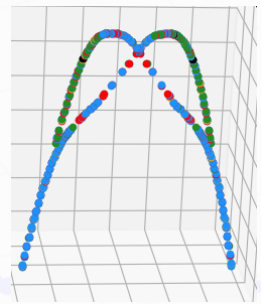
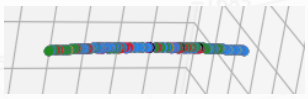
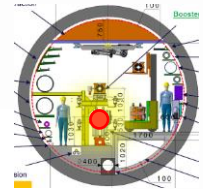
Entry and exit points for all the components

Trajectory

Generation of the tunnel around that trajectory

Simulation of fiducial locations on the components

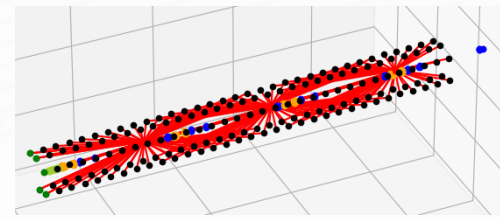
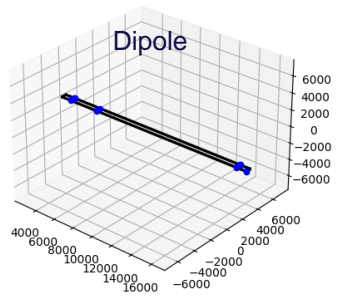
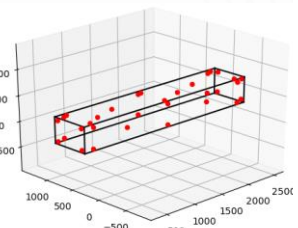
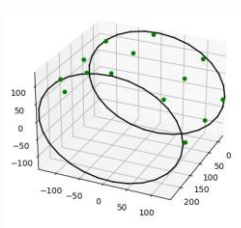
Generation of measurements (between measuring instrument, tunnel walls and components)



Sextupole

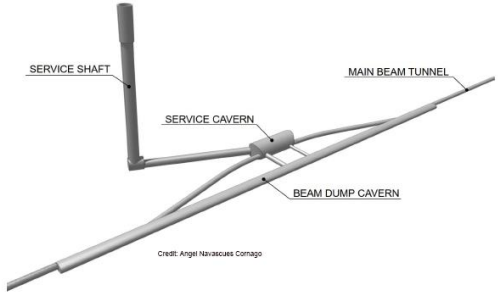
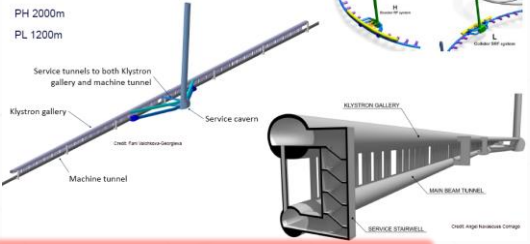
Quadrupole

Dipole

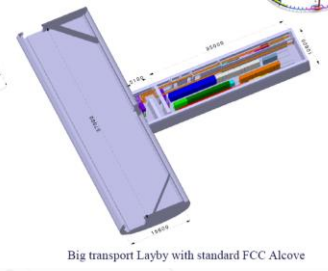
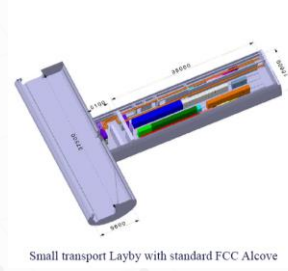
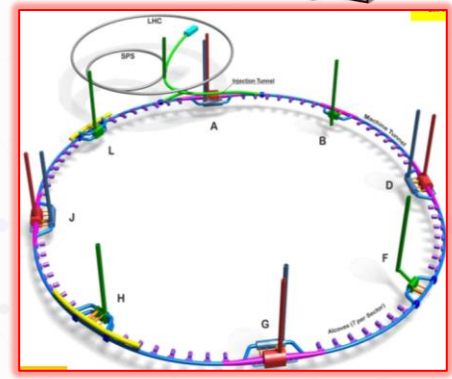
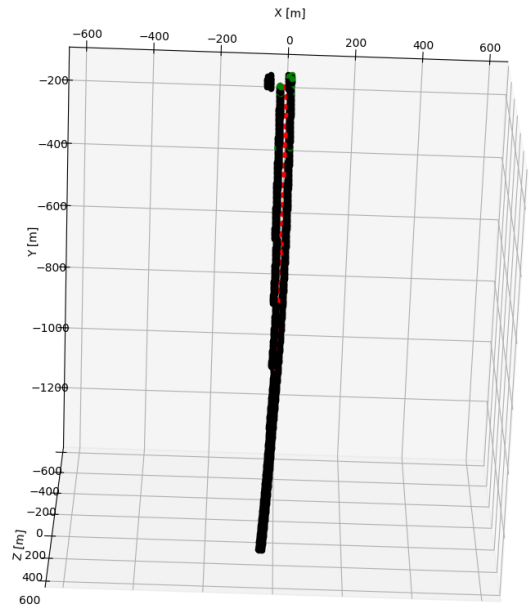


