FCC-EE MACHINE DETECTOR INTERFACE ALIGNMENT STUDIES

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Many thanks to :
Manuela Boscolo, Francesco Fransesini, Michael Koratzinos, Hélène Mainaud Durand, Mika Masuzawa, Luigi Pellegrino and Vivien Rude

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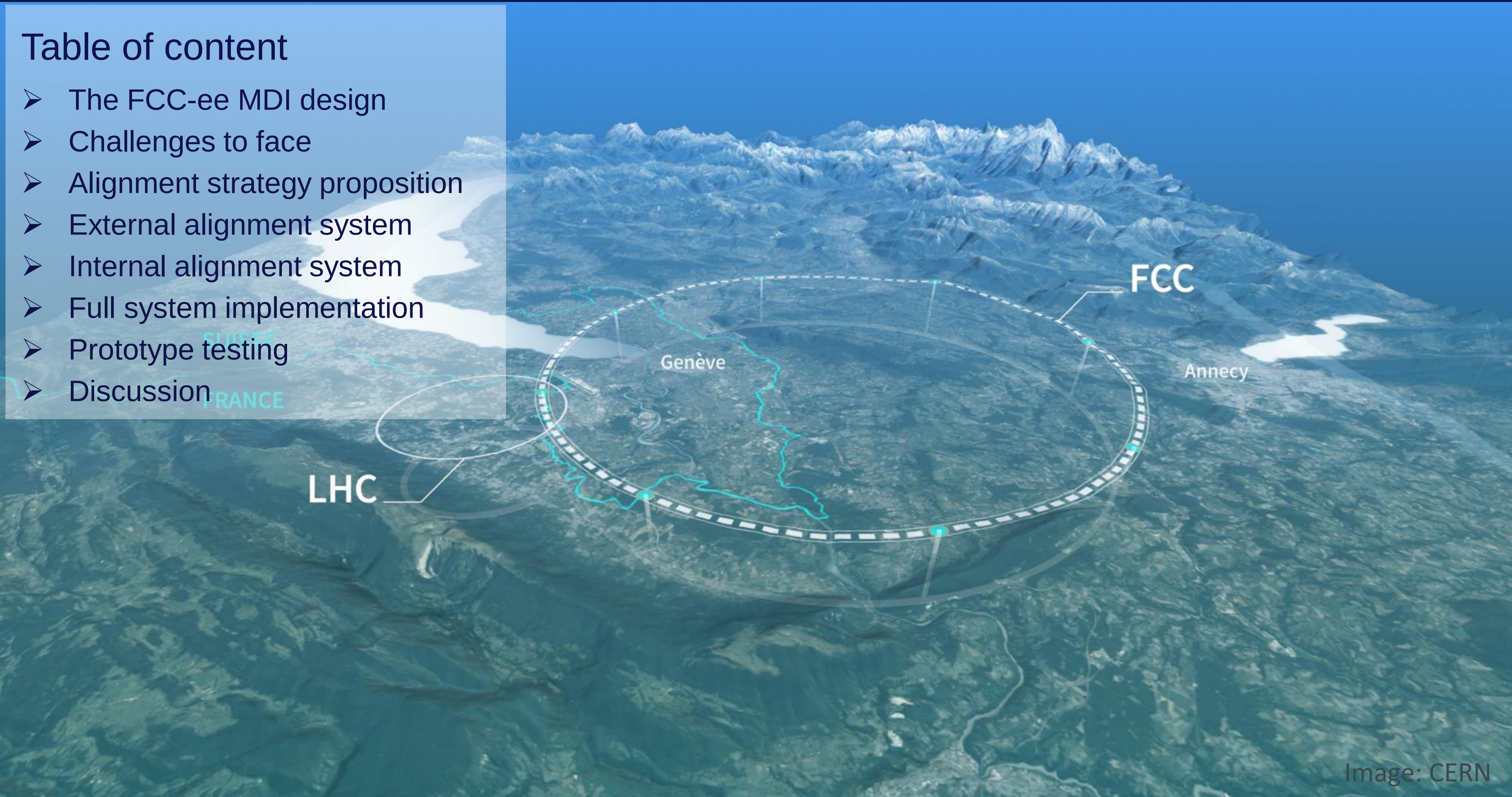
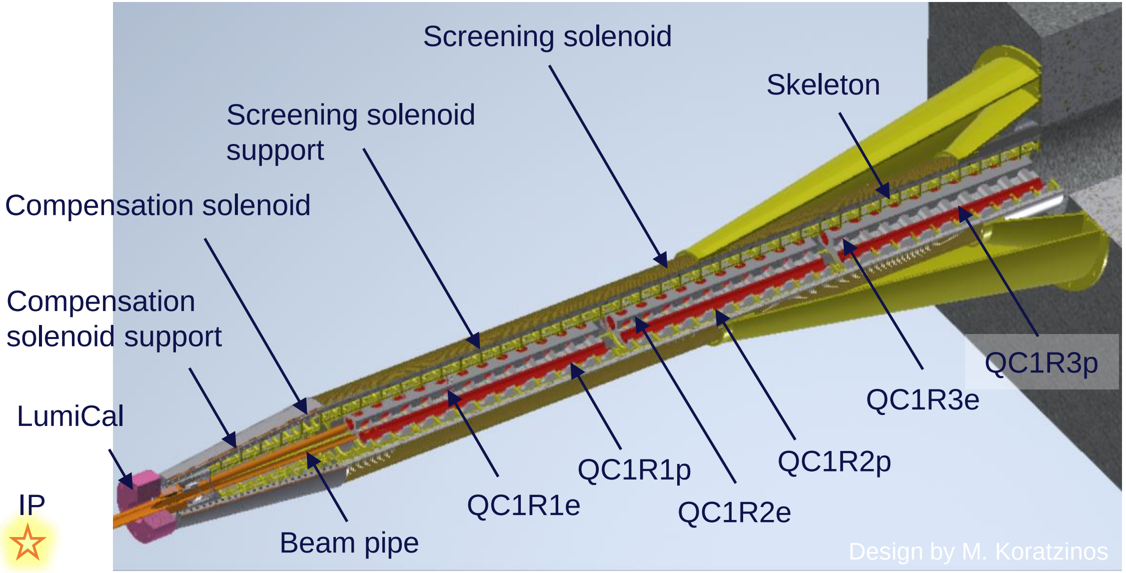


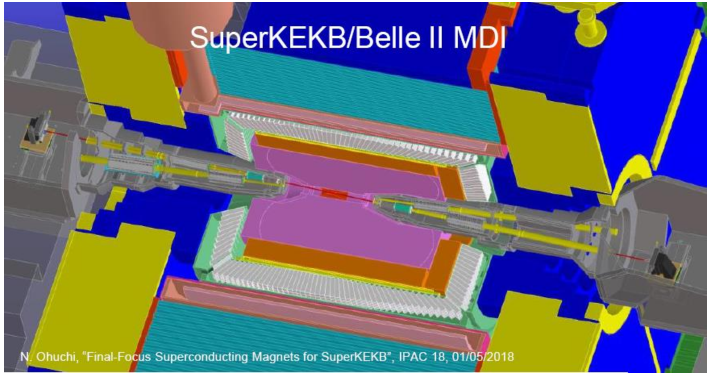
Image: CERN

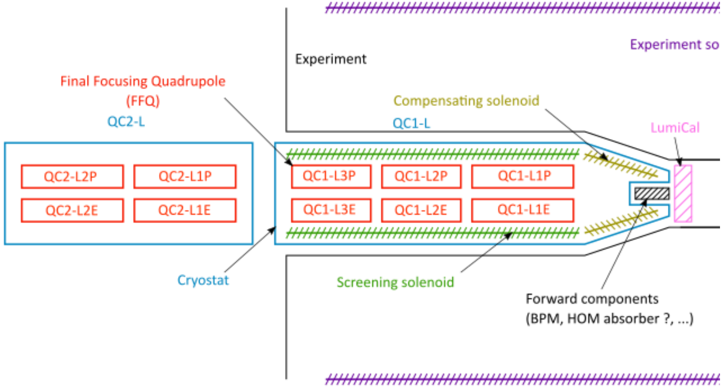
The FCC-ee Machine Detector Interface (MDI) design

- Crab waist configuration (big crossing angle and small L*) => accelerator components inside the detector
- Still a extremely early design which continues evolving



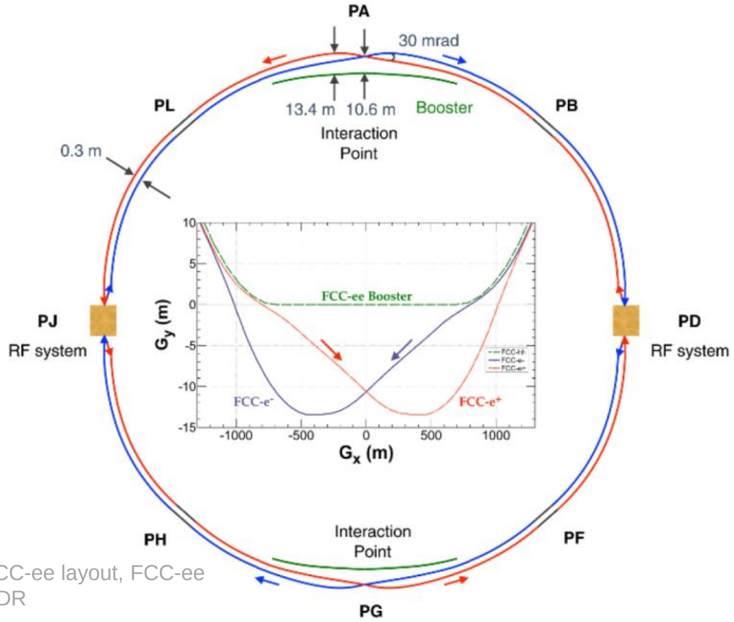
Design similar to :





Why do we need a precise alignment in the FCC-ee interaction region ?

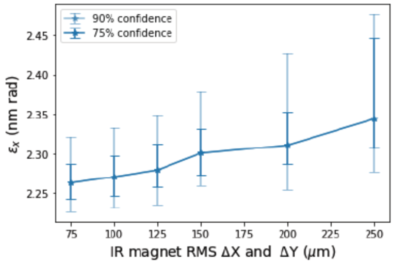
- Maximise performance in terms of integrated luminosity
- Maintain the related background at a tolerable level for the experiments (includes minimizing synchrotron radiation)
- Minimize emittance blow-up

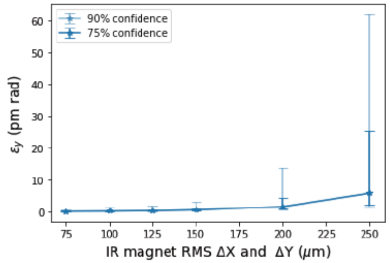


FCC-ee layout, FCC-ee CDR

IR magnets alignment - transverse misalignments (ΔX and ΔY)

Type	ΔX (μm)	ΔY (μm)	ΔPSI (μrad)	ΔS (μm)	ΔTHETA (μrad)	ΔPHI (μrad)
IR quadrupole	varied	varied	250	200	100	100
IR sextupoles	varied	varied	250	200	100	100
All other magnets	as listed in Table on slide 7					

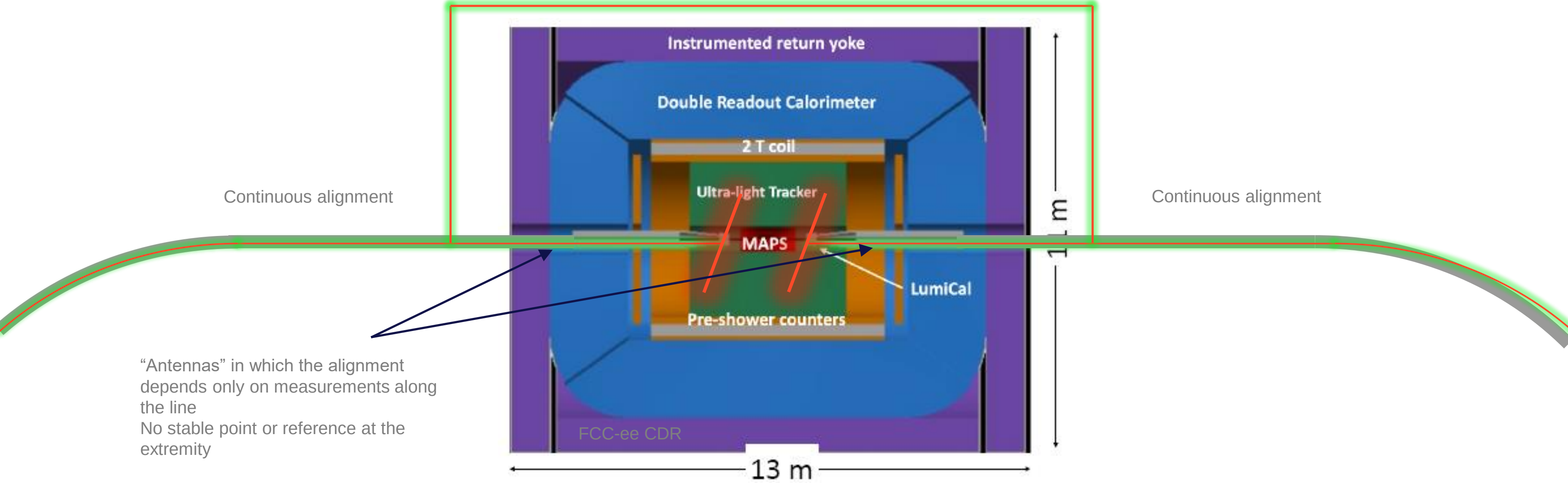




"Status and plans for optics corrections and emittance performance",Tessa Charles, Bernhard Holzer, Katsunobu Oide, Frank Zimermann and the FCC-ee optics team, FCC-week 2021

Why does it need to be more precise than in the rest of the machine ?

- Maintain the related background at a tolerable level for the experiments (includes minimizing synchrotron radiation)
- “Hole” in the machine => “hole” in the alignment -> align both side precisely so they collide



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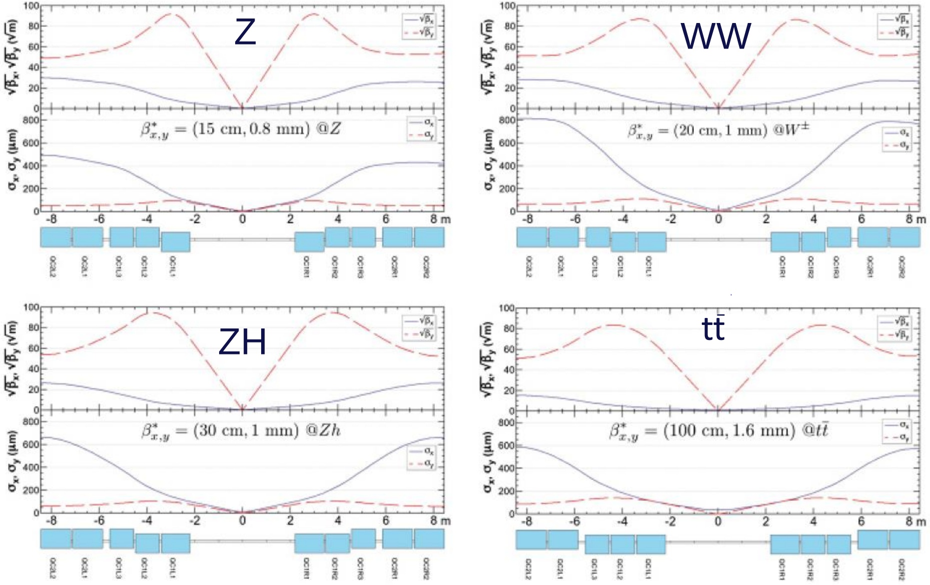
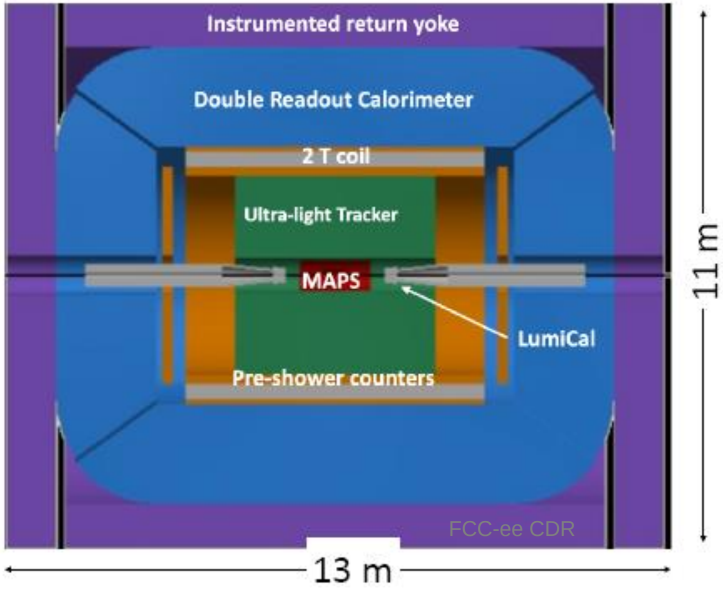
- Maintain the related background at a tolerable level for the experiments (includes minimizing synchrotron radiation)
- “Hole” in the machine => “hole” in the alignment -> align both side precisely so they collide
- Minimal beam size in the entire ring + collide as precisely as possible near the center of the experiment

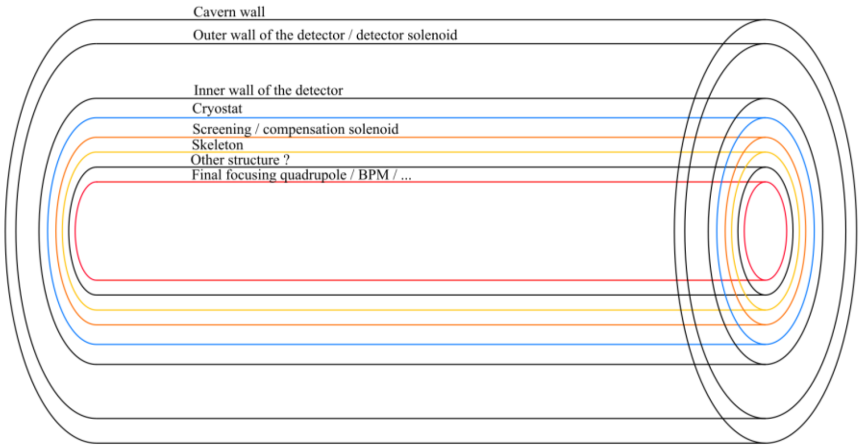
FCC-ee CDR

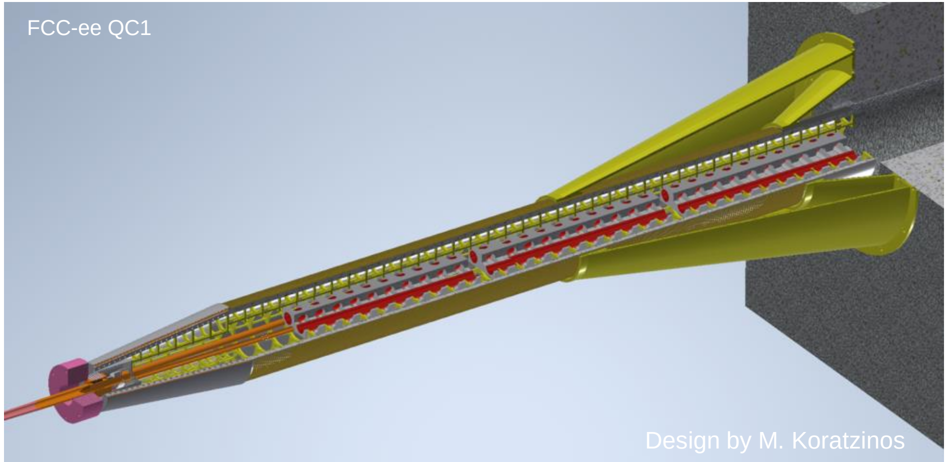


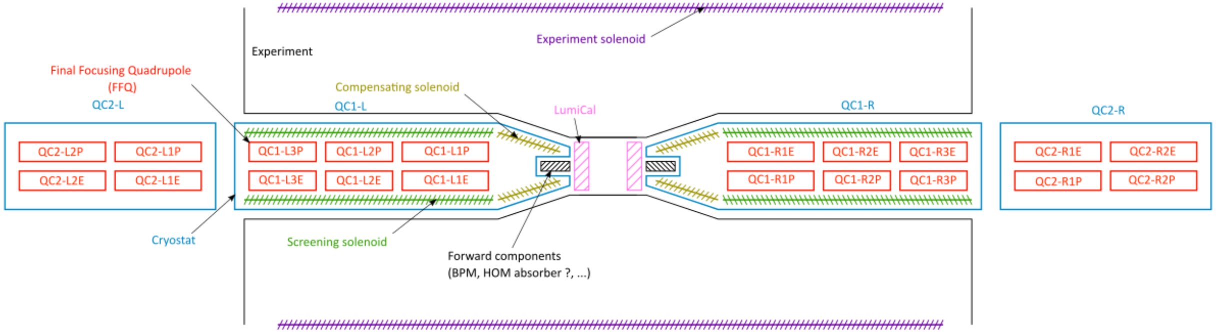


Why is this alignment difficult to do ?

