HiLumi
HL-LHC PROJECT

Frequency Scanning Interferometry for absolute measurements and its applications

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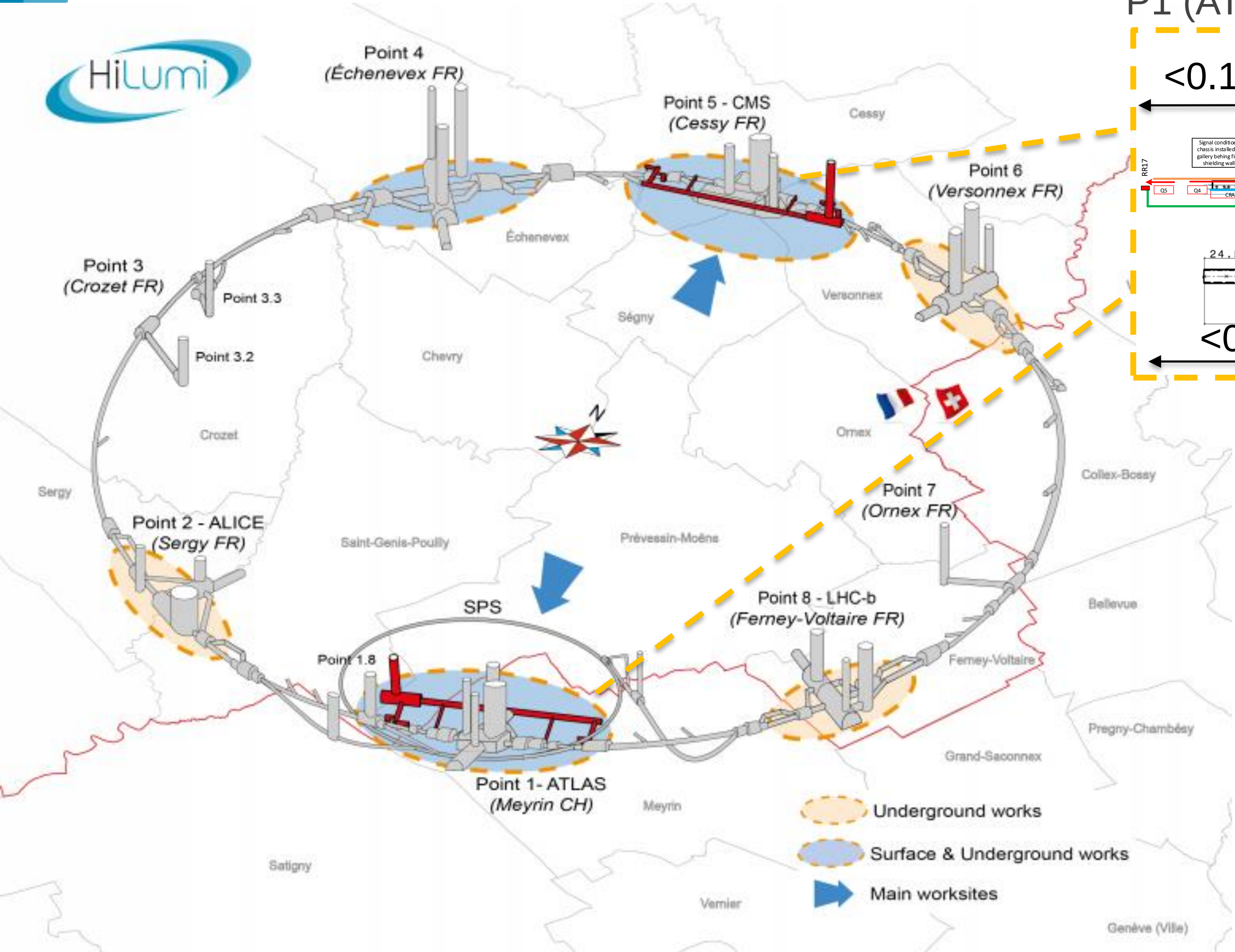
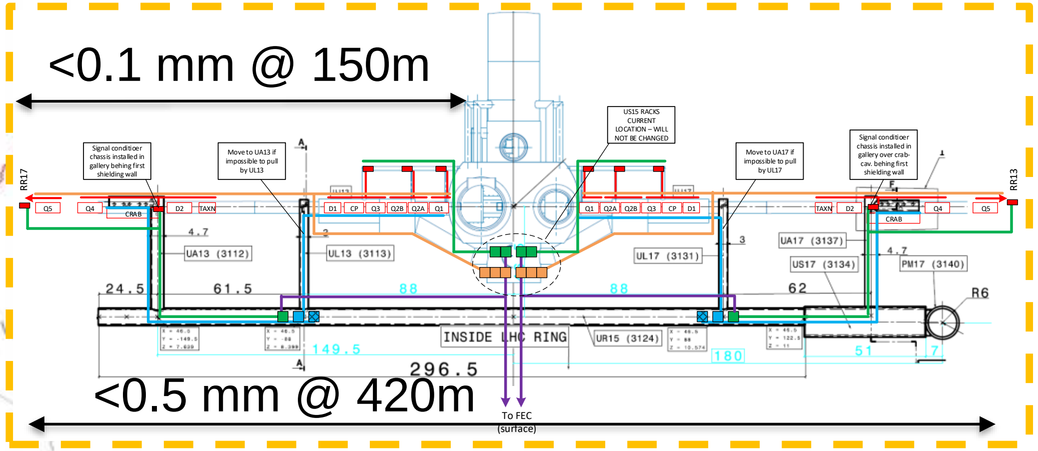
Outline