Tunnel point network is different depending on the location

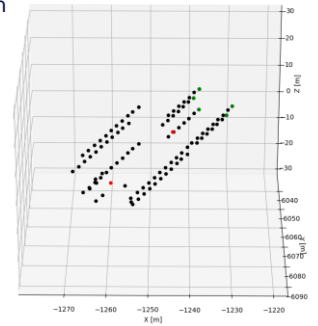
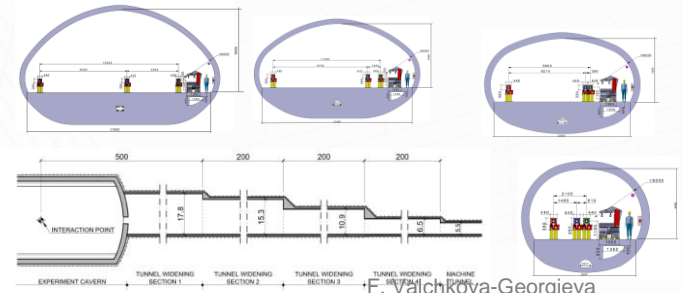
F. Valchkova-Georgieva Klystron Galleries



Reference points in the tunnel around the IP

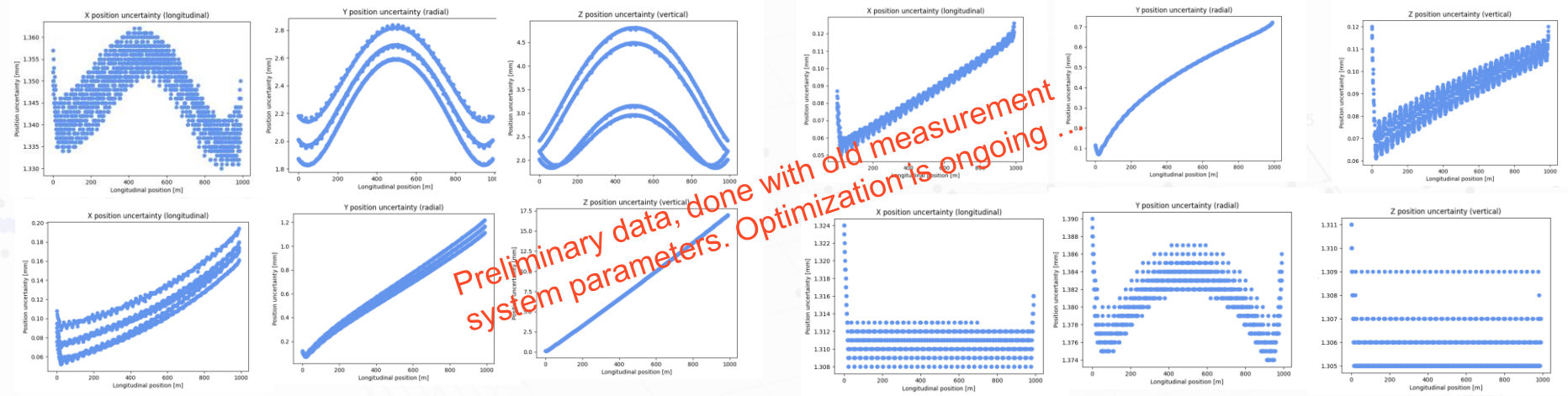


Reference points in the tunnel at an alcove



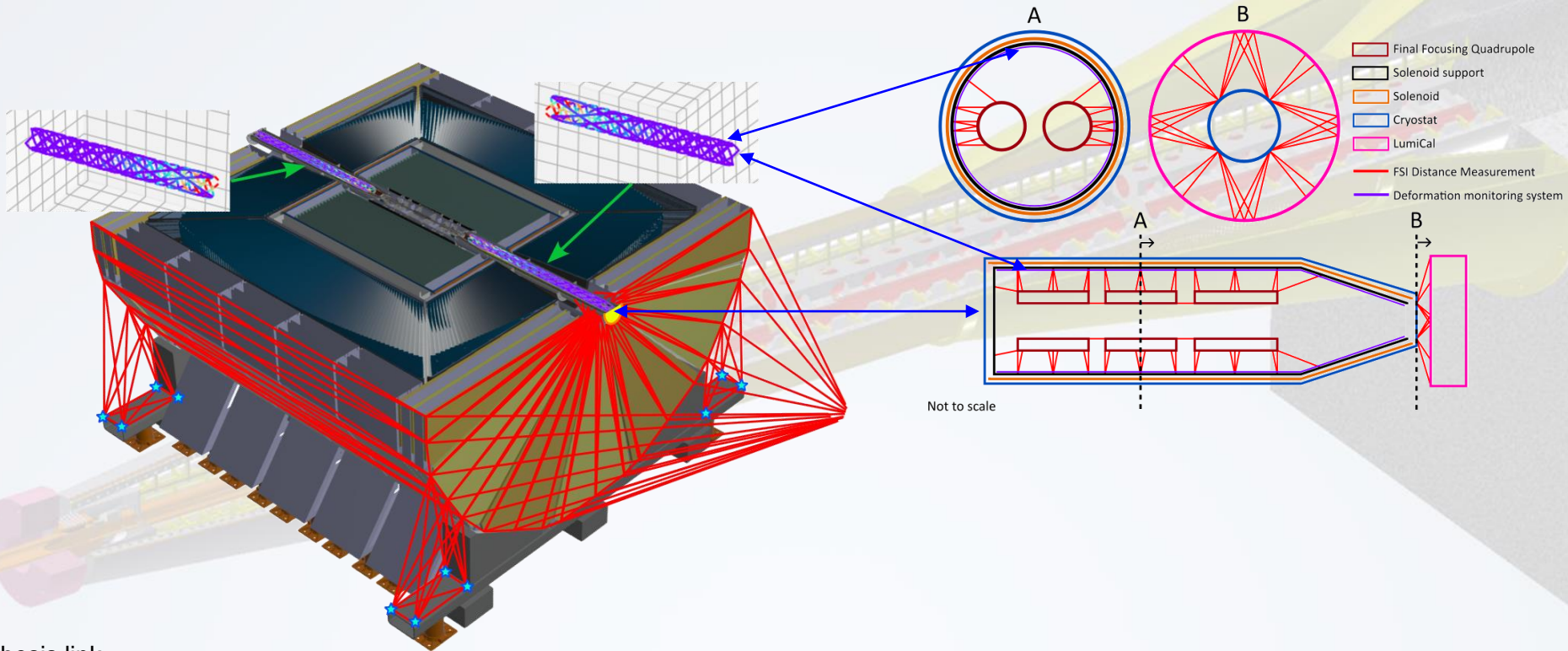
Status

A code has been created to get the position uncertainty of points and/or components depending on a set of tunable parameters (tunnel geometry, point network density, measurement system characteristics ...).



Upgrade of the current adjustment software is required as it cannot compute more than 2 km of tunnel at once. Temporary solutions are used to perform simulations, but the challenge needs to be addressed.