- Design (lot of components to measure, layered design, very little space, design not definitive)







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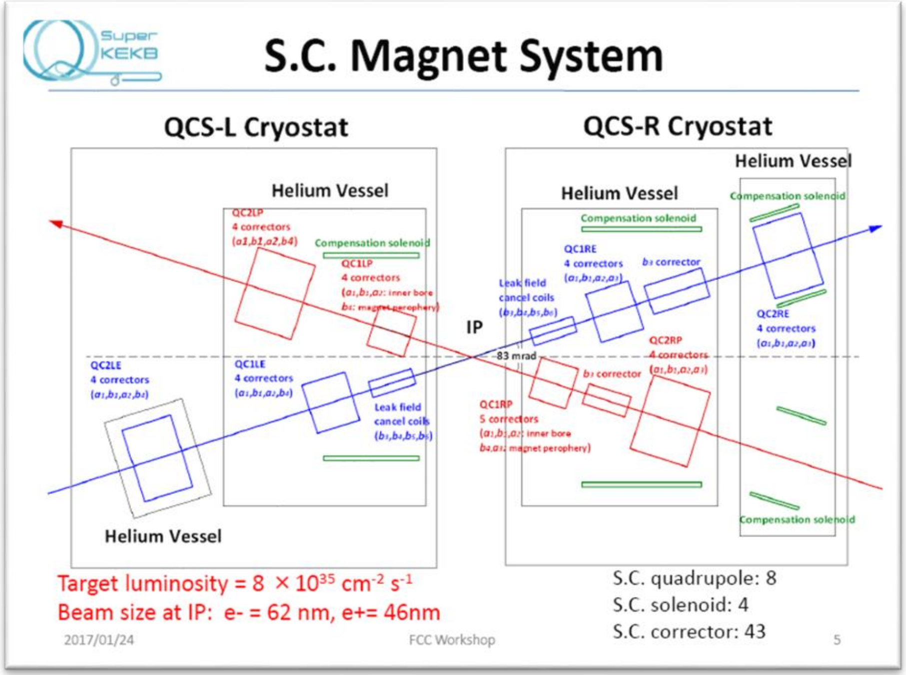
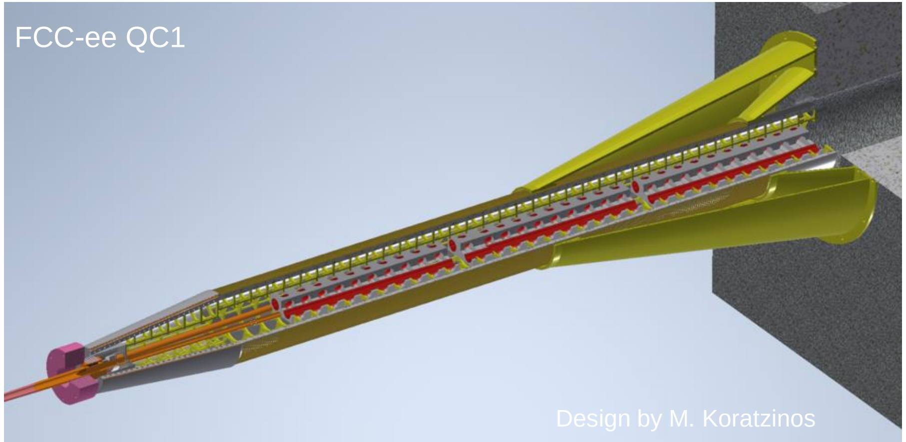




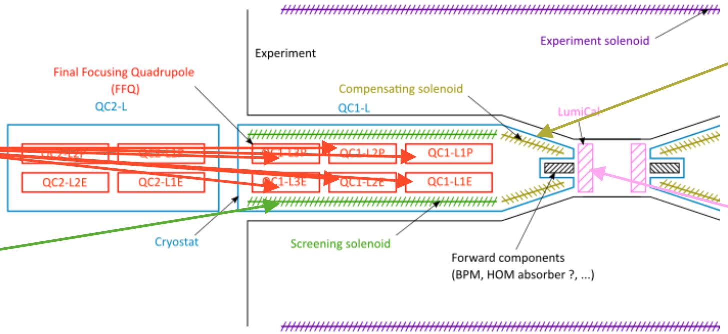
“Superconducting magnet system for SuperKEKB Interaction region”, Norihito Ohuchi, FCC workshop, 24/01/2017

Why is this alignment difficult to do ?

- Design (lot of components to measure, layered design, very little space, design not definitive)
- Conditions (cryogenic temperature, radiations, magnetic fields)
- Requirements (very tight alignment requirement, especially on Final Focusing Quadrupoles, BPM, Screening and Compensation solenoids, and LumiCal)

FFQ : Alignment tolerance at 30 µm + Monitoring

Screening solenoid : Alignment tolerance at ~100 µm + Monitoring



Compensation solenoid : Alignment tolerance at ~100 µm + Monitoring

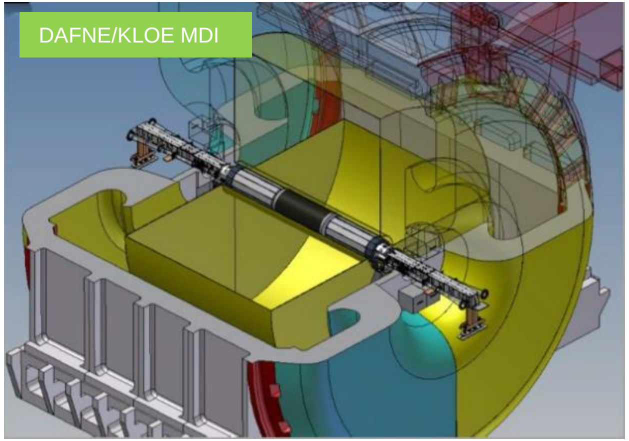
LumiCal
Alignment tolerance at 50 µm w.r.t. the IP (longitudinal) + Monitoring

Misalignment tolerances include all possible error sources such as: manufacturing errors, assembly errors, deformation both during/after installation and during operation, magnetic field measurements, metrology measurement, reference network and alignment measurement, anticipated degradation in the alignment over time as a function of ground motion and other effects.

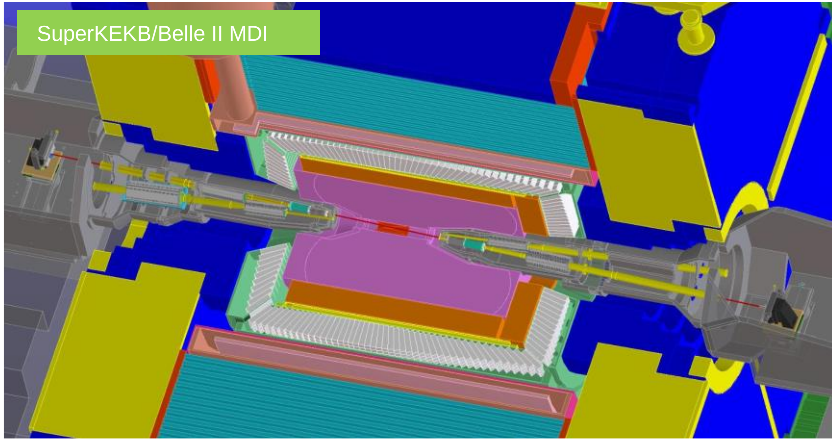
Experience from previous accelerator projects indicates that a reasonable assumption for the relative radial alignment precision can be derived by applying a factor 1/3.

Alignment tolerance at 30 µm => alignment precision required <10 µm

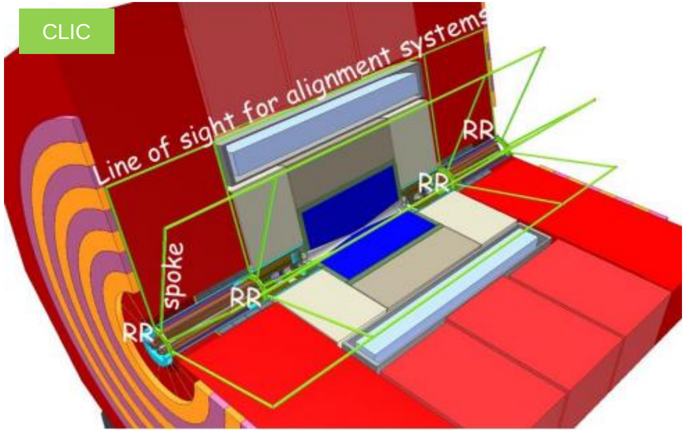
Hasn't it been done in the past ? Is there any similar MDI ?



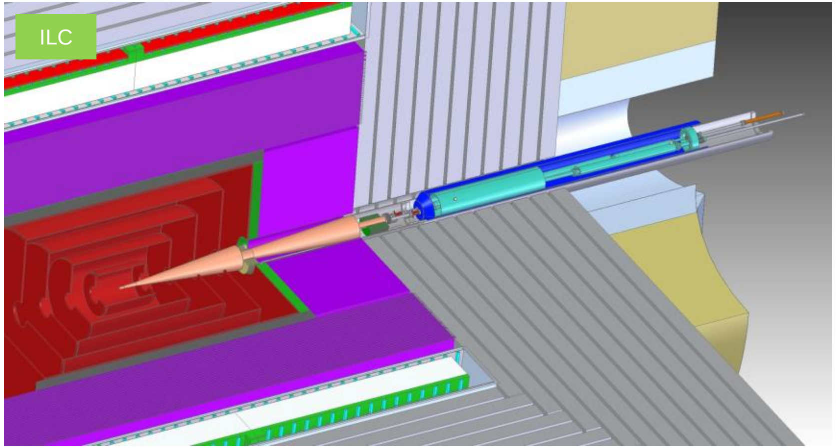
L. PELLEGRINO, MDI mechanical design, integration and assembly at DAFNE/KLOE with the crab-waist configuration, 3rd FCC-ee MDI workshop, 9-20 September 2019, CERN.



N. Ohuchi, "Final-Focus Superconducting Magnets for SuperKEKB", IPAC 18, 01/05/2018

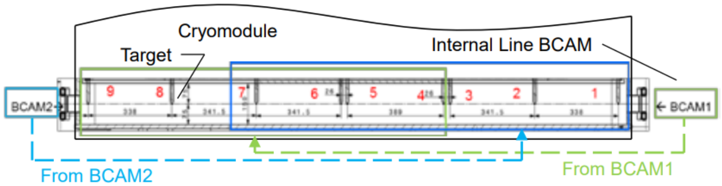


CLIC Machine Detector Interface, MDI mini workshop, HKUST IAS, Philip Burrows on behalf of Lau Gatignon, 2020



Marcel Stanitzki, The SiD Detector – Machine Backgrounds, 01/2020, Hong Kong

Can existing sensors do the job ?



HIE-ISOLDE alignment and system, technical design and project status, J.-C. Gayde, 2012.

BCAM, Open Source Instrument

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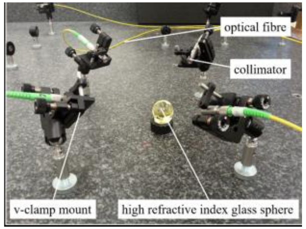
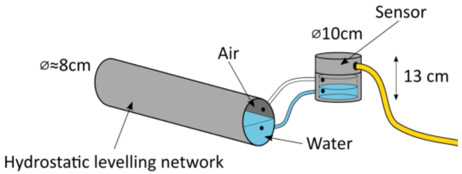
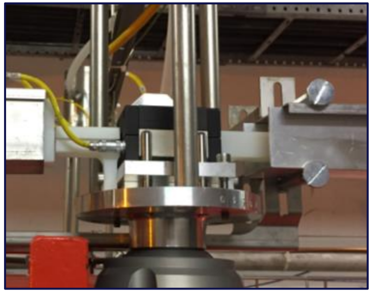
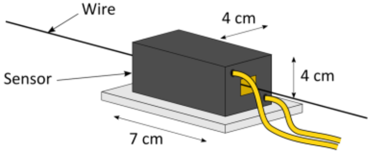


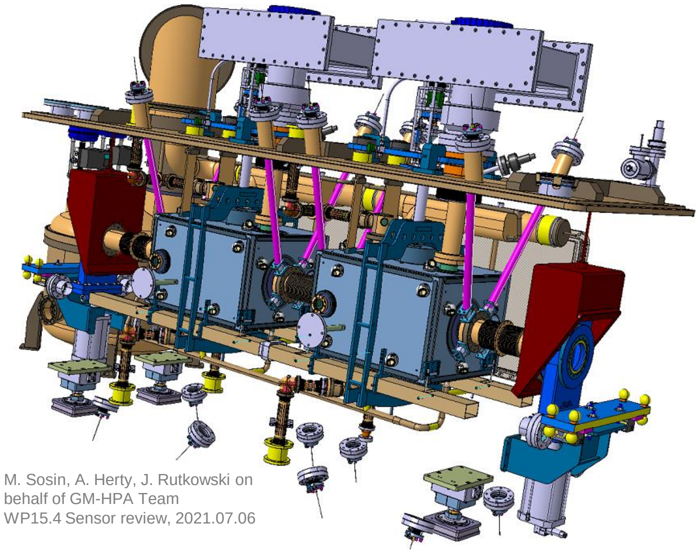
Hydrostatic Leveling System (HLS)



Wire Positioning Sensor (WPS)







M. Sosin, A. Herty, J. Rutkowski on behalf of GM-HPA Team
WP15.4 Sensor review, 2021.07.06

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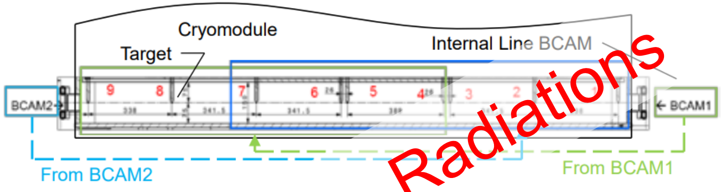

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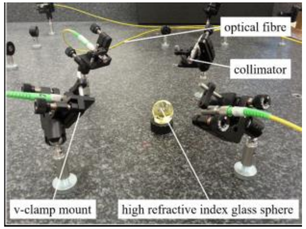

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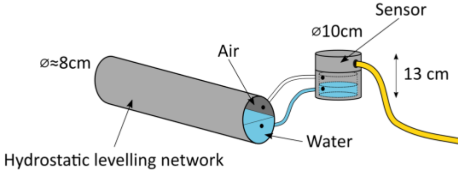

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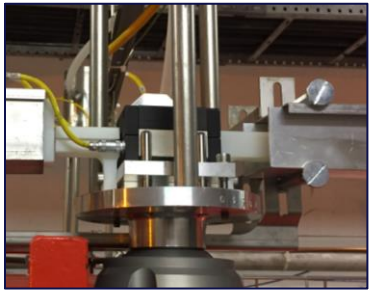

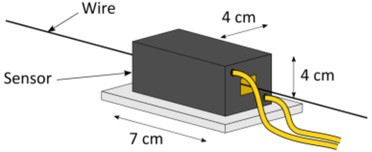

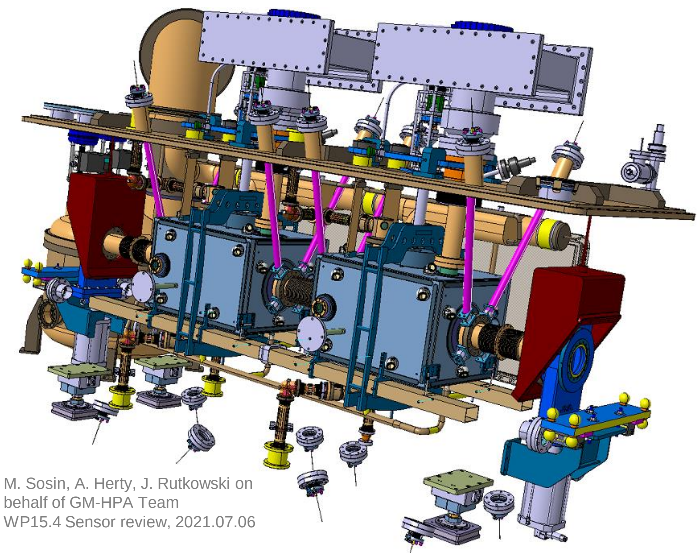

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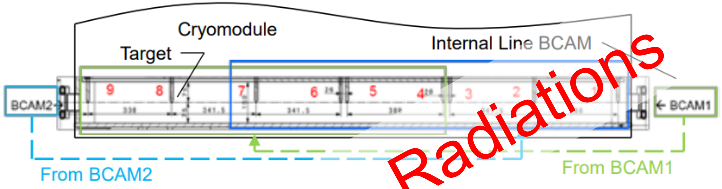

Radiations

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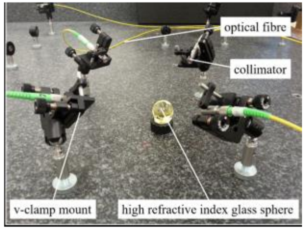

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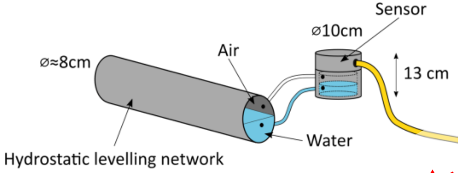