- High-Luminosity LHC (HL-LHC) and alignment systems
- Frequency Sweeping Interferometry (FSI) – classical approach
- First HL-LHC FSI applications
- Multi-target FSI (MT-FSI) as an alternative for robust measurements
- MT-FSI instrumentation examples
- Conclusions

CERN HL-LHC Upgrade and Alignment Monitoring Systems



P1 (ATLAS) & P5 (CMS) Long Straight Sections



Alignment of LSS components

- Vertical levelling of components (w.r.t. water surface)
- Radial alignment (stretched wire)
- Roll angle monitoring (inclinometers)
- Magnets longitudinal position monitoring
- Position monitoring of cold (nominal 2 .. 4 K) objects inside cryostats

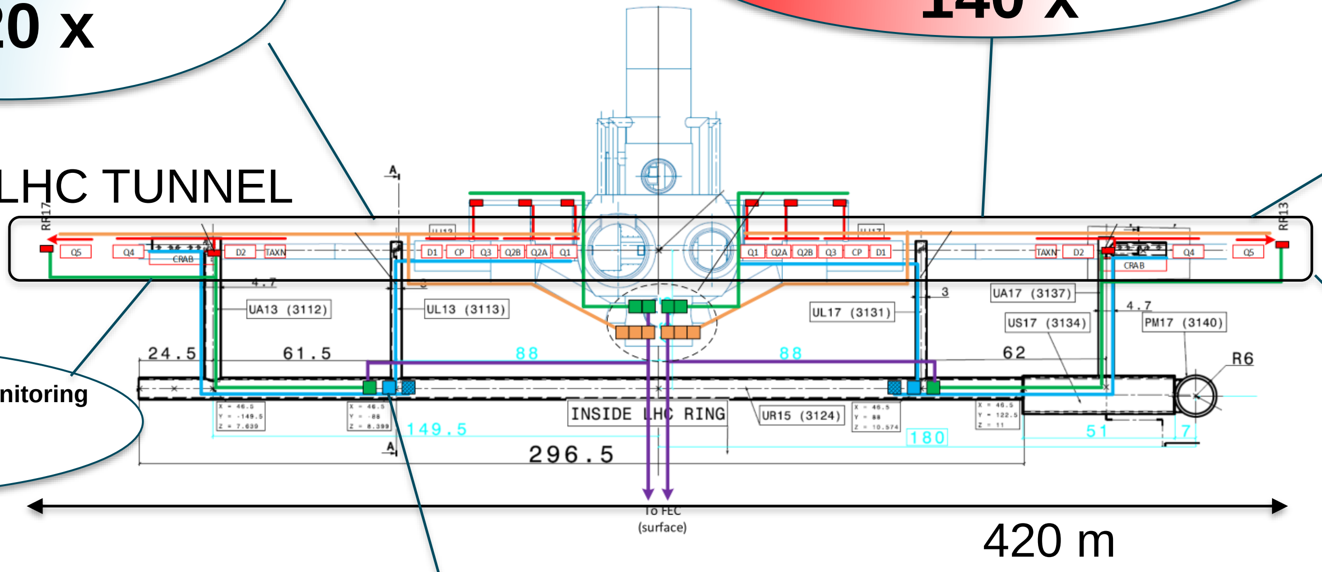
HL-LHC alignment monitoring and FSI

Internal monitoring cold components (crab-cavities, inner triplets) Nominal Temp.: 2 .. 4 K
320 x

Wire Position Sensor (X-Y position measurement w.r.t. stretched, conductive wire)
140 x

Hydrostatic levelling sensor (humidity close to 100%)
120 x

TID ~1MGy
T=20..25 °C



Inclinometer
70 x

Magnets longitudinal position monitoring
48 x

Interferometer (radiation safe location)

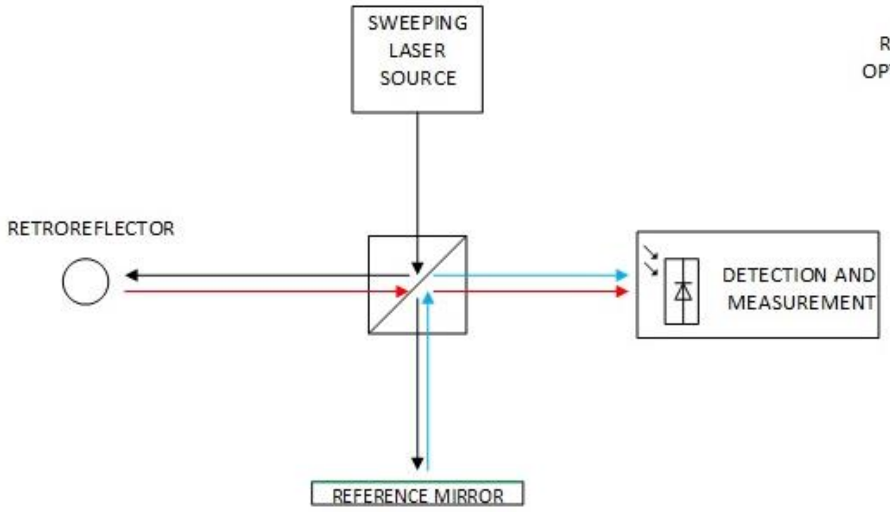
Capacitive

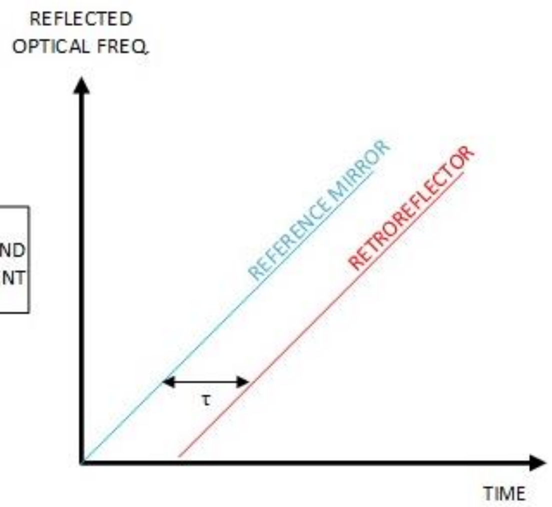
FSI

Why Frequency Sweeping Interferometry?