MDI



MDI

External alignment and monitoring system

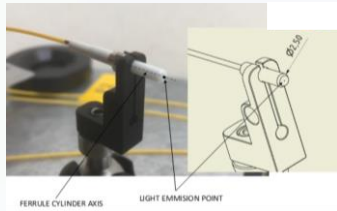
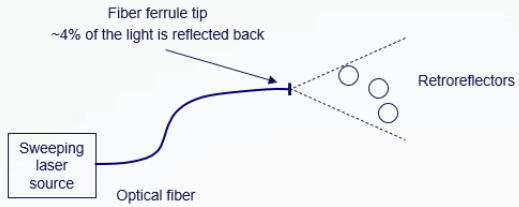
Permanent network of interferometric distance measurements based on Frequency Scanning Interferometry (FSI).



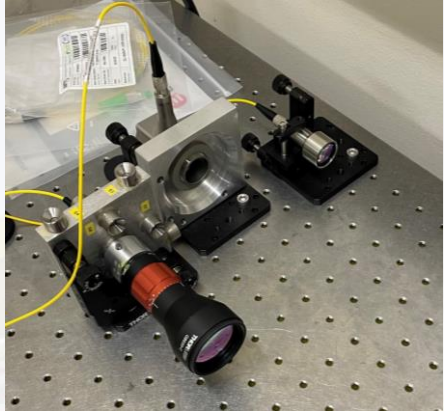
Goals :

- Monitoring of the interface at the end of QC1
- Monitor the alignment between QC1 and QC2.
- Monitor the alignment between the inner components and the experiment solenoid.
- Monitor the alignment between the two sides of the experiment.

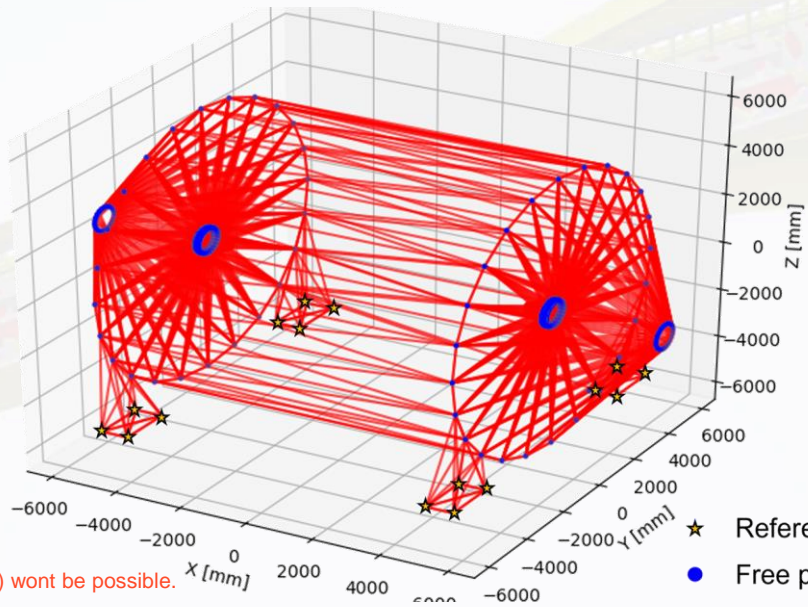
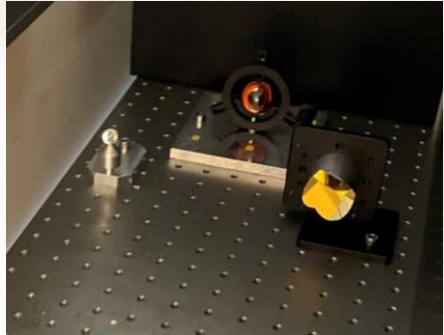
Optimal network : too much measurements, some (plenty) wont be possible. Any update on the design would be much welcomed.