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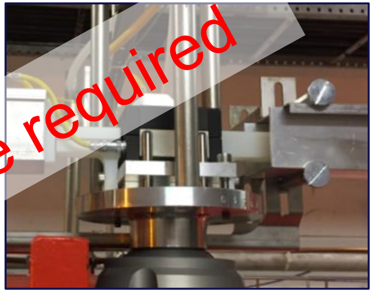
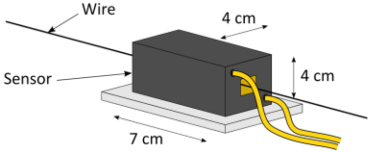
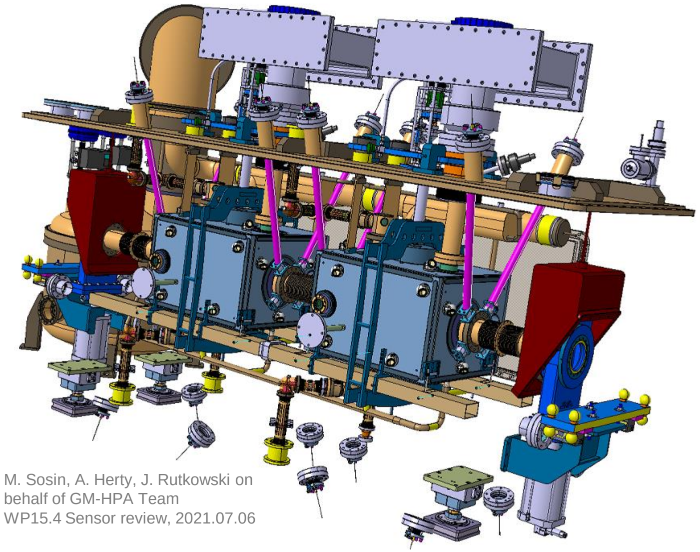




Infrastructure required



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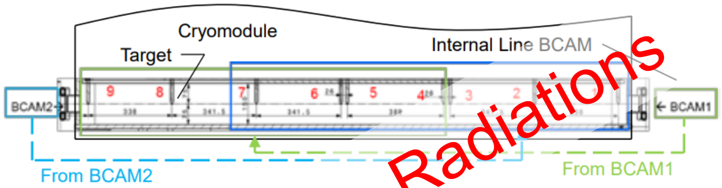

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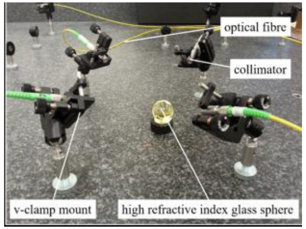

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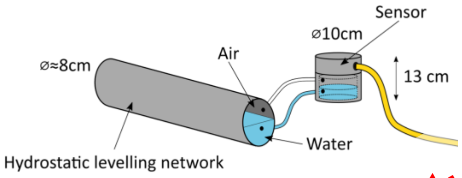

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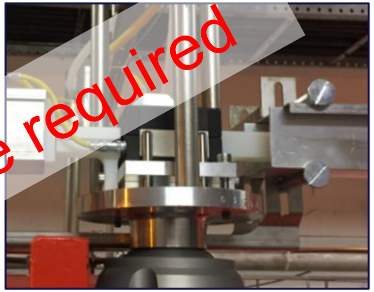

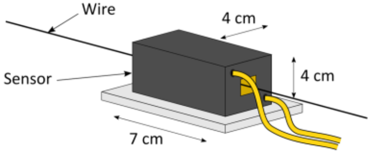

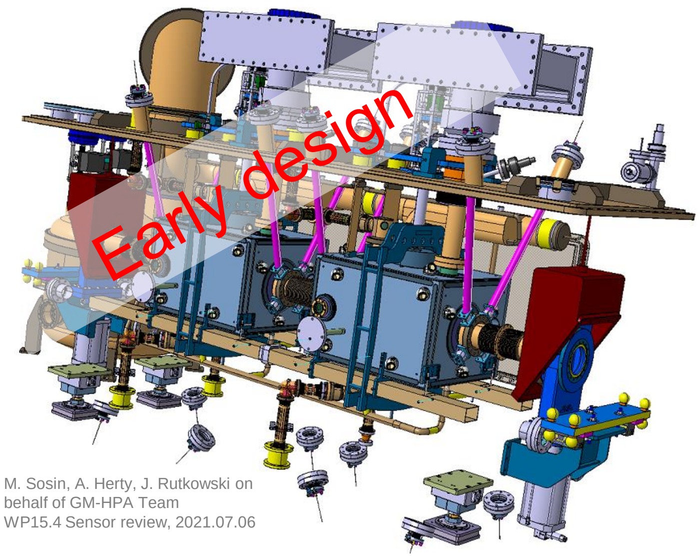

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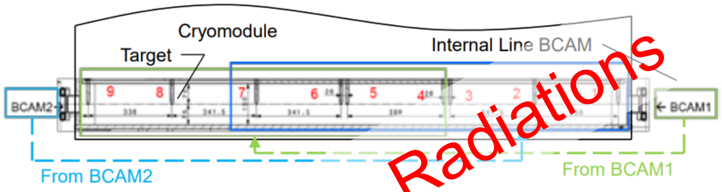
Can existing sensors do the job ?

- Other sensor technology share the same limitations (inductive, ultrasonic …)
- Underlined by the absence of solutions from the CLIC and ILC projects



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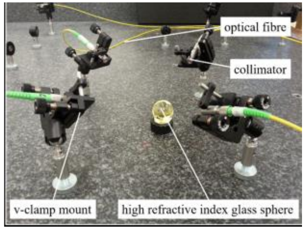

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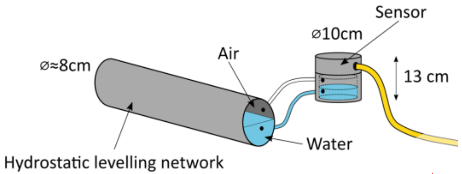

Infrastructure required

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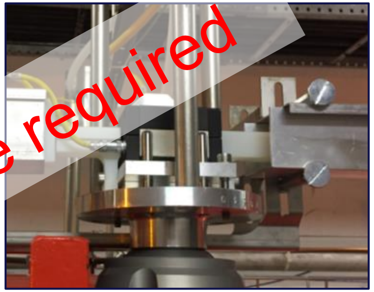
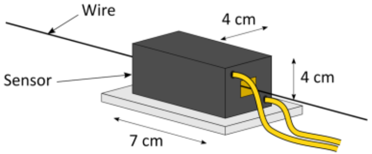
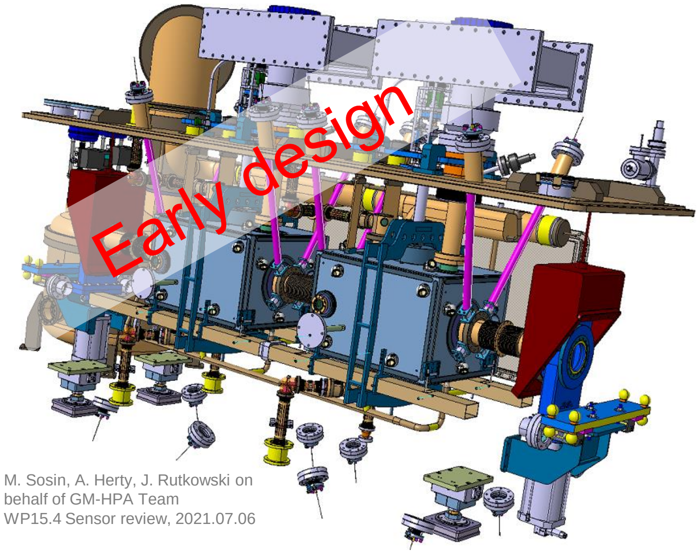




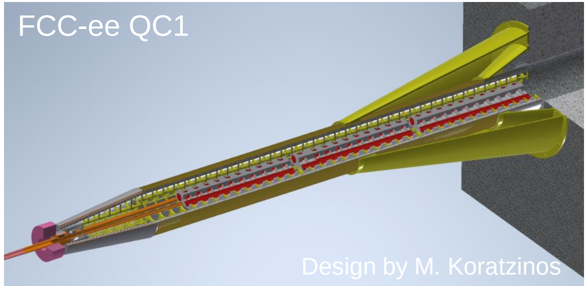


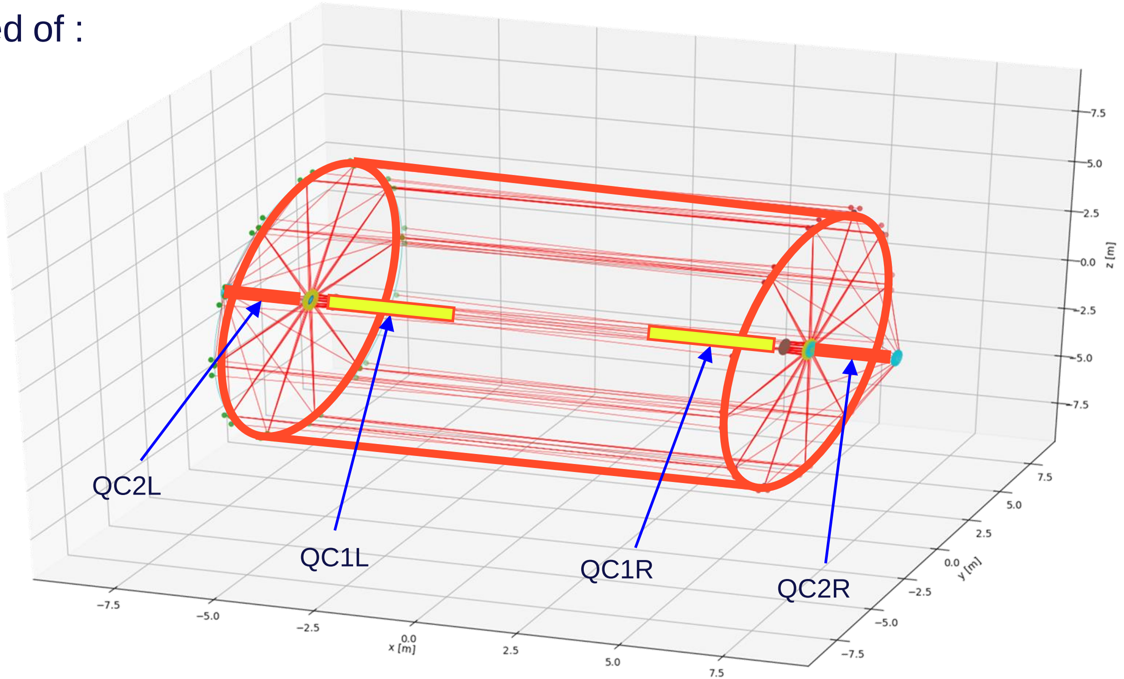
Early design

M. Sosin, A. Herty, J. Rutkowski on behalf of GM-HPA Team WP15.4 Sensor review, 2021.07.06

Proposition of a strategy for the alignment and monitoring of the MDI

- Alignment and monitoring system composed of :
  - External alignment system
  - Internal alignment system





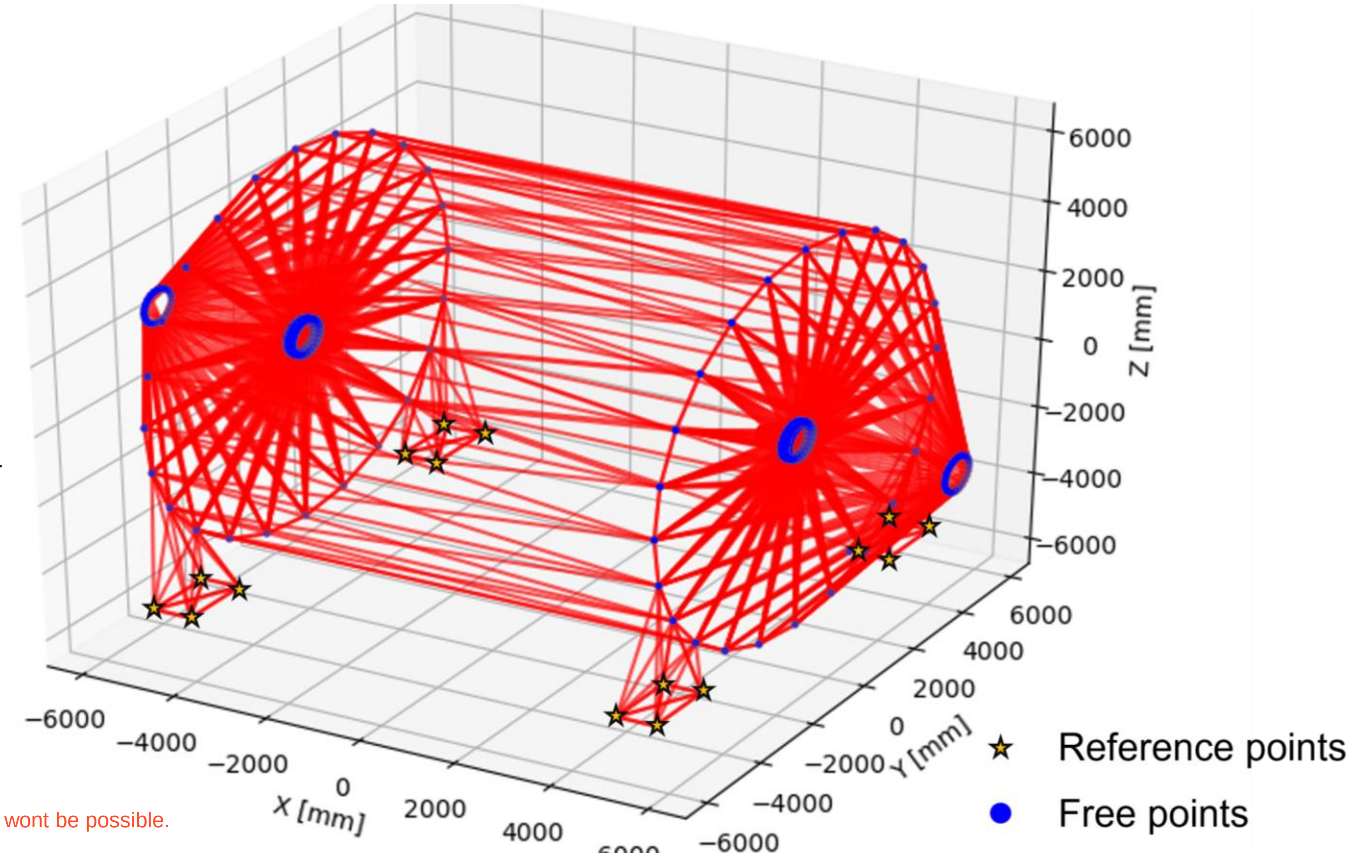
Goals :
- Monitor an interface at the end of QC1 to retrieve the position of internal component (monitored thanks to the internal monitoring system).
- Monitor the alignment between QC1 and QC2.
- Monitor the alignment between the inner components and the experiment solenoid.
- Monitor the alignment between the two sides of the experiment.

External alignment and monitoring system

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

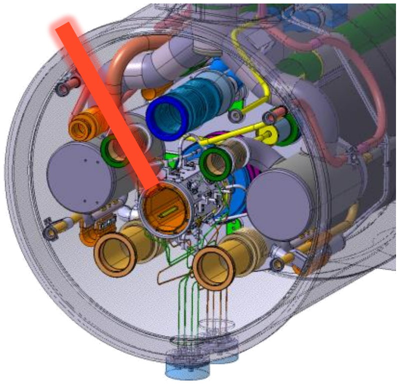
Goals :

- 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.



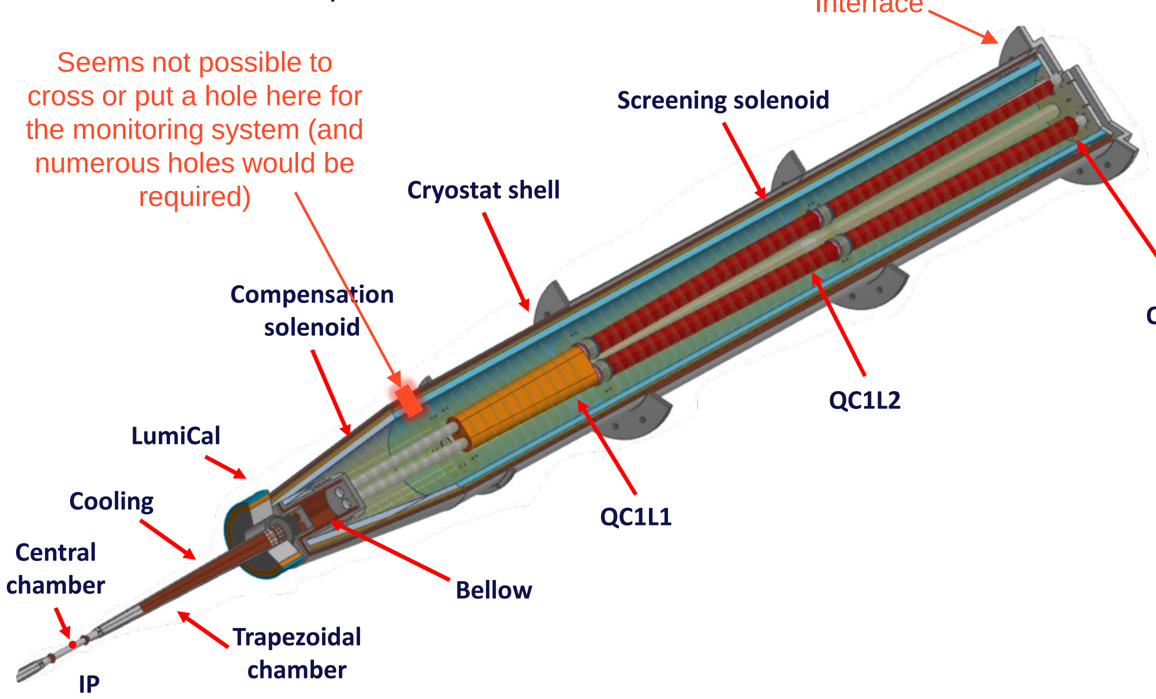
Optimal network : too much measurements, some (plenty) wont be possible.
Any update on the design would be much welcomed.