- **Absolute distance measurement needed**
- **Measurement uncertainty (per ch) better than 10 µm / 10 µrad required**
- Capacitive sensors very sensitive to dust and EM noise (replaced to optical ones where possible)
- Cabling and sensors cost need to be decreased
  - Big amount of channels, Large installation
- Simple and maintenance free systems needed (difficult access due to high radiation levels)

Introduction - Frequency Sweeping Interferometry





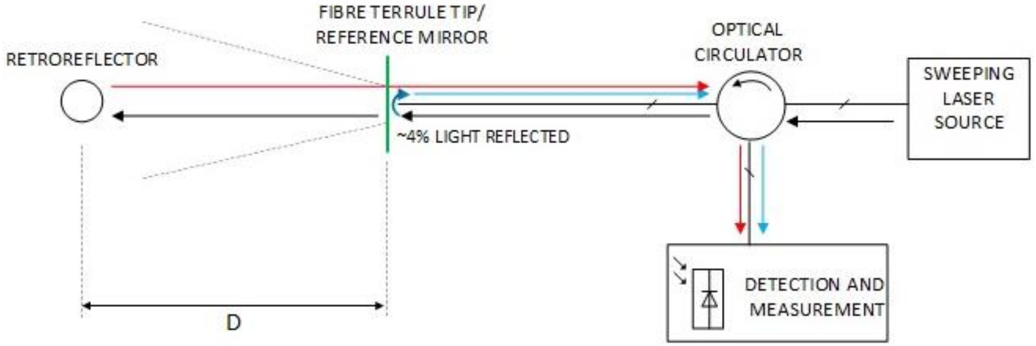
$$I(t,\tau) = A \cdot \cos[2\pi(\alpha\, \tau t + f_0\, \tau)]$$

A – magnitude of the signal;

τ - is the time delay between the signals from the reflecting target and reference mirror arrival to photodetector;

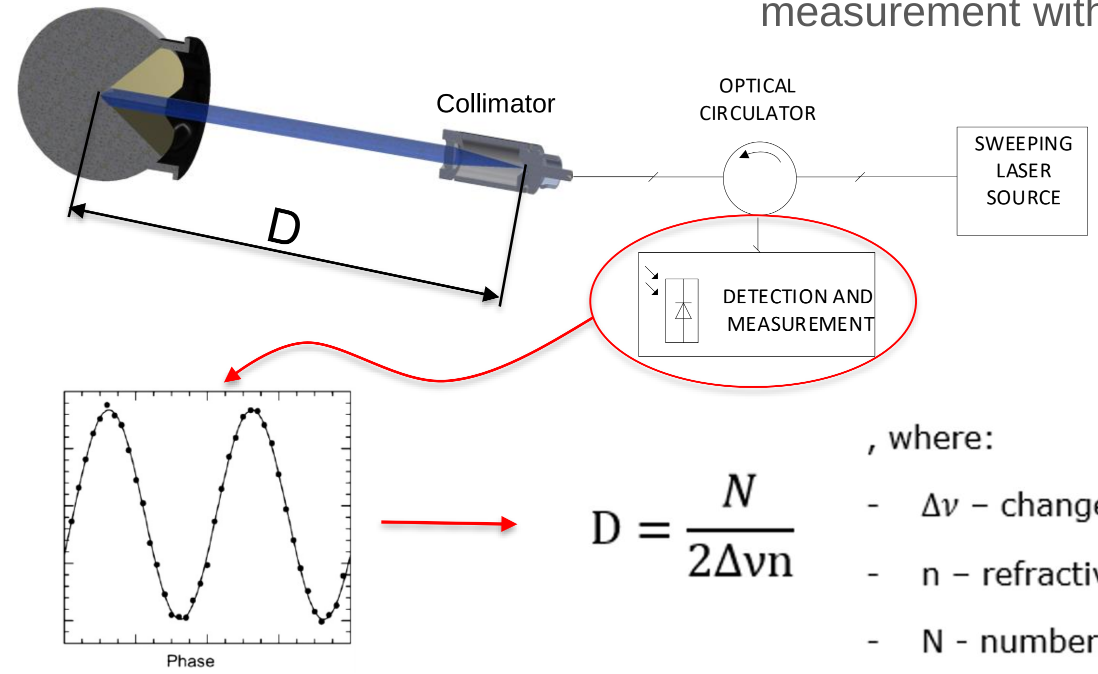
α – is a sweep rate of the laser ($\alpha = \frac{d\nu}{dt}$ - laser frequency change in time);

f_0 – is an optical frequency of the laser at the time t_0.