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.



R&D on optics and reflectors

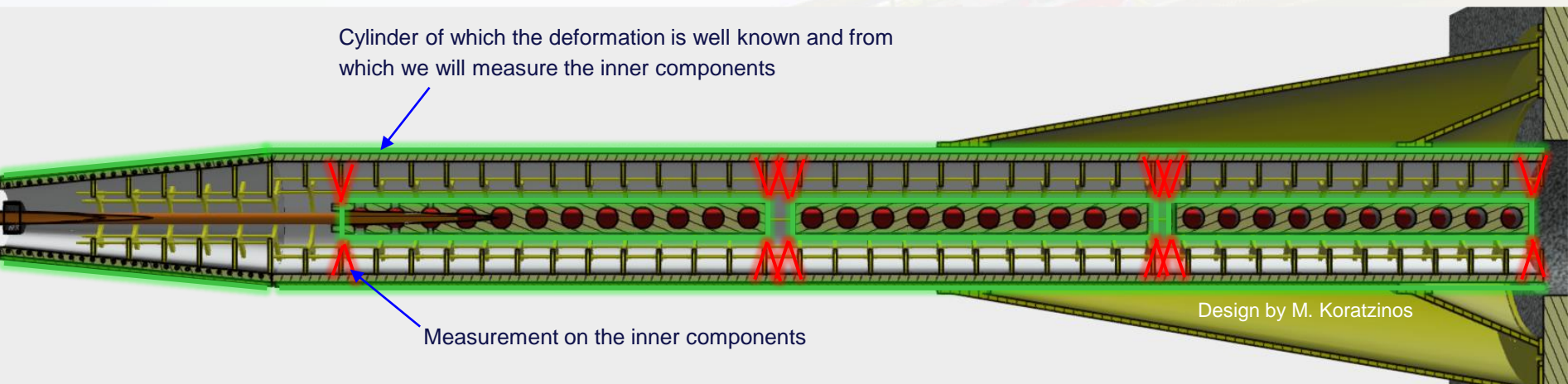
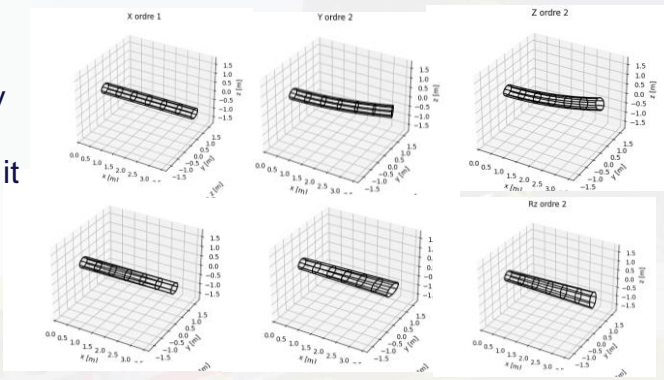


★ Reference points
 ● Free points

Internal alignment system

- Goal : monitor the deformation extremely precisely over the length of the assembly
- Create a network of points accurate enough so another system can measure from it onto the inner components
- Deformation monitoring system + distance measurement system