Internal alignment system

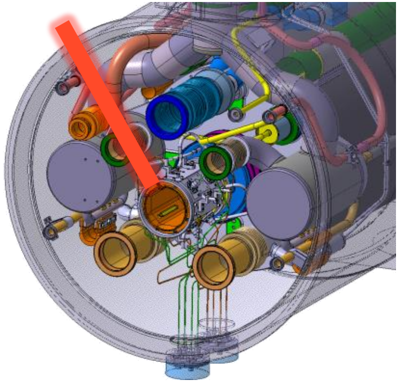


- Goal : monitor the deformation extremely precisely over the length of the assembly
- Create a network of points accurate enough so another system can measure from it onto the inner components

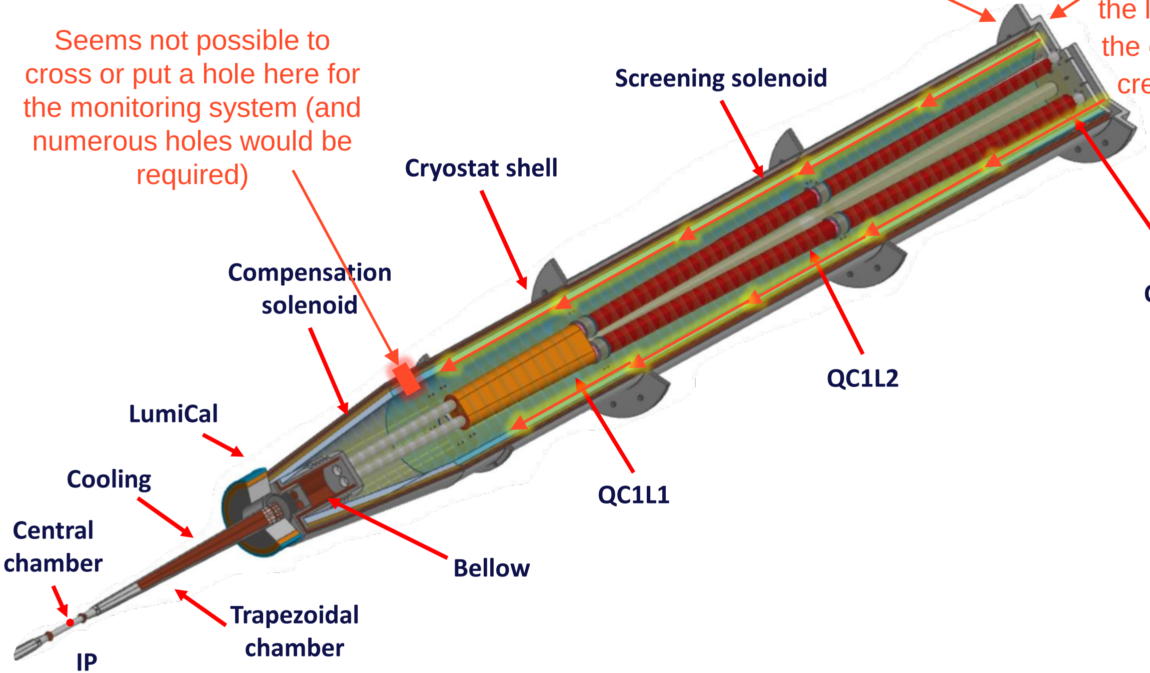
Seems not possible to cross or put a hole here for the monitoring system (and numerous holes would be required)



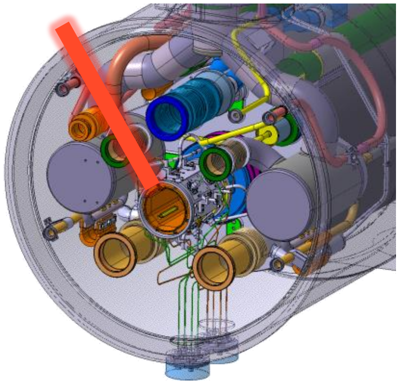
Internal alignment system



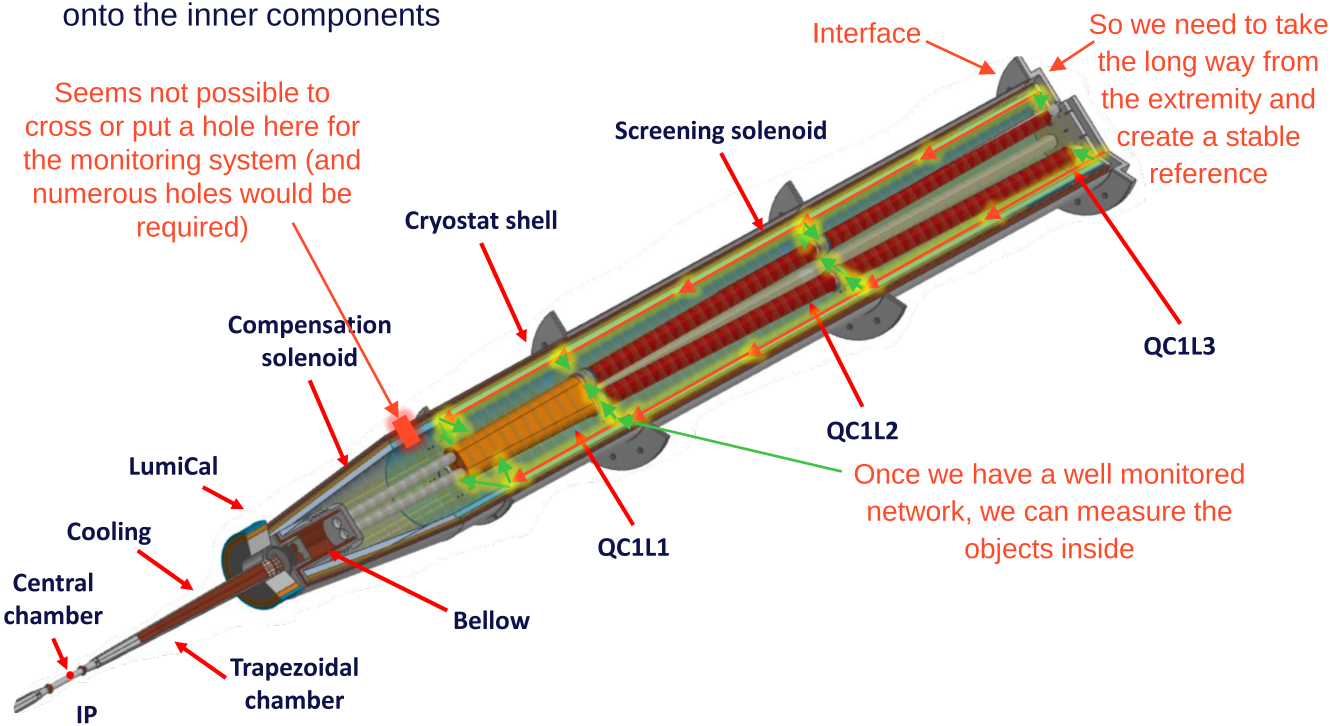
- Goal : monitor the deformation extremely precisely over the length of the assembly
- Create a network of points accurate enough so another system can measure from it onto the inner components



Internal alignment system



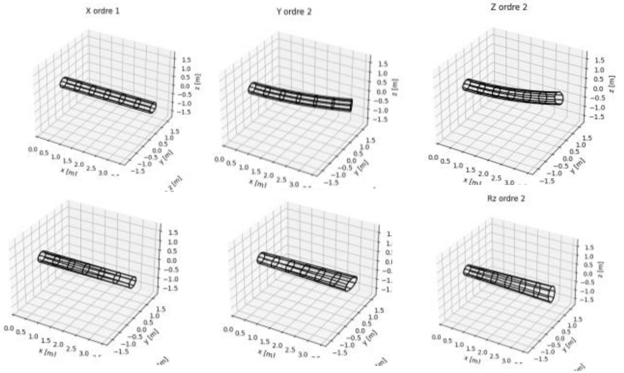
- Goal : monitor the deformation extremely precisely over the length of the assembly
- Create a network of points accurate enough so another system can measure from it onto the inner components

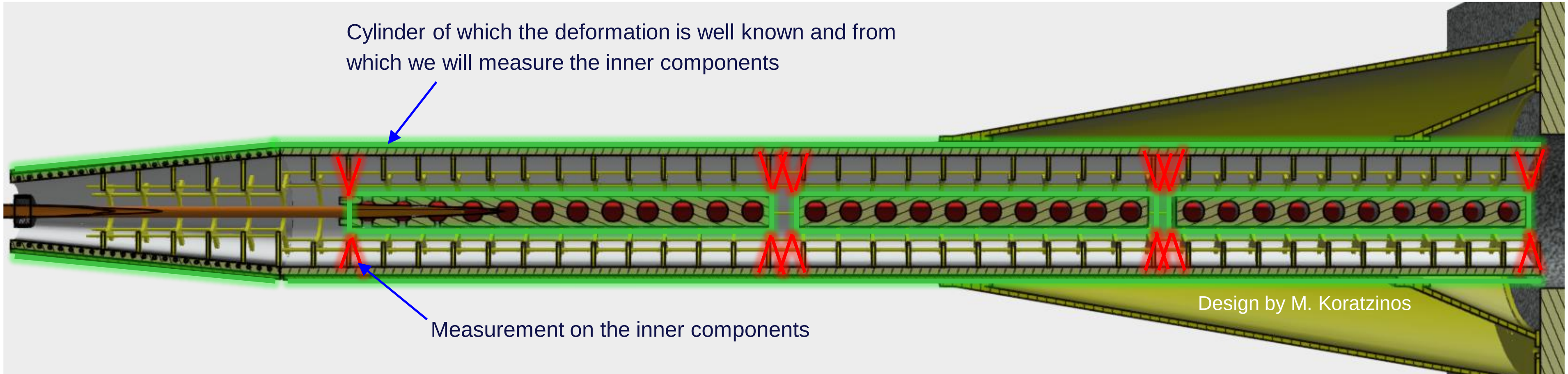


Internal alignment system

- Goal : monitor the deformation extremely precisely ove 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

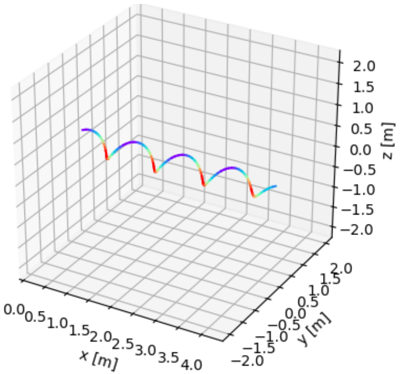




- Measurement system waiting for design update.

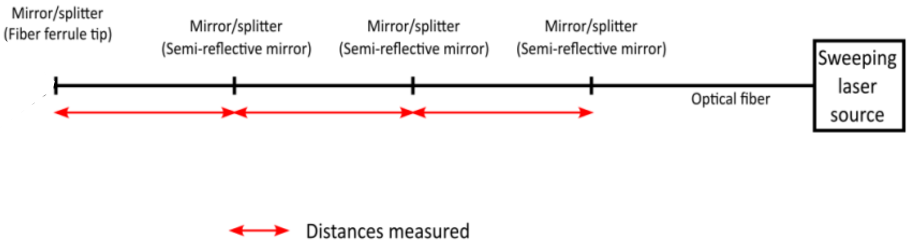
Deformation monitoring

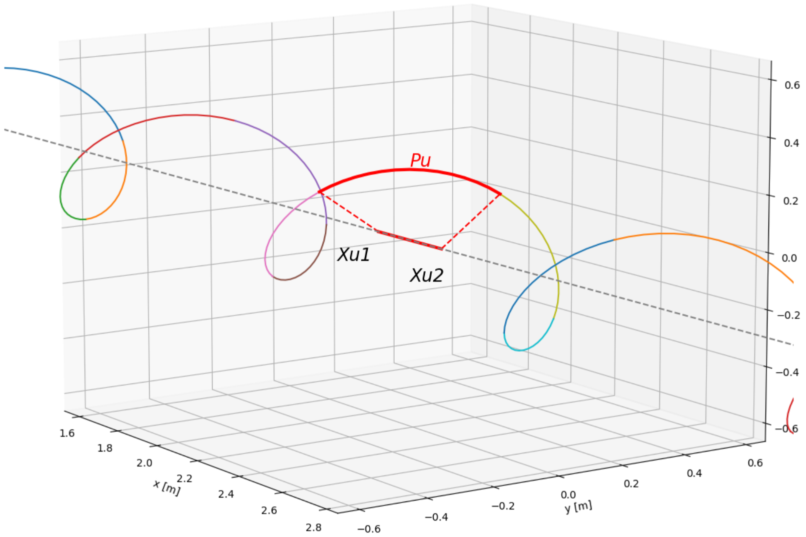
https://iopscience.iop.org/article/10.1088/1361-6501/acc6e3



- Optical fiber placed in a helix shape, separated in portion by semi-reflective mirrors, which can be simultaneously and independently measured
- Helixes defined by their length, radius, step, number and position of portions

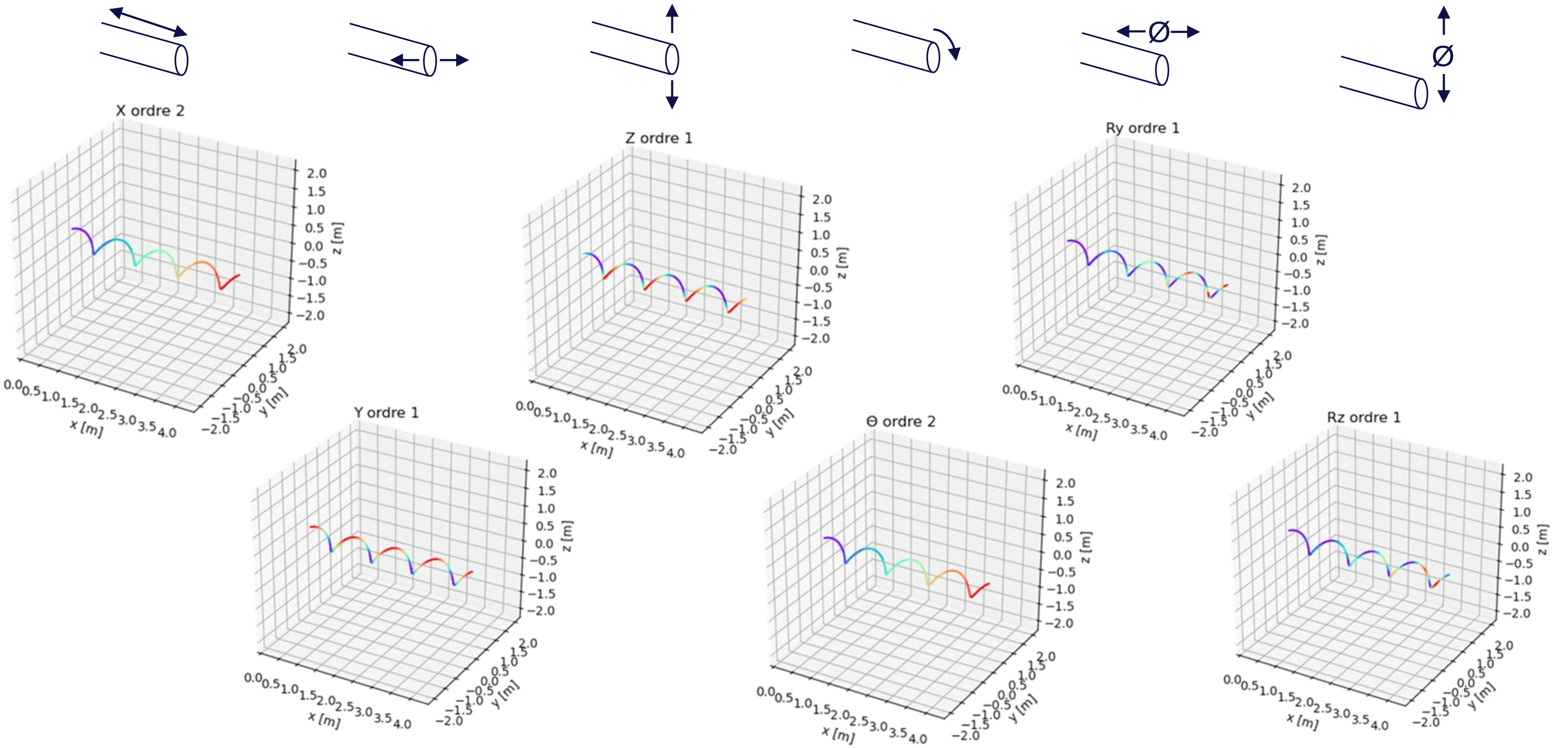
- Two technology available for such measurements :
  - SOFO (Surveillance d’Ouvrage par Fibre Optique) (locked at a prototype state)
  - In-line multiplexed and distributed FSI measurement (in development at CERN)





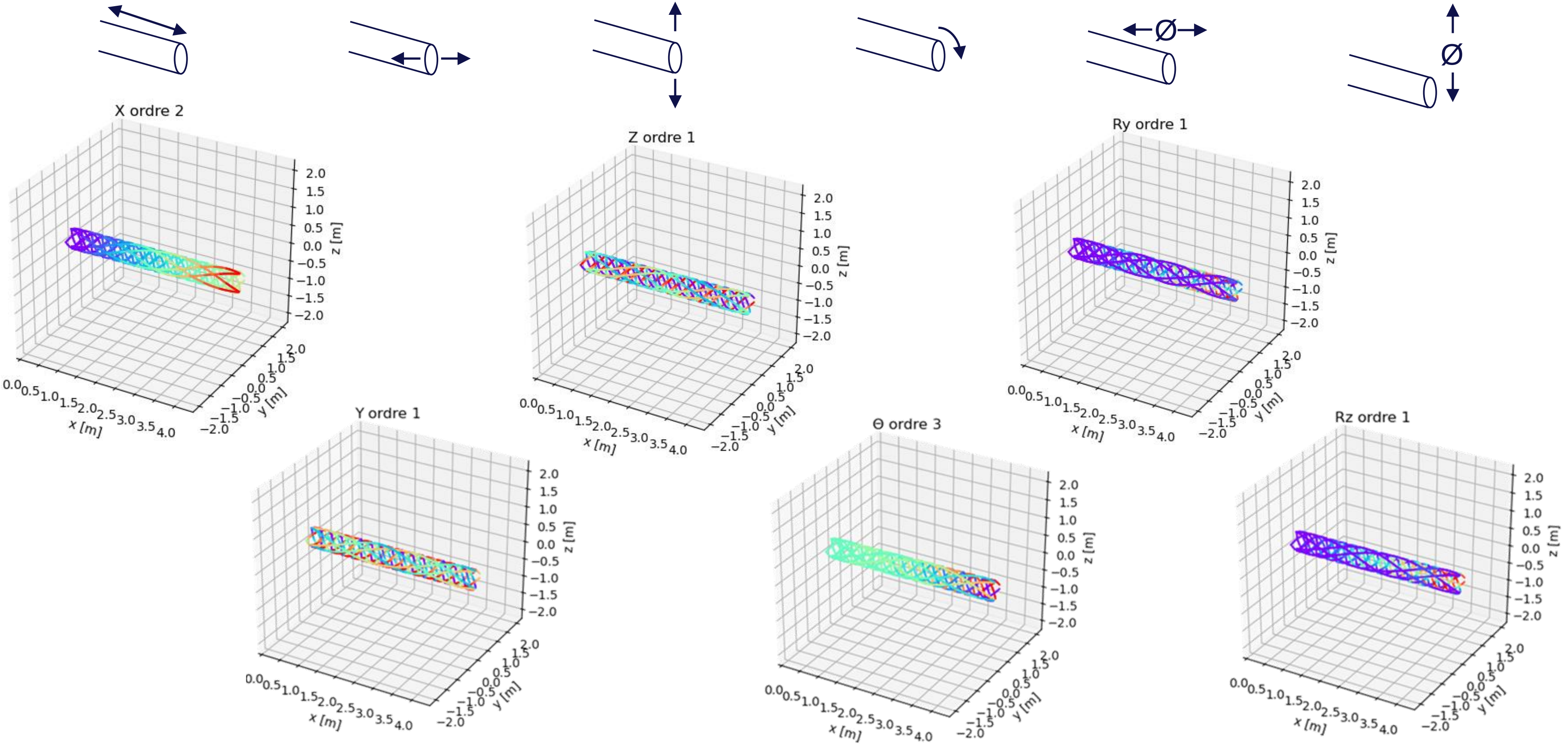
Deformation monitoring

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



Deformation monitoring

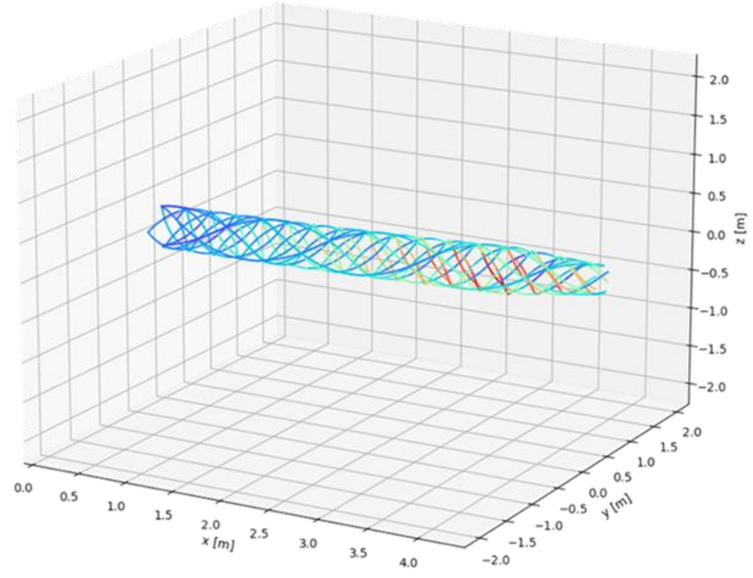
https://iopscience.iop.org/article/10.1088/1361-6501/acc6e3