Classical FSI

Frequency Scanning Interferometry allows for **absolute** distance measurement with **µm** uncertainty

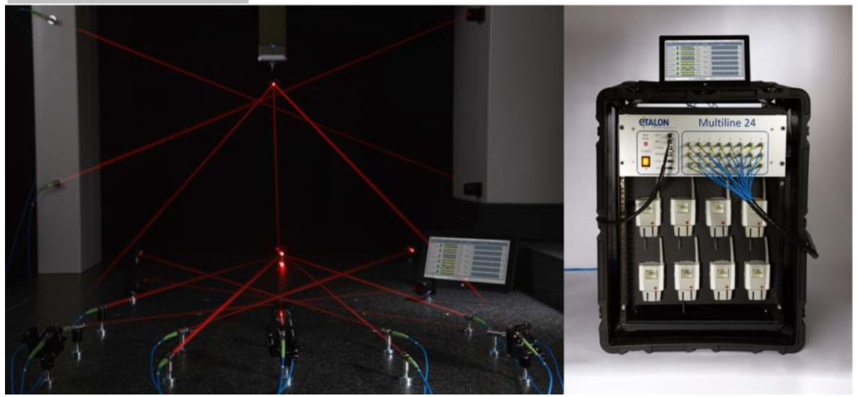


$$D = \frac{N}{2\Delta\nu n}$$

, where:

- $\Delta\nu$ – change of the laser frequency during sweep;
- n – refractive index of light transmission medium;
- N - number of cycles of signal measured during laser sweep;

ETALON ®

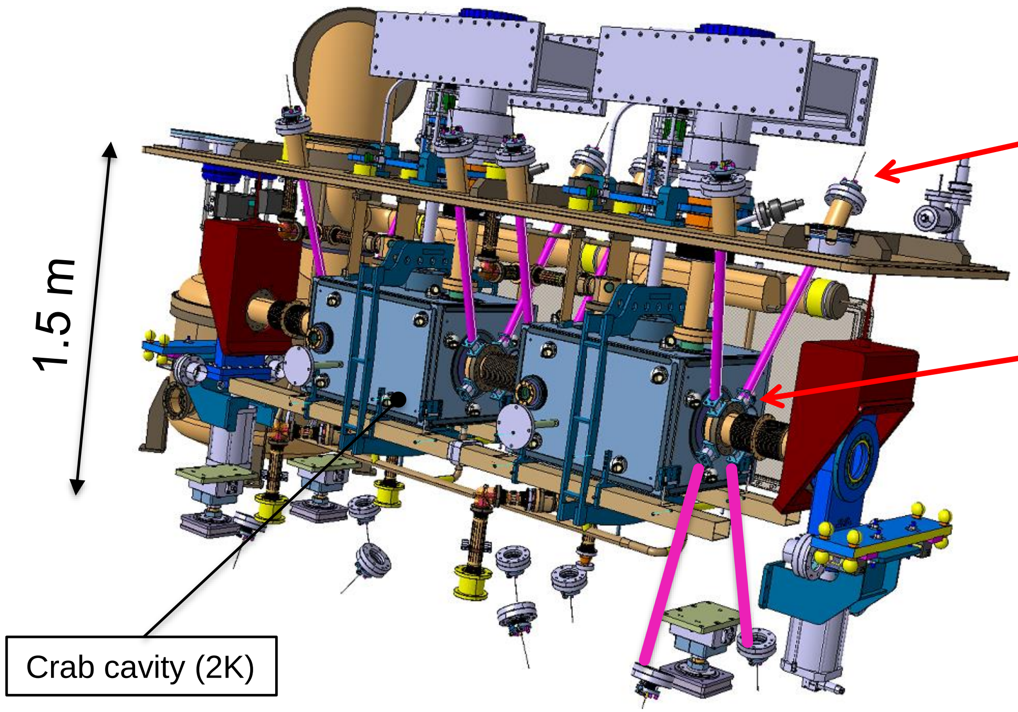