Deformation models

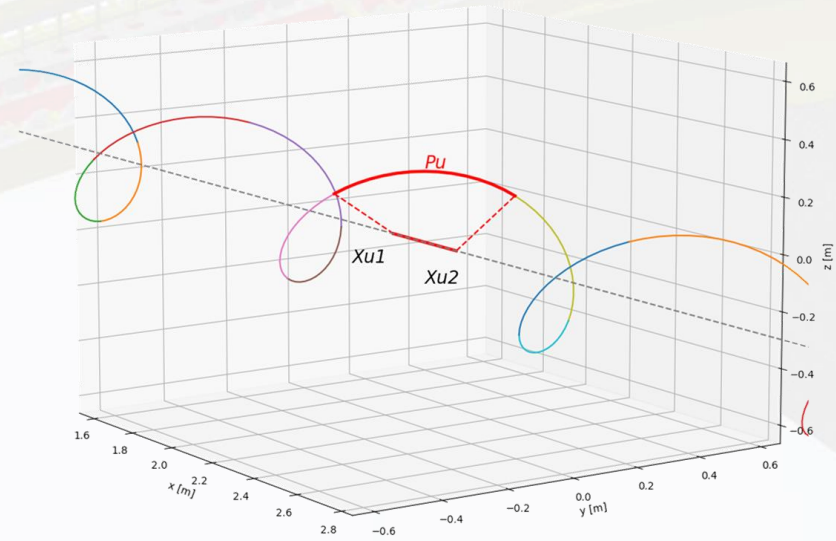
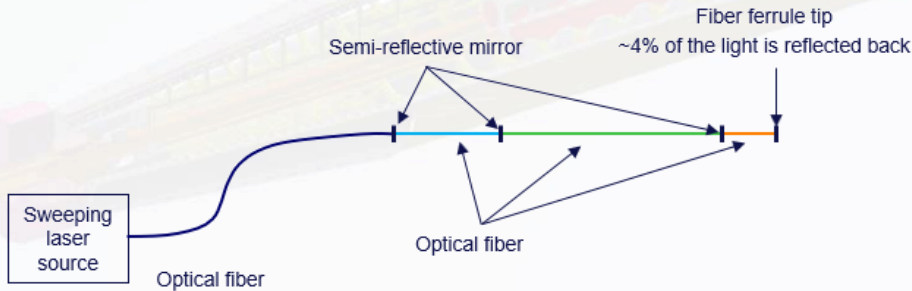
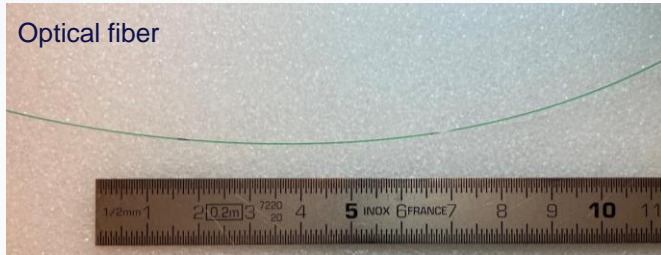
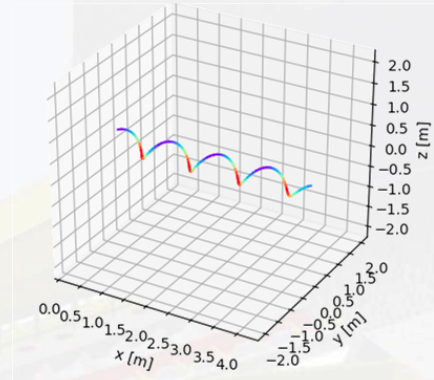


- Measurement system waiting for design update.

Deformation monitoring

<https://iopscience.iop.org/article/10.1088/1361-6501/acc6e3>

- Optical fiber placed in a helix shape, separated in portion by semi-reflective mirrors, which can be simultaneously and independently measured
- Helices defined by their length, radius, step, number and position of portions
- Technology used : In-line multiplexed and distributed FSI measurement (in development at CERN)

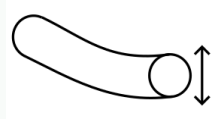
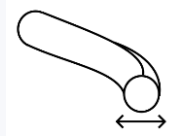


Deformation monitoring

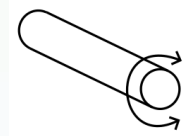
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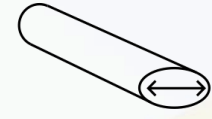
X ordre 2



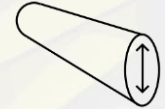
Z ordre 1



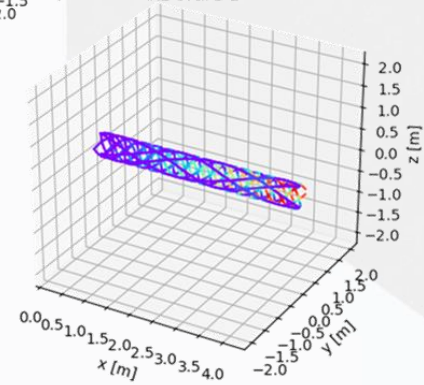
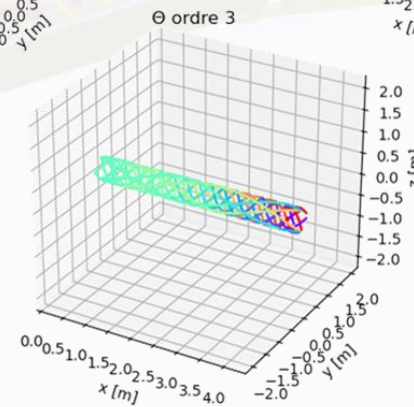
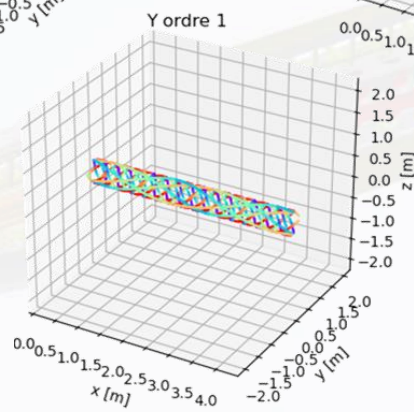
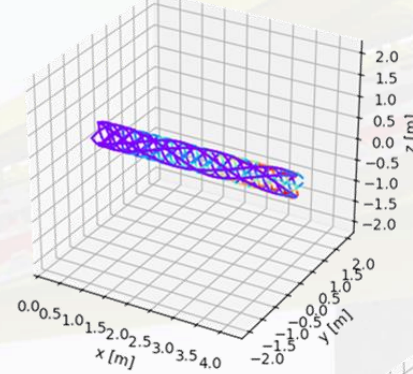
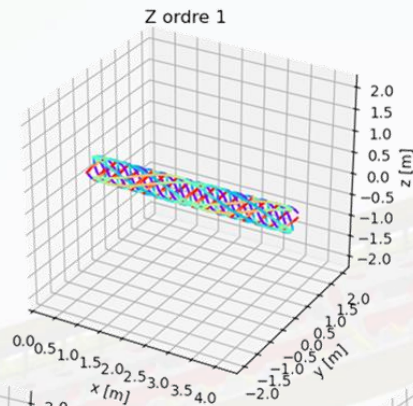
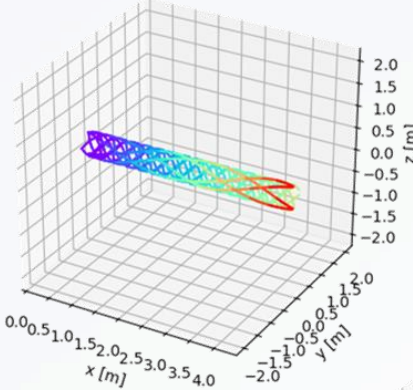
Θ ordre 3