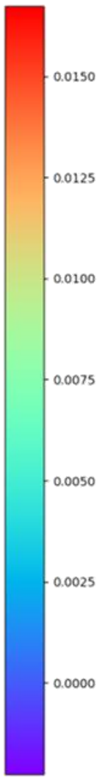


Deformation monitoring

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

Helixes observations
(= 3D lengths of portions)





+ equation of portion length as function of the deformation polynomials

Least square adjustment

→

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

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

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

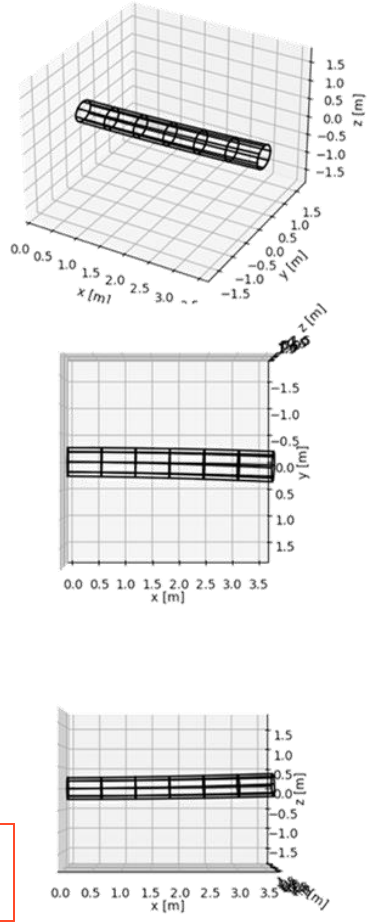
$$P_\theta(t) = \sum_{i=1}^{n} d_i t^i$$

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

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

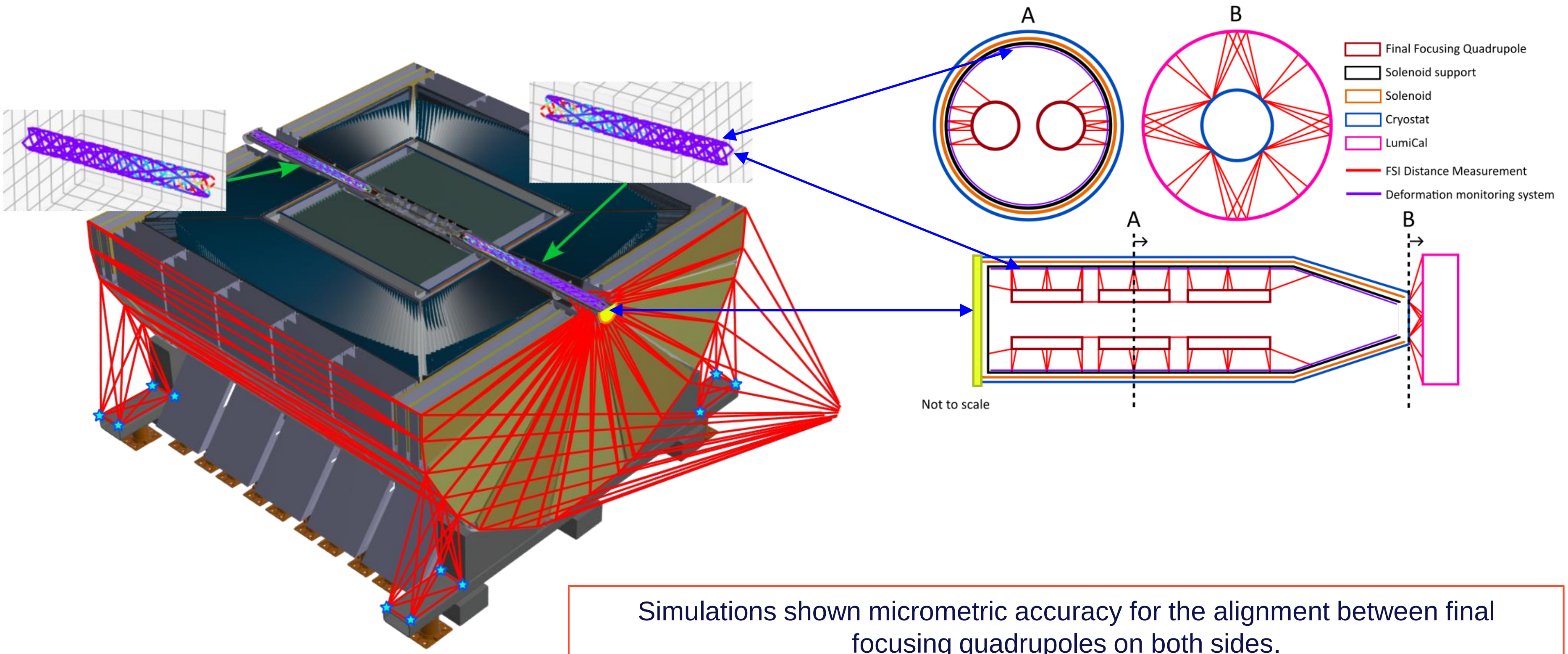
→

Cylinder deformations



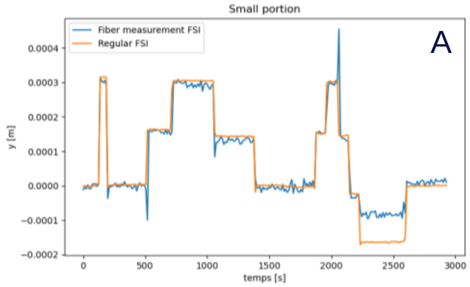
Simulations shown micrometric accuracy
To be confirmed by a prototype

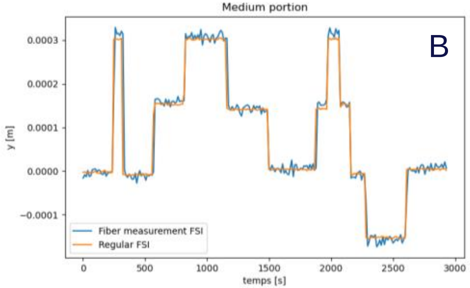
Full alignment and monitoring system

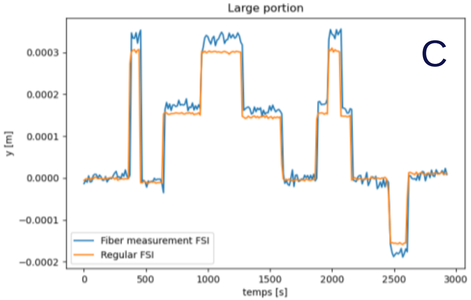


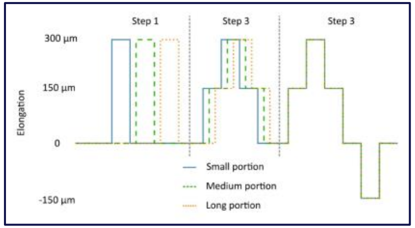
Simulations shown micrometric accuracy for the alignment between final focusing quadrupoles on both sides.
To be refined with upcoming updates of the detector design.

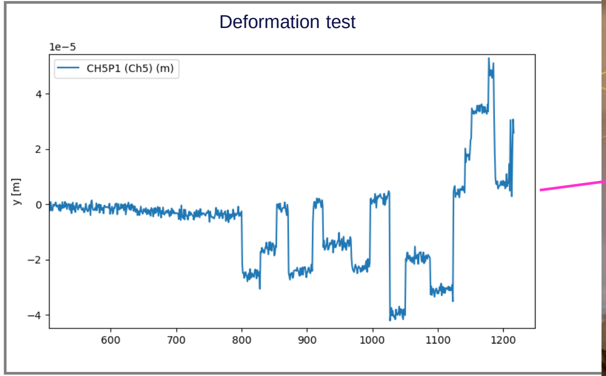
Prototype testing

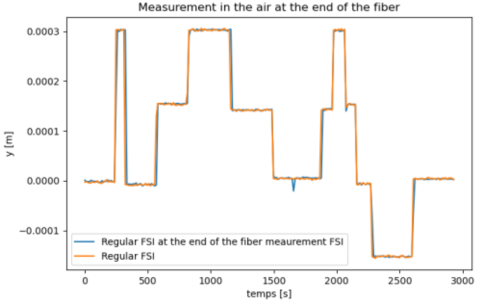


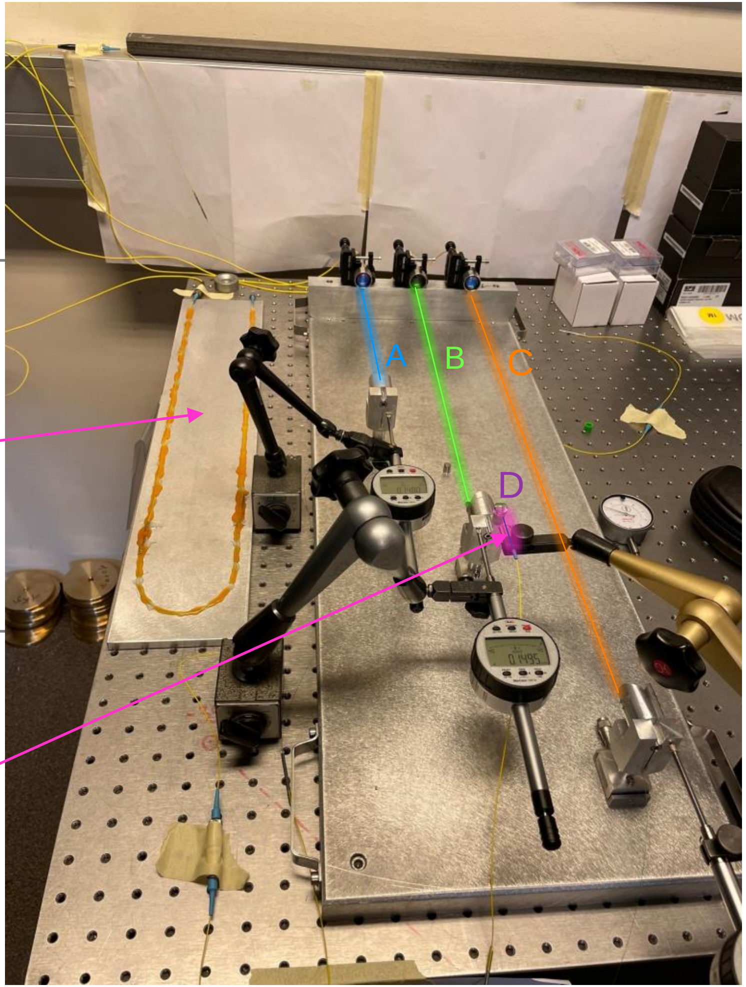






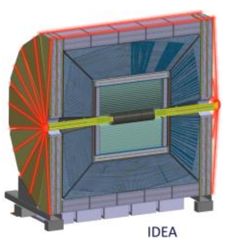


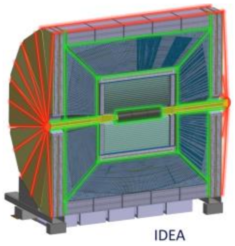




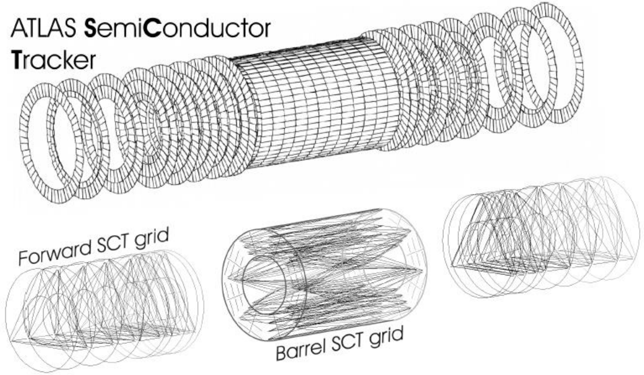
Alignment strategy proposal

The MDI alignment system could be seen as a standalone backbone, on which sub-system alignment systems could connect.



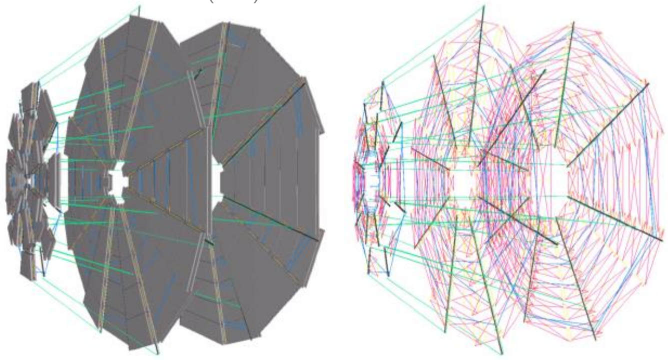


Gibson, S. M., et al. "Monitoring the heart of ATLAS using Frequency Scanning Interferometry." Proceedings of the Eighth International Workshop on Accelerator Alignment, CERN, Geneva. 2004.



- Layout of the alignment system in the silicon detector modules in the ATLAS SemiConductor Tracker.
- Use of Frequency Scanning Interferometry.
- Relative alignment of the detector parts up to bellow 50µm

Aefsky, S., et al. "The optical alignment system of the ATLAS muon spectrometer endcaps." Journal of Instrumentation 3.11 (2008): P11005.



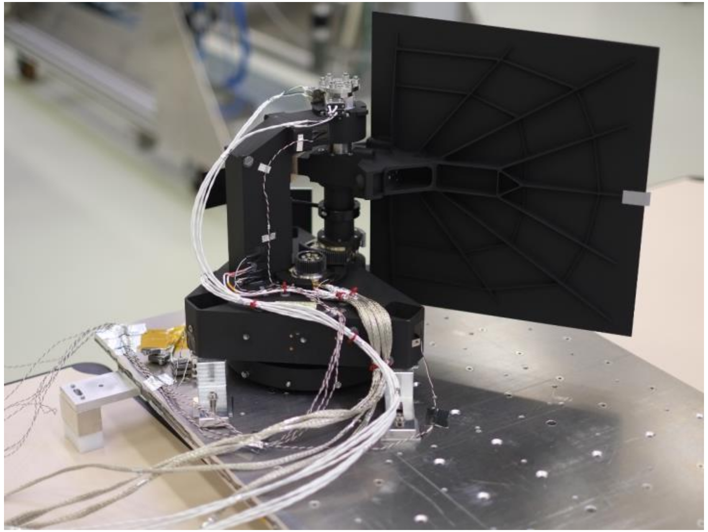
- Layout of the alignment system in one muon spectrometer endcap.
- Use of optical alignment systems.
- Relative alignment of the detector parts up to bellow 100µm

⇒ Thanks to the detectors it is possible to measure the position of the IP and/or the position of the beam (relatively accurately with respect to the detector part)
⇒ This could be linked with the alignment system installed on the accelerator, allowing to link the position of the IP, the LumiCals and the FFQ.
⇒ Would be a win-win to link with relative measurement the machine and the detector (especially for the dense FCC-ee MDI).

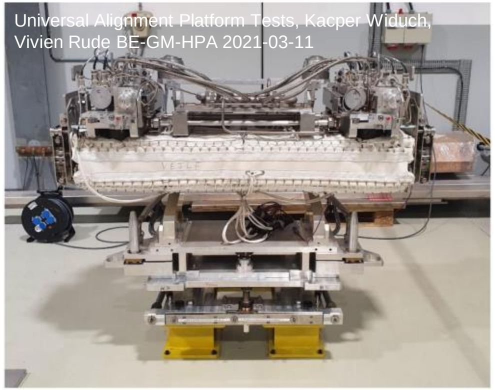
Re-adjustment system

The EUCLID VIS Read-out Shutter Unit, which will operate in space (very similar to conditions inside the MDI)

- 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.



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

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.

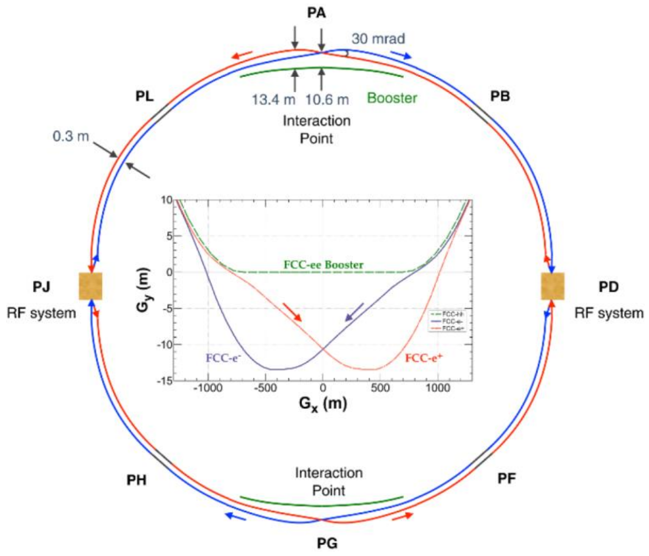
Systems to work in these conditions exist, the difficulty is to <u>quantify their advantage compared to a loss of luminosity due to any misquantified misalignment value or to the need to dismount, disassemble, realign, reassemble and remount the assembly.</u>

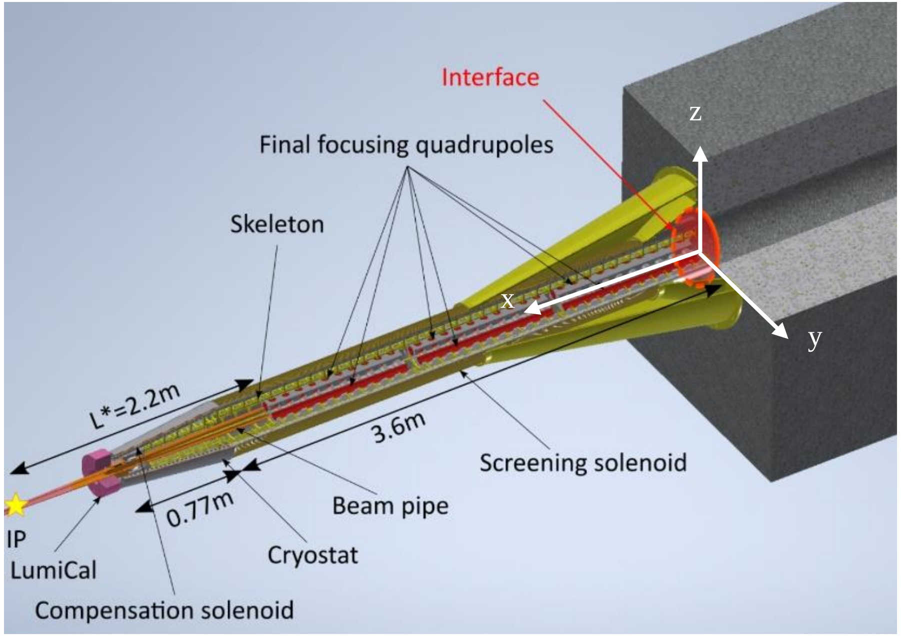
Thank you for your attention

Spares

Coordinate system definition

Deformations are defined in the (O, Ox, Oy, Oz) Euclidean system linked to the interface plate, shown in Figure 11. The origin of this system is the centre of the plate, the Ox is perpendicular to the plate (and ideally is the bisector of the crossing angle between the two beams), Oy is the intersection of the plane of the plate and the plane formed by the incoming and outgoing beams and Oz is the last vector in order to form an oriented orthogonal system.