Ry ordre 1



Rz ordre 1

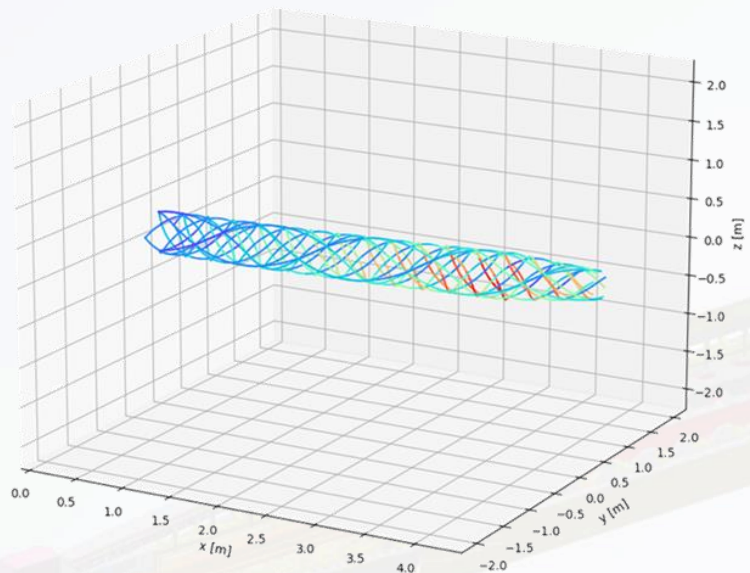


Deformation monitoring

<https://iopscience.iop.org/article/10.1088/1361-6501/acc6e3>

Cylinder deformations

Helixes observations
(= 3D lengths of portions)



+ equation of portion length as function of the deformation polynomials

Total : 3600 measurements and $\approx 3 \text{ cm}^3$ space taken by the sensing system in the assembly.



Least square adjustment

$$P_x(t) = \sum_{i=1}^n a_i t^i$$

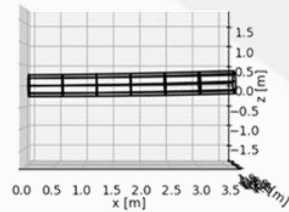
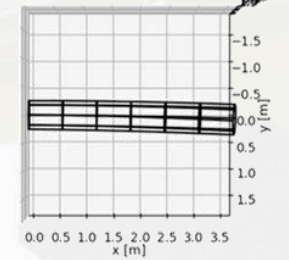
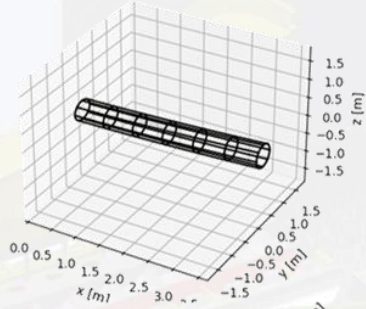
$$P_y(t) = \sum_{i=1}^n b_i t^i$$

$$P_z(t) = \sum_{i=1}^n c_i t^i$$

$$P_\theta(t) = \sum_{i=1}^n d_i t^i$$

$$P_{r_{xy}}(t) = \sum_{i=1}^n e_i t^i$$

$$P_{r_{xz}}(t) = \sum_{i=1}^n f_i t^i$$



Simulations shown micrometric accuracy
To be confirmed by a prototype

Deformation monitoring

First prototype



Deformation monitoring

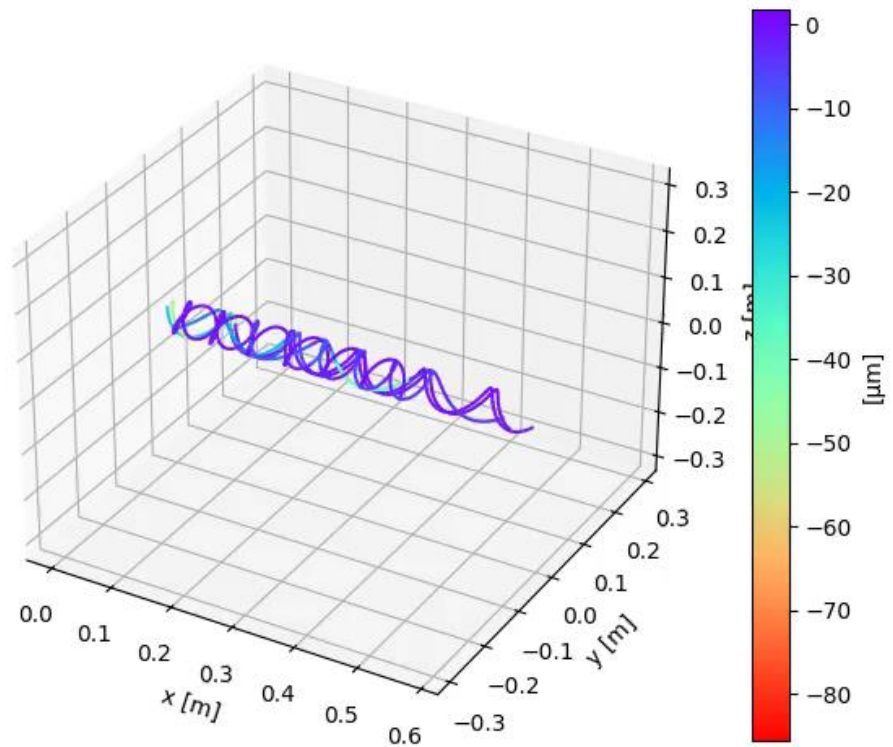
The goals of the prototype were:

- Establish a process for the assembly of the 'big' prototype (1/2 scale)
- Study the difficulties during the positioning/gluing
- Study the 'as-built' result and deal with real data
- Get ready for the next prototype, a 2m long tube

This prototype was not meant for deformation testing.



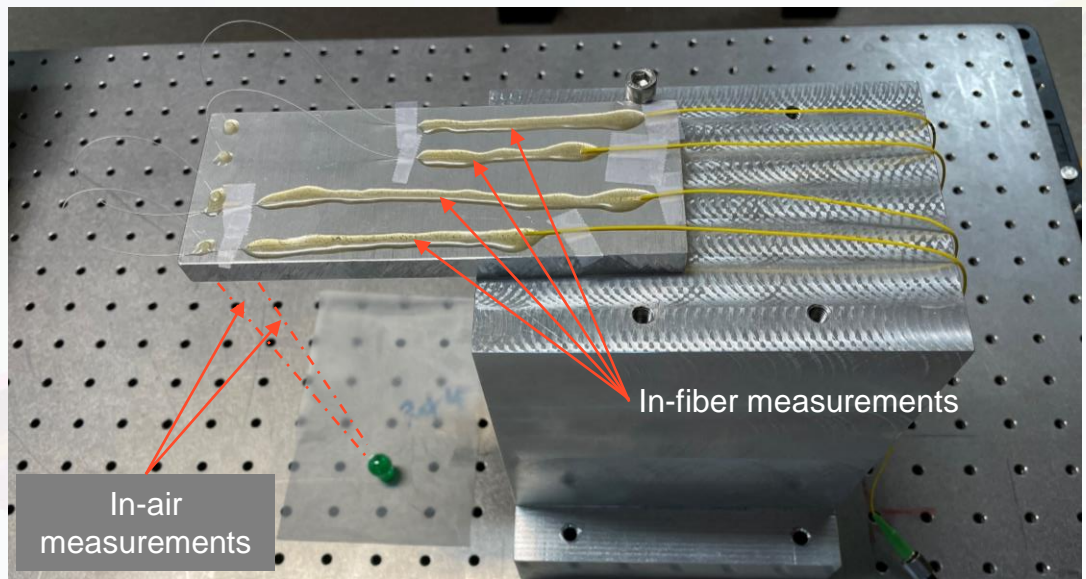
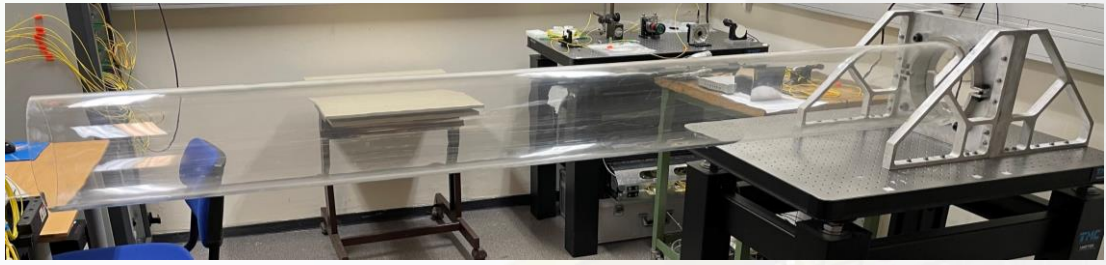
8 hours measurement
Shrinkage of the fibres due to the curing of the glue