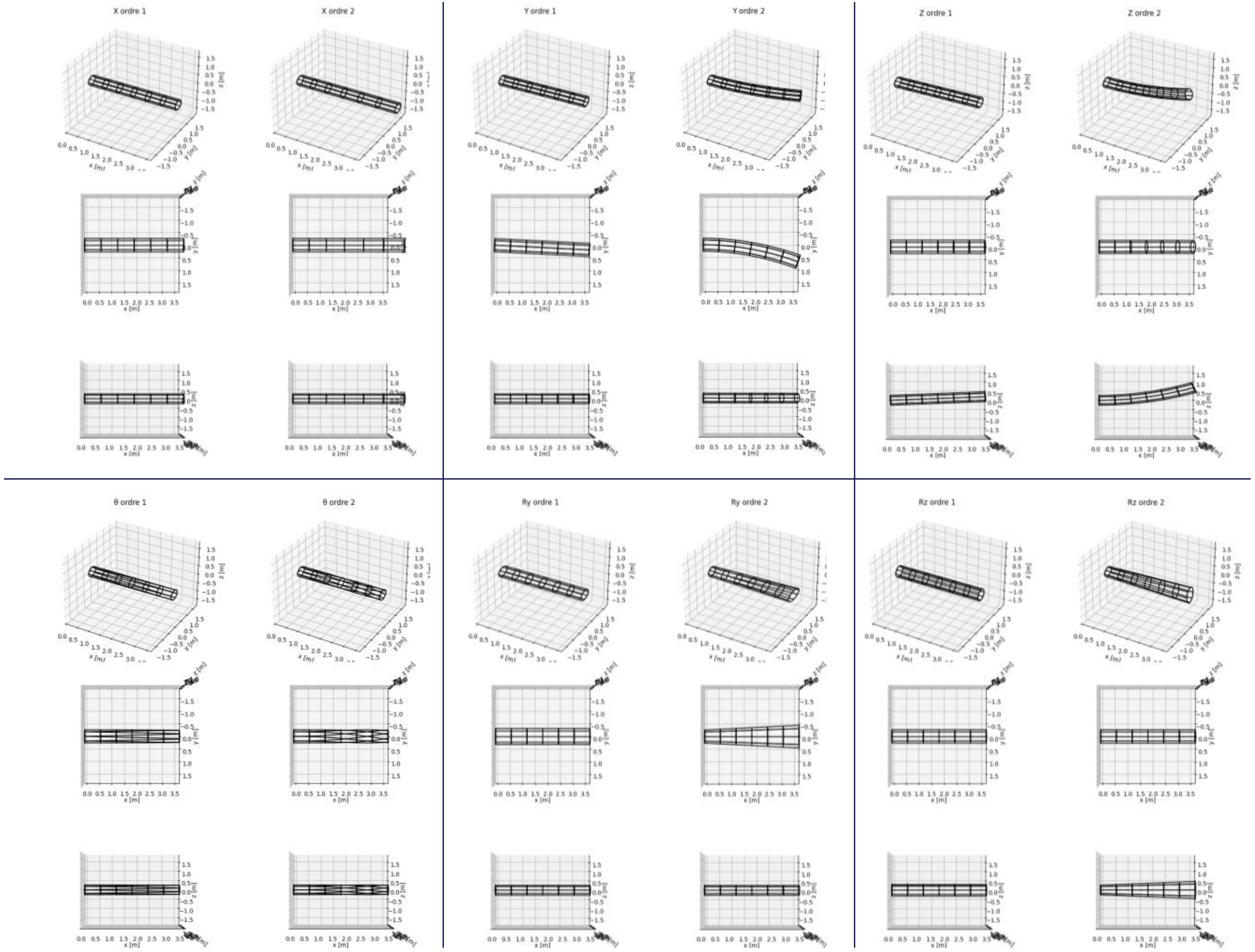
Deformation model

- Polynomial (classic model, easy to manipulate)
- 6 polynomial of degree 4
  - Elongation
  - Radial deformation (horizontal)
  - Radial deformation (vertical)
  - Torsion
  - Radius deformation (horizontal)
  - Radius deformation (vertical)

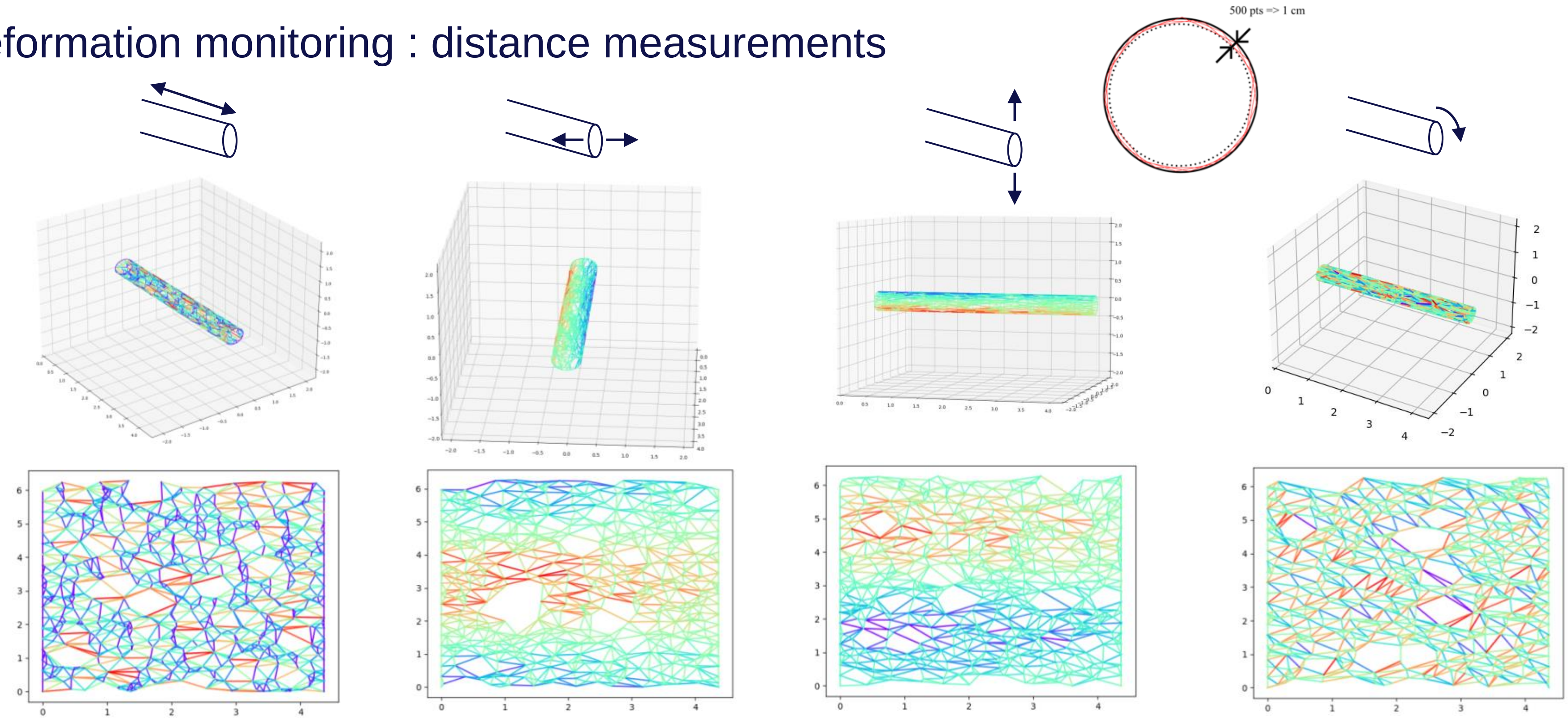
$$P_x(t) = \sum_{i=1}^{n} a_i t^i \qquad P_\theta(t) = \sum_{i=1}^{n} d_i t^i$$

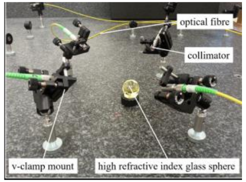
$$P_y(t) = \sum_{i=1}^{n} b_i t^i \qquad P_{ry}(t) = \sum_{i=1}^{n} e_i t^i$$

$$P_z(t) = \sum_{i=1}^{n} c_i t^i \qquad P_{rz}(t) = \sum_{i=1}^{n} f_i t^i$$



Deformation monitoring : distance measurements





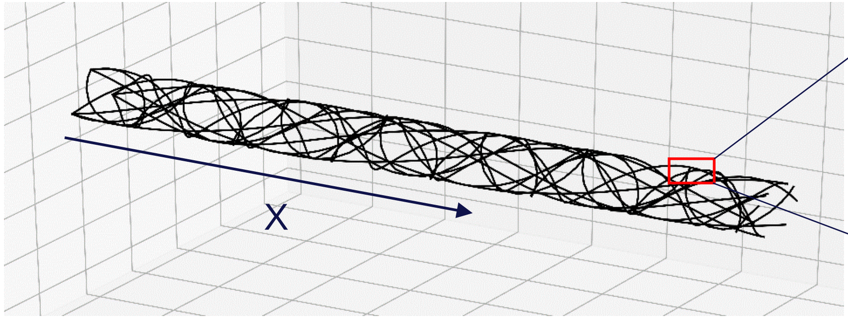
Gayde, J-Ch, and Kamugasa, S., "Evaluation of Frequency Scanning Interferometer Performances for Surveying, Alignment and Monitoring of Physics Instrumentation." (2018): WEPAF069.

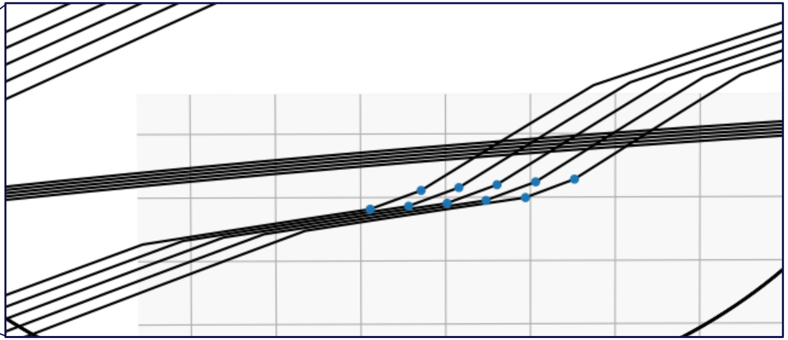
Advantages :
- Usual distance measurement
- Rather simple equations

Disadvantages :
- Takes a lot a space in the cryostat
- Rather difficult to implement
- Lot of R&D required

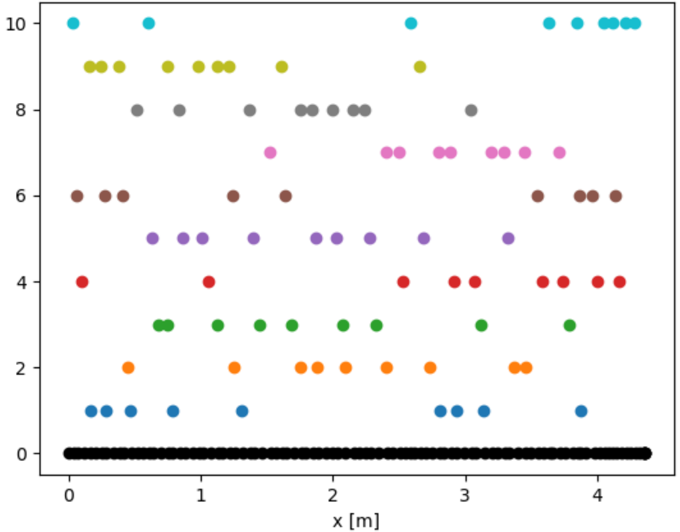
It has been put aside for now as it is less realistic than the other system and easier to come back on if needed (simpler equations)

Additional implementation : multiple helixes and realistic intersection





Automatic intersection computation and automatic modification of the radius for helixes going above another one.



Automatic position determination of the retroreflectors along the fibers, in order to have different lengths and a homogeneous coverage along the cylinder length.

Known precision requirements for the inner components

"Final Focusing quads misalignment (QC1_1-QC1_3 and QC2_1-QC2_2) (if not respected, beams do not collide):

- Geodesy : transverse shift of FF quads with sigma xy= 25µm
- vibrations : transverse shift of FF quads with sigma xy= 0.1µm

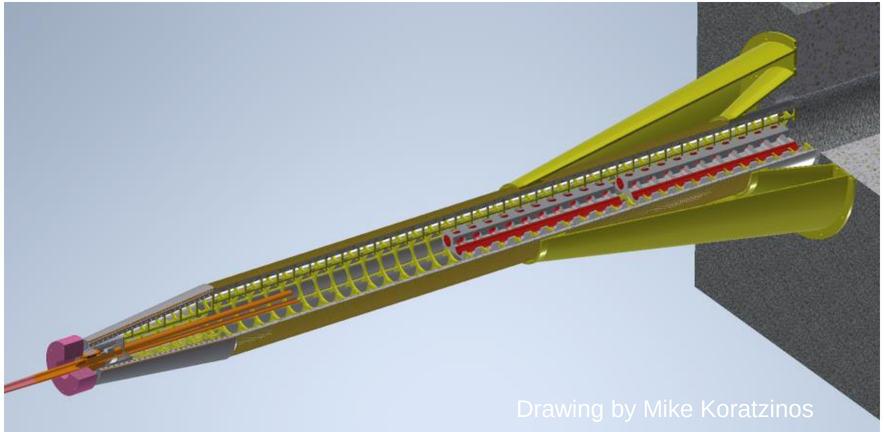
IR BPM misalignment (if not respected, beams do not collide) :

- geodesy : transverse shift of BPM with sigma xy= 25µm
- vibrations : errors of BPM reading with sigma xy= 0.1µm"

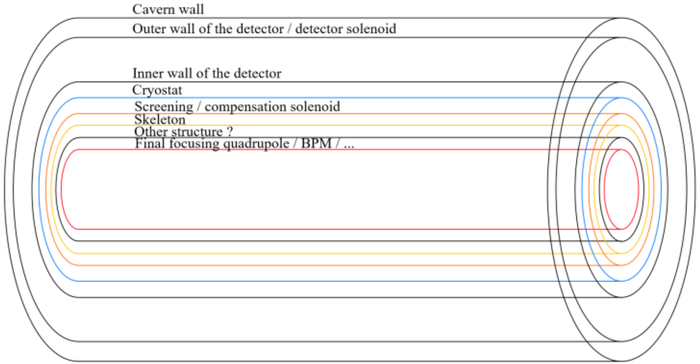
" The distance between the two calorimeters has to be measured to 110 µm"

"Distance LumiCal/ nominal IP to be controlled/ measured to ~50µm level"

"IR quadrupoles and sextupoles (75µm in radial and longitudinal, 100µrad roll), BPM (40µm in radial and 100µrad for the roll relative to quadrupole placement)."



"For a 1mrad tilt of the detector solenoid (wrt the rest of the system – beam, screening and compensation solenoid) the corresponding uncorrected distortion is unacceptably large."



"Alignment accuracy of SC magnets = 100µm"

"Internal misalignment should be better than 30µm"

"Measurement of the component's position inside the detector is needed"

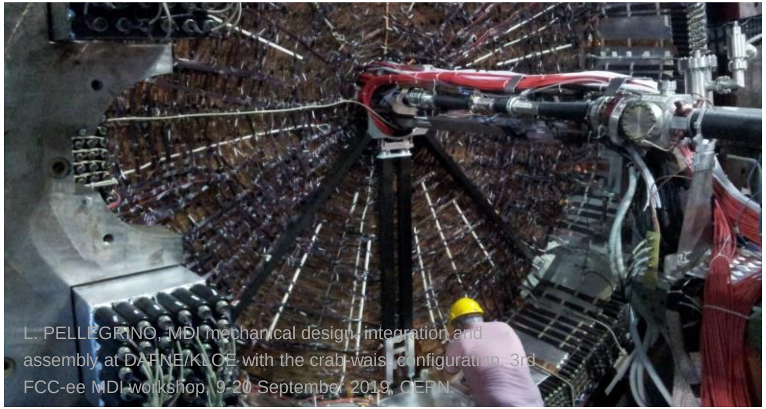
DAΦNE/KLOE MDI

Alignment (strongly summarized)

1. Alignment of the elements on the girder (part of the cylinder) thanks to a laser tracker.

2. Installation of the cylinder inside the experiment, and re-alignment of the articulated cylinder thanks to laser tracker target supports and screws.

3. Occasional partial check, can't be regular because of obstacles on the lines of sight of the laser tracker targets (cables, pipes …)

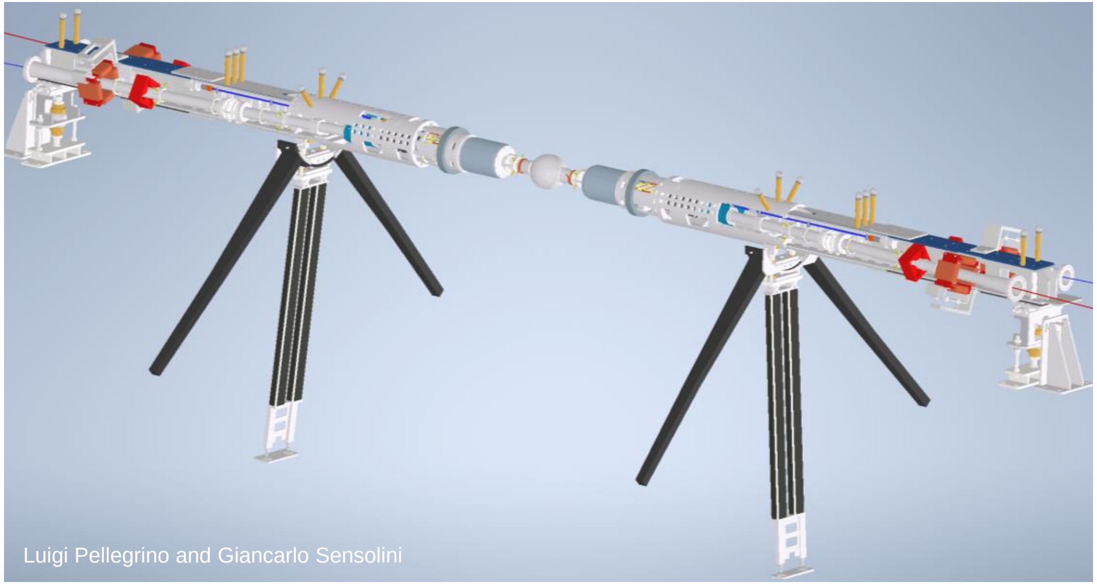


L. PELLEGRINO, MDI mechanical design, integration and assembly at DAFNE/KLOE with the crab waist configuration, 3rd FCC-ee MDI workshop, 9-20 September 2019, CERN.