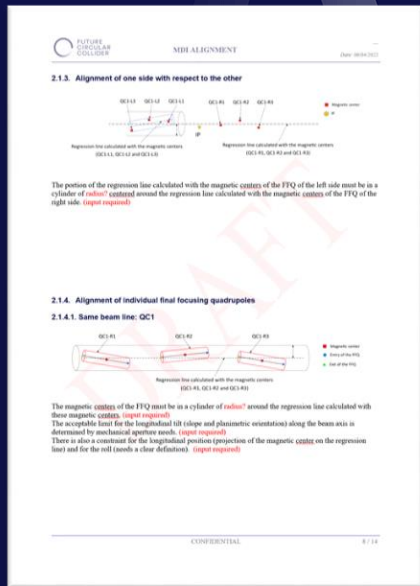
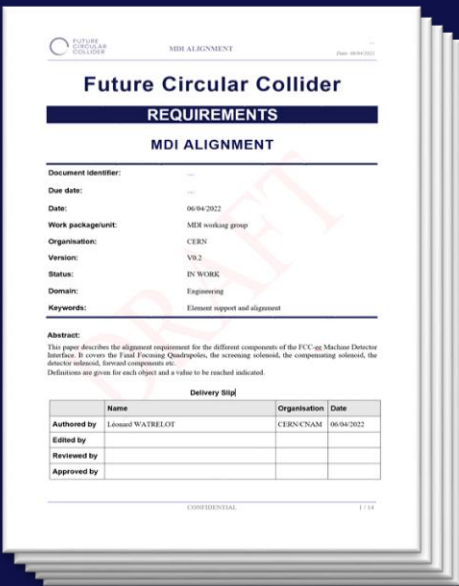
Deformation monitoring, next steps :

- Assemble the 2m long prototype
- Implement distance measurement from the tube towards components inside
- Perform deformations
- Crosscheck using different sensor systems (laser tracker, probe sensor)

Parts getting ready for a 2m long tube deformation study



Thank you for your attention



Additional subjects needed to be looked at :

- Tunnel marking
- Magnet support
- Adjustment solutions
- Magnet deformation
- Automatisisation
- Alignment data storage and handling
- ...

I'm still trying to gather alignment requirements

Re-adjustment system

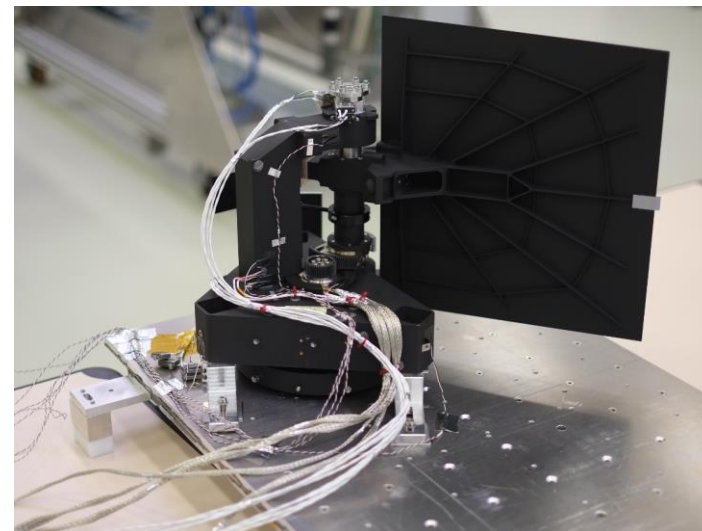
- Interest of having a system able to move one or multiple element without requiring to disassemble the entire QC1 ?
- Not necessary to be accurate at 10 μm , a system able to correct major displacements ~ 0.2 mm to 1mm (due to transport, gravity deformation, movement during cool down, intense magnetic fields ...) would be already extremely convenient.
- Not necessary to work at cryogenic temperatures only at room temperature would be already extremely convenient.
- Not necessary to be able to work during the run of the machine, during shut downs would be already extremely convenient.

A lot of possibilities are open, from the system working only at warm temperature allowing a re-adjustment to the 0,1mm level of major components at the end of shut downs, to the system able to realign in real time and during the run of the machine the cold components to the micrometer level.

Systems to work in these conditions exist, the difficulty is to quantify their advantage compared to a loss of luminosity due to any misquantified misalignment value or to the need to dismount, disassemble, realign, reassemble and remount the assembly.

The EUCLID VIS Read-out Shutter Unit, which will operate in space

Larchevêque, C., et al. "The Euclid VIS read-out shutter unit: a low disturbance mechanism at cryogenic temperature." *arXiv preprint arXiv:1801.07496* (2018).



Universal Alignment Platform Tests, Kacper Widuch, Vivien Rude BE-GM-HPA 2021-03-11