$L^* = 0.3$ m
$\theta_{cross} = 50$ mrad

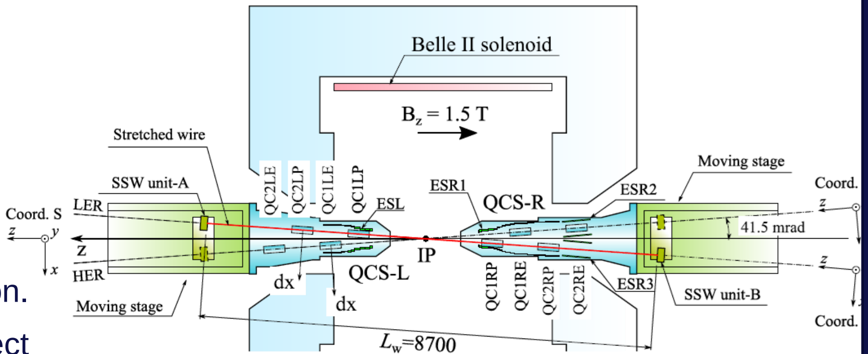
Beam size :
$\sigma^*_x = 250\ \mu m$
$\sigma^*_y = 3.1\ \mu m$
$\sigma_z = 15$ mm

Alignment aim :
$\sim 100\ \mu m$



Luigi Pellegrino and Giancarlo Sensolini

SuperKEKB/Belle II MDI



Arimoto, Yasushi, et al. "Magnetic measurement with single stretched wire method on SuperKEKB final focus quadrupoles." IPAC'19, Melbourne, Australia, 19-24 May 2019

Alignment (strongly summarized)

1. Pre-alignment of the components before installing them in the cryostat, fiducialization.
2. Alignment of the cryostat (QCS) with respect to the beam line.
3. Installation of the cryostats inside the experiment.
4. Check of the position of the inner magnets thanks to the Single Stretched Wire (SSW) method coupled with capacitive measurement between the cryostat and the experiment before the run of the machine.

Final correction on the beam thanks to corrector magnets.

Table 2: Measured x-Offset, y-Offset and Roll Angle Relative to Design Parameters. Units of length and angle are mm and mrad, respectively.

Quads.	X-offset Solenoid on	X-offset Solenoid off	Y-offset Solenoid on	Y-offset Solenoid off	$\Delta\theta$ Solenoid on
QC1LE	−0.21	−0.16	−0.29	−0.56	−1.6
QC2LE	0.13	0.11	−0.54	−0.68	−1.5
QC1RE	0.25	0.14	−0.37	−0.54	0.0
QC2RE	0.08	0.07	−0.58	−0.63	−0.7
QC1LP	−0.03	−0.14	−0.21	−0.38	−1.7
QC2LP	−0.31	−0.41	−0.68	−0.83	−4.0
QC1RP	0.64	0.69	−0.30	−0.43	2.0
QC2RP	0.43	0.45	0.04	−0.19	−1.7

Arimoto, Yasushi, et al. "Magnetic measurement with single stretched wire method on SuperKEKB final focus quadrupoles." IPAC'19, Melbourne, Australia, 19-24 May 2019

Many thanks to Mika Masuzawa for all the information on SuperKEKB alignment.

N. Ohuchi, "Final-Focus Superconducting Magnets for SuperKEKB", IPAC 18, 01/05/2018

$L^* = 1.22$ m HER
$\theta_{cross} = 83$ mrad

Beam size :
$\sigma^*_x = 10.7\,\mu m$
$\sigma^*_y = 0.062\,\mu m$
$\sigma_z = 6$ mm

Alignment aim :
~ 100 µm

$L^* = 0.76$ m LER
$\theta_{cross} = 83$ mrad

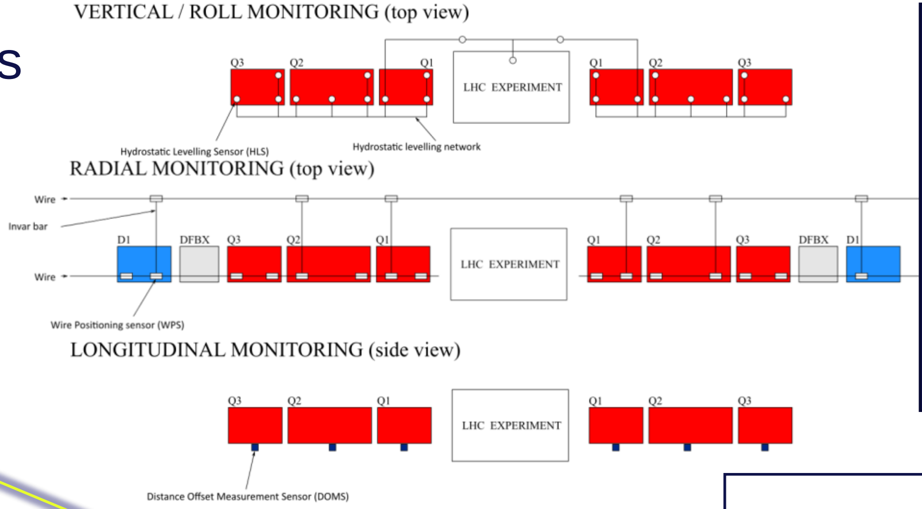
Beam size :
$\sigma^*_x = 10.1\,\mu m$
$\sigma^*_y = 0.048\,\mu m$
$\sigma_z = 5$ mm

Alignment aim :
~ 100 µm

Summary of MDI challenges

LHC/ATLAS MDI

Alignment (strongly summarized)

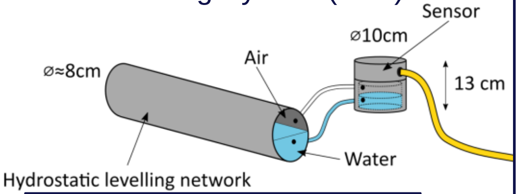


$L^* = 23$ m
$\theta_{cross} = 285$ µrad

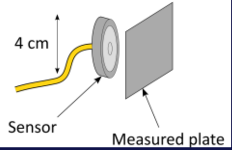
Beam size :
$\sigma^*_x = 16.7$ µm
$\sigma^*_y = 16.7$ µm
$\sigma_z = 75$ mm

Alignment aim :
~ 100 µm

Hydrostatic Leveling System (HLS)

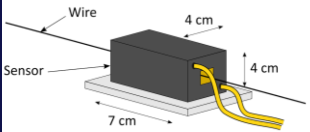


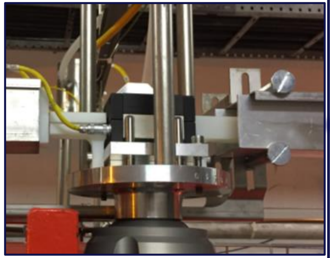
Distance Offset Measurement Sensor (DOMS)



Remotely Controlable Actuators

Wire Positioning Sensor (WPS)





CLIC MDI

No solution found yet.

Proposed solution

QD0 sticks far in the detector and requires :

- stable support
- Power, cooling
- Antisolenoid
- Vacuum elements
- Access, connection disconnection

The problem has evolved throughout the years :

- Only one detector
- QD0 have been removed from the experiment

2 µm pre-alignment over 500m (L^*=3,5m)
=> 10 µm pre-alignment over 500m (L^*=3,5m)
=> 10 µm pre-alignment over 500m (L^*=6,5m)

$L^* = 3.5$ m 500 GeV
$\theta_{cross} = 20$ mrad

Beam size :
$\sigma^*_x = 0.202$ µm
$\sigma^*_y = 0.0023$ µm
$\sigma_z = 0.072$ mm

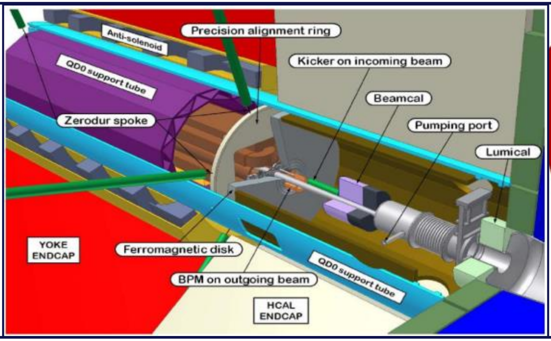
Alignment aim :
~ 10 µm

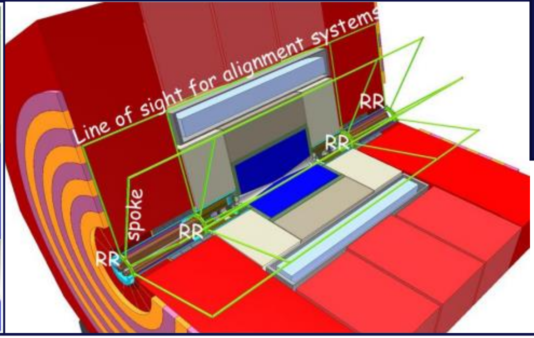
$L^* = 3.5$ m 3TeV
$\theta_{cross} = 20$ mrad

Beam size :
$\sigma^*_x = 0.040$ µm
$\sigma^*_y = 0.001$ µm
$\sigma_z = 0.044$ mm

Alignment aim :
~ 10 µm

Attempt :
Monitoring QD0 thank to zerodur rods and optical alignment system inside the detector. But it was not shown to work.

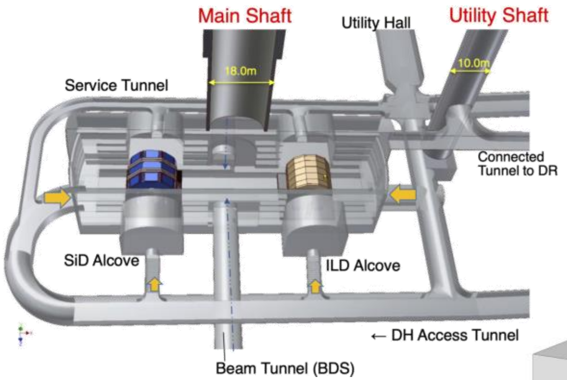




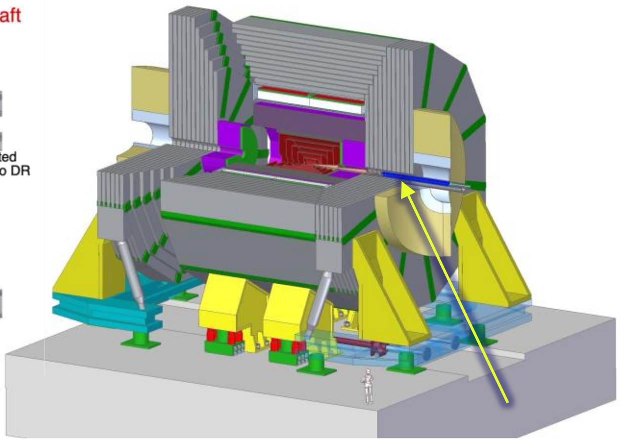
CLIC Machine Detector Interface, MDI mini workshop, HKUST IAS, Philip Burrows on behalf of Lau Gatignon, 2020

ILC MDI

Introduction



Roman Poschl, (Selected) MDI Issues of ILD, MDI Workshop at IAS Conference, 01/2020, Hong Kong



Marcel Stanitzki, The SiD Detector – Machine Backgrounds, 01/2020, Hong Kong

$L^* = 3.5$ m 250 GeV
$\theta_{cross} = 14$ mrad

Beam size :
$\sigma^*_x = 0.516\ \mu m$
$\sigma^*_y = 0.0077\ \mu m$
$\sigma_z = 0.300$ mm

Alignment aim :
~ 20 µm

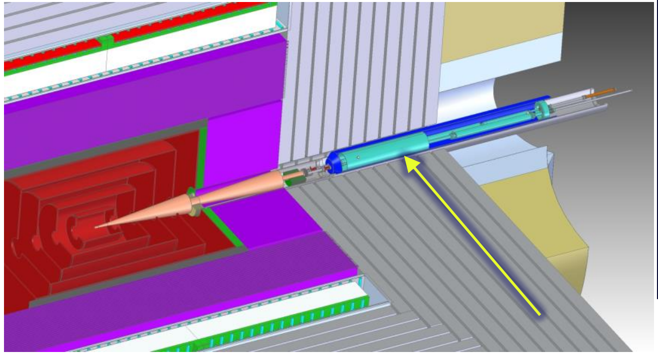
$L^* = 3.5$ m 500 GeV
$\theta_{cross} = 14$ mrad

Beam size :
$\sigma^*_x = 0.474\ \mu m$
$\sigma^*_y = 0.0059\ \mu m$
$\sigma_z = 0.300$ mm

Alignment aim :
~ 20 µm

Similar to the CLIC MDI :
- 2 detectors in push-pull configuration,
- 2 different L*, both < detector size

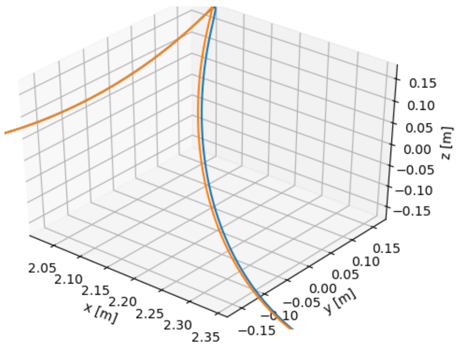
(And it is still the case)
- Alignment precision of 20 µm as requirement for QD0 prealignment system



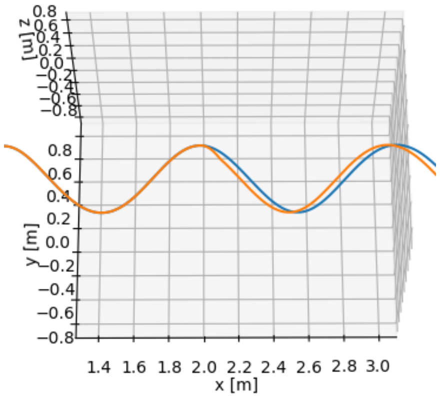
Marcel Stanitzki, The SiD Detector – Machine Backgrounds, 01/2020, Hong Kong

Additional implementation

Helix installation error models



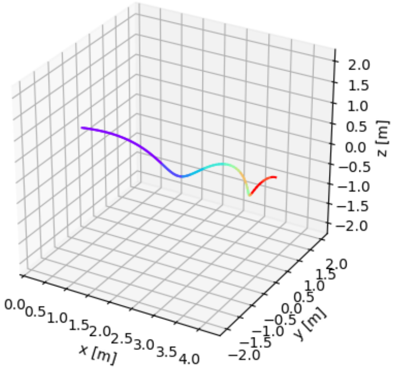
Punctual step error, but catches with theoretical position



Punctual step error implying a offset for the rest of the helix length

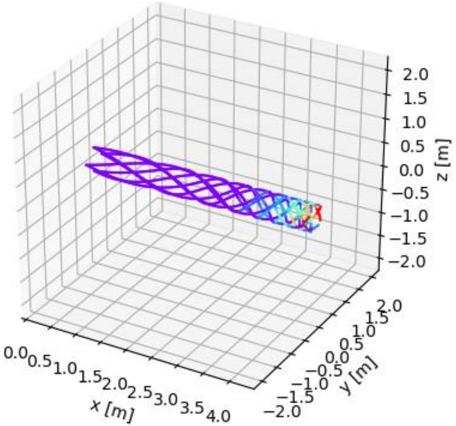
Easily seen in the least square adjustment residues (lot of redundancy)

Variable step helixes



Ex : Smaller step as it goes forward inside the detector

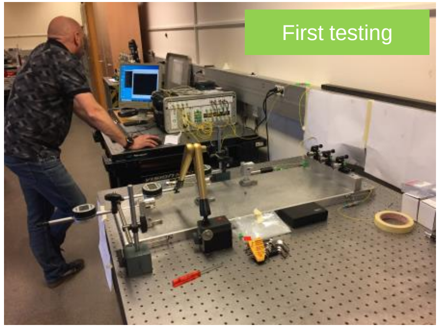
Allow to choose where to have more dense or more precise measurements



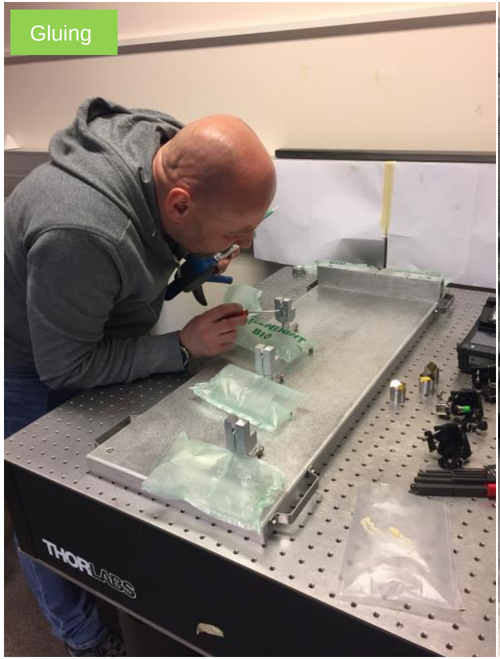
Model implemented and working

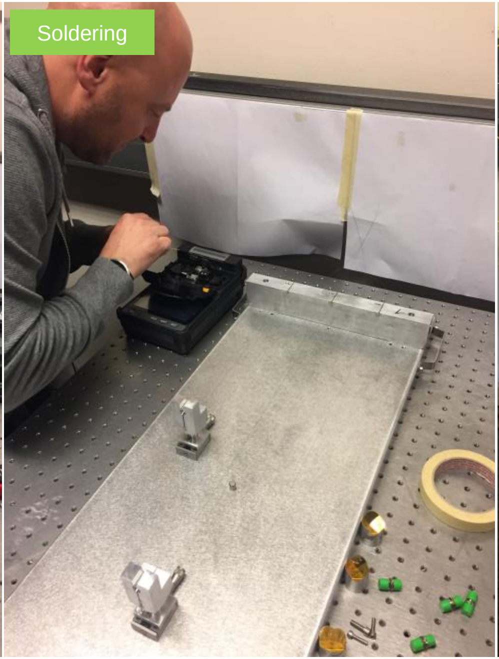
Additional tests to be done (comparison between full variable step network, hybrid variable and fix step network, full fixed step network)

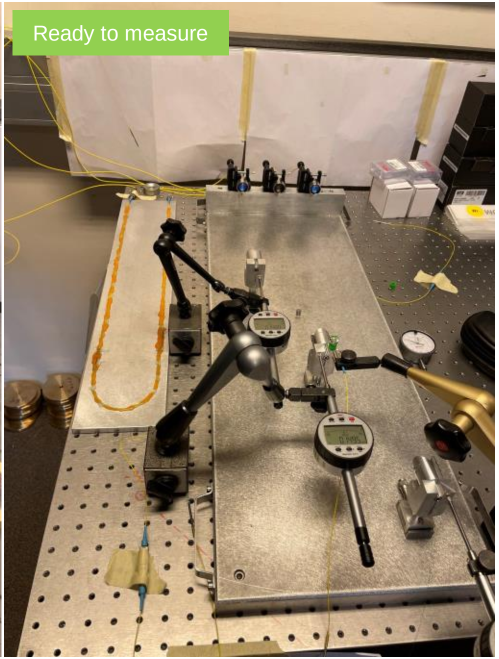
FSI “in-fiber” prototype and first tests



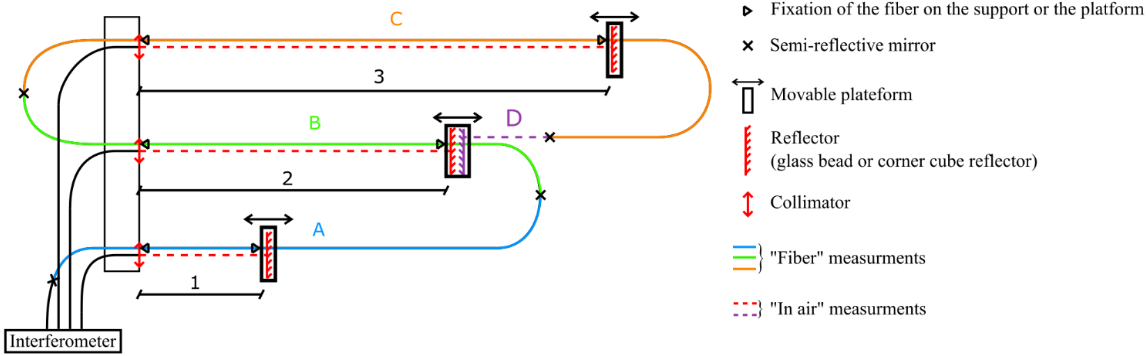
- A prototype of the “in-fiber” FSI have been build and a testing bench assembled to test it.
- First tests have been done and additional ones are ongoing.

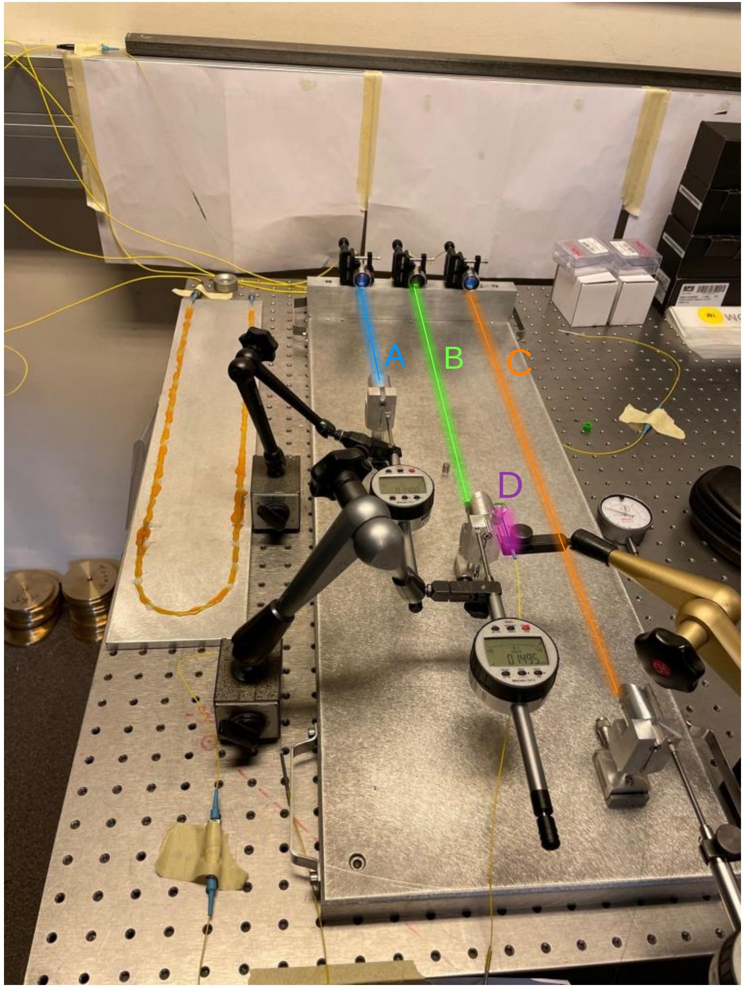






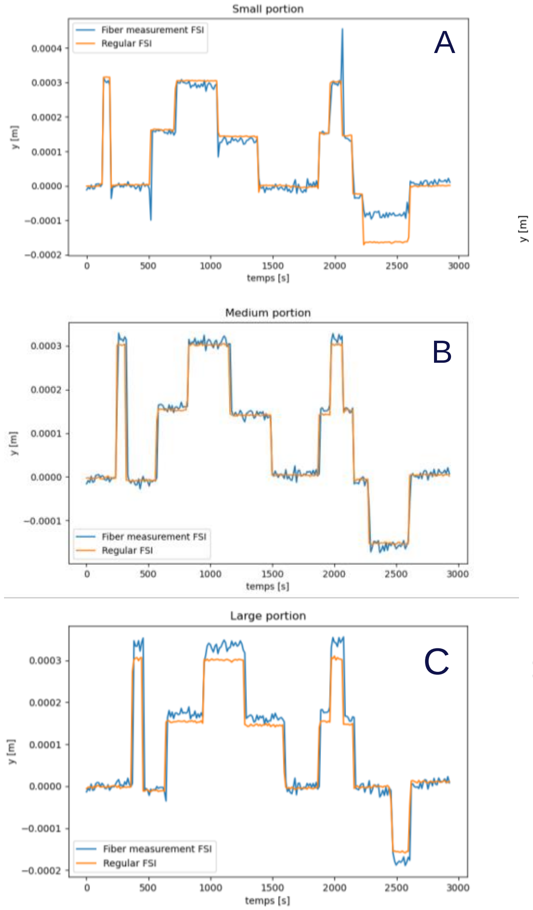
FSI “in-fiber” prototype and first tests

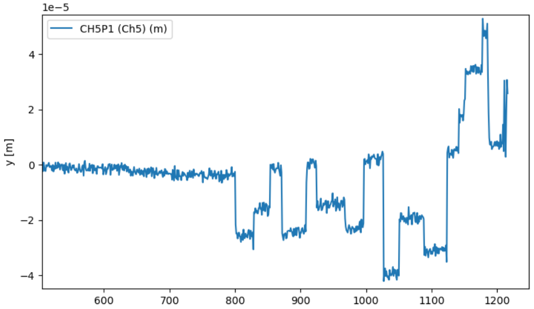


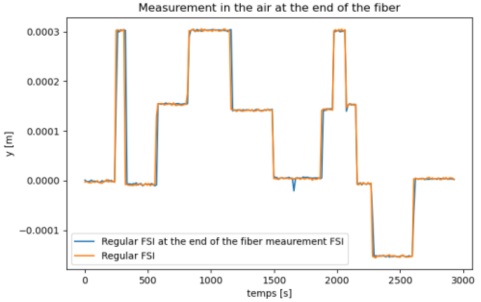


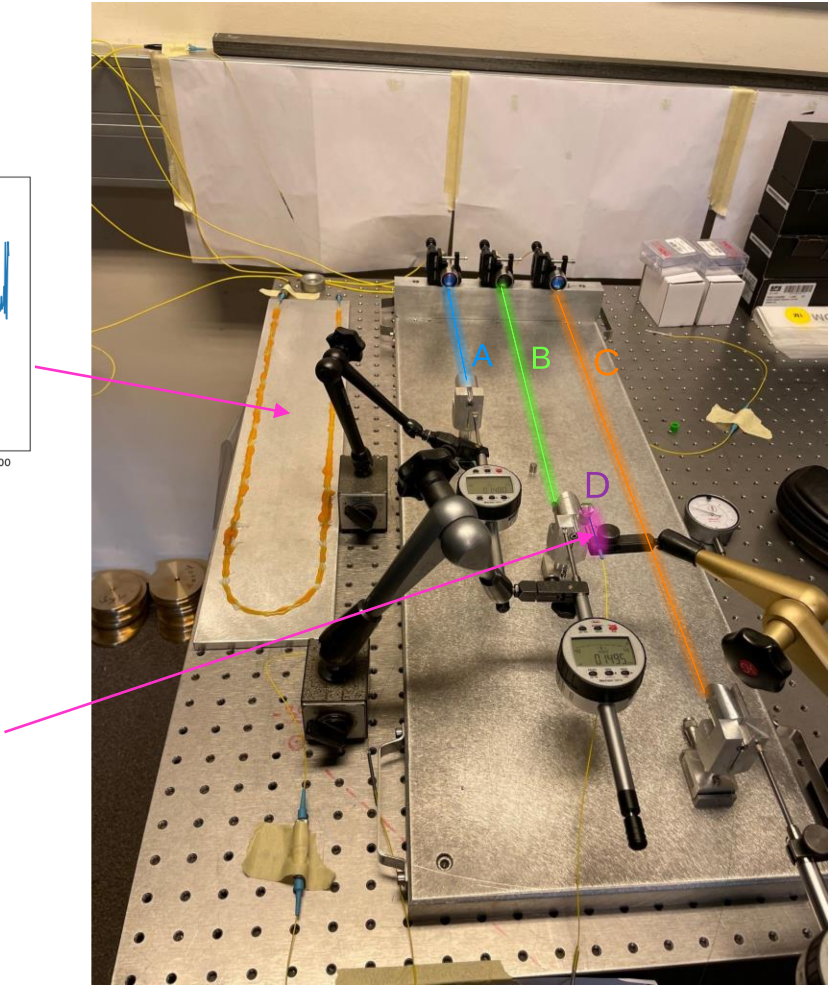
- A bench has been assembled
- 3 independent measuring portions + “regular” in-air measurement at the end
- Verification thanks to regular FSI measurements
- “Stability bench” made by gluing a fiber to an aluminium plate

FSI “in-fiber” prototype and first tests

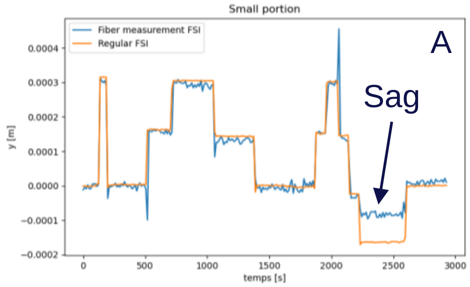


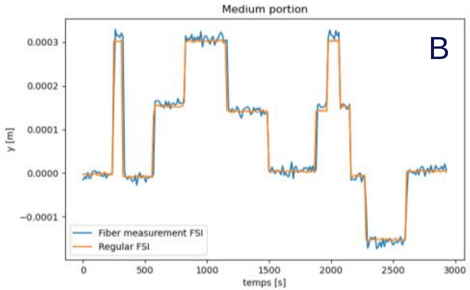


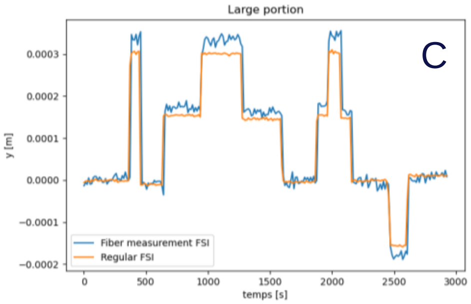


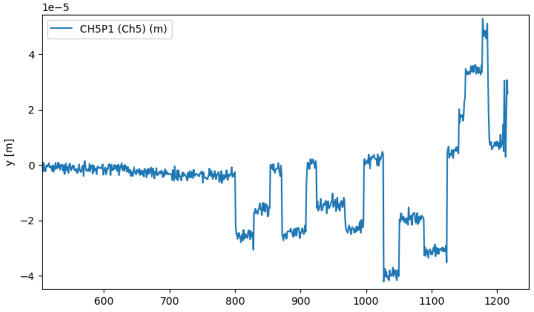


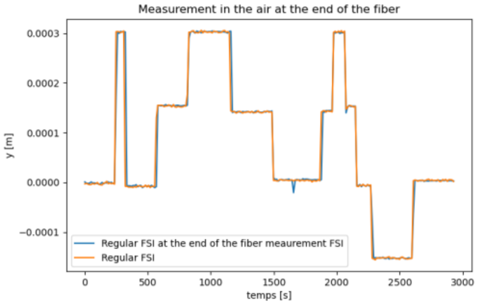
FSI “in-fiber” prototype and first tests

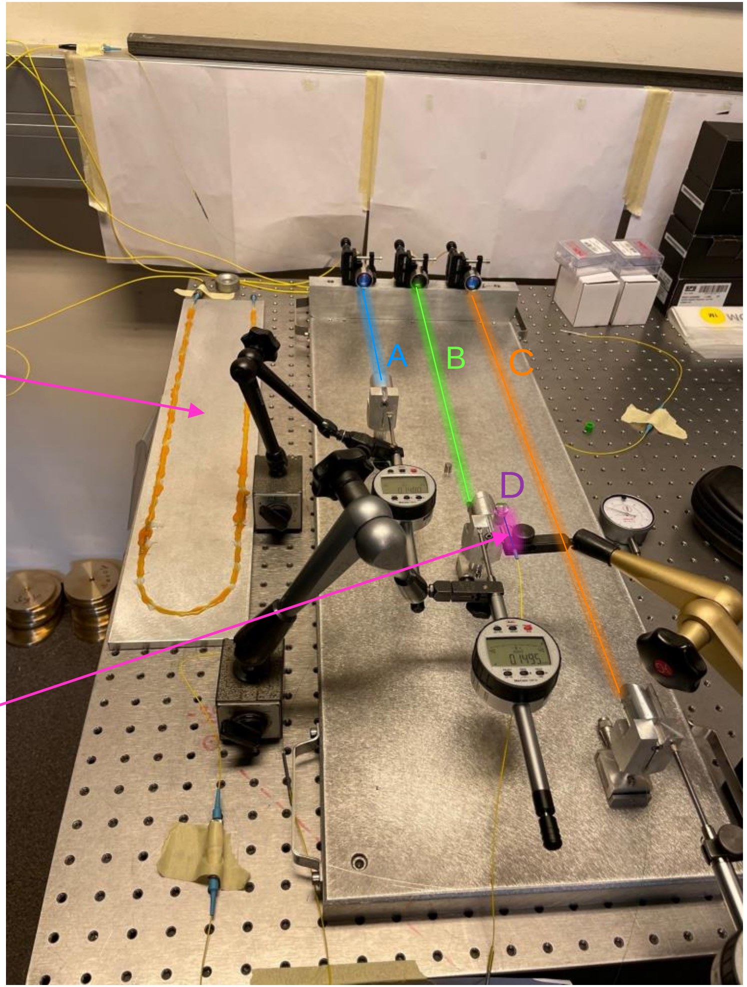




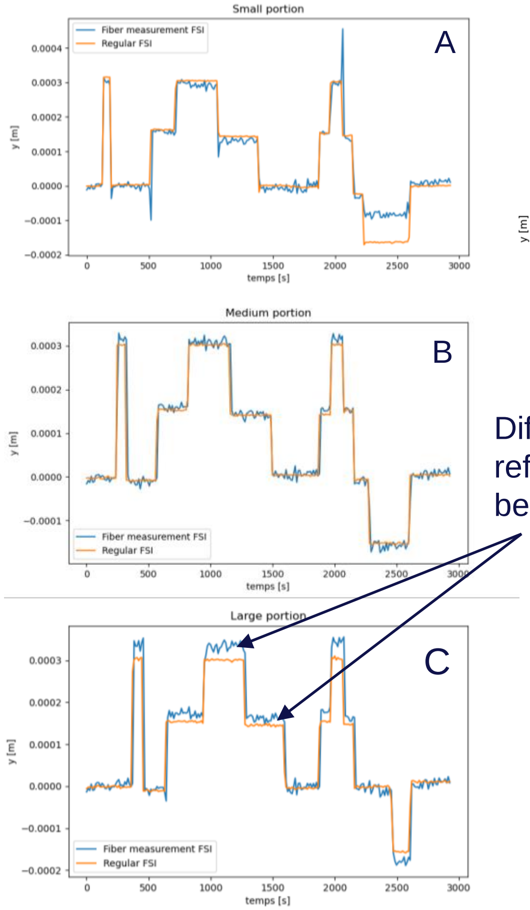


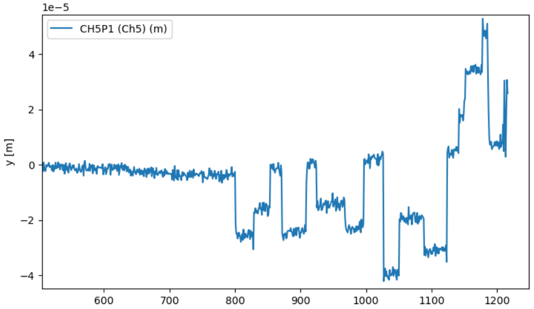




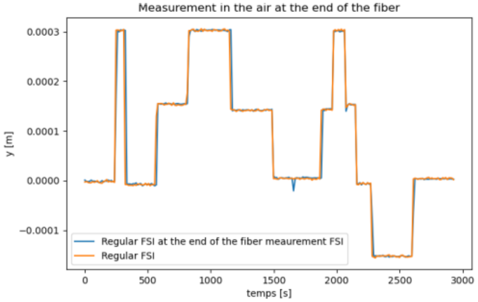


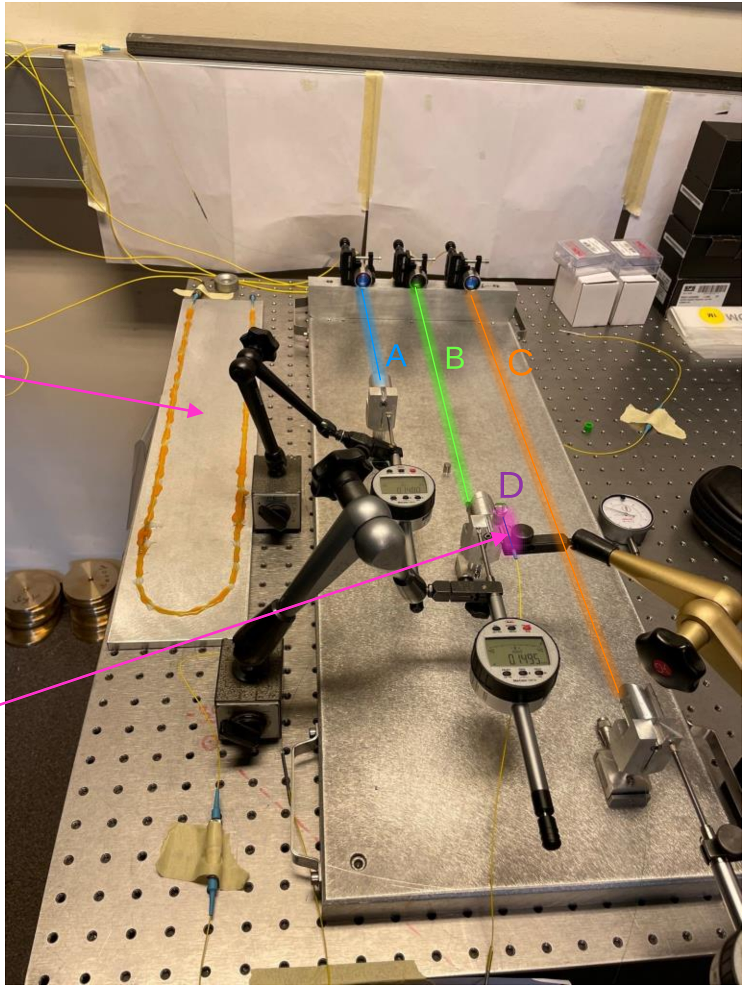
FSI "in-fiber" prototype and first tests



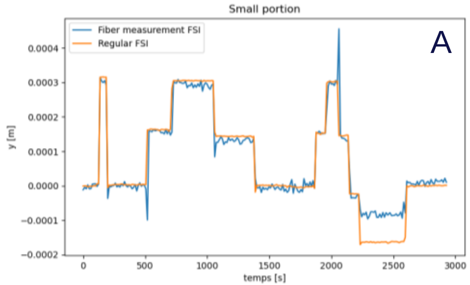


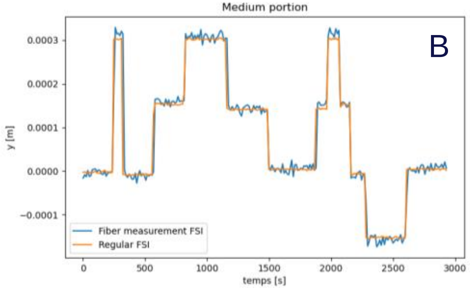
Difference of refraction index between air and glass

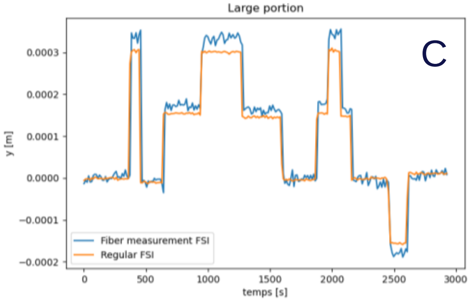




FSI “in-fiber” prototype and first tests







Hyp. : fiber sliding in the protecting sleeve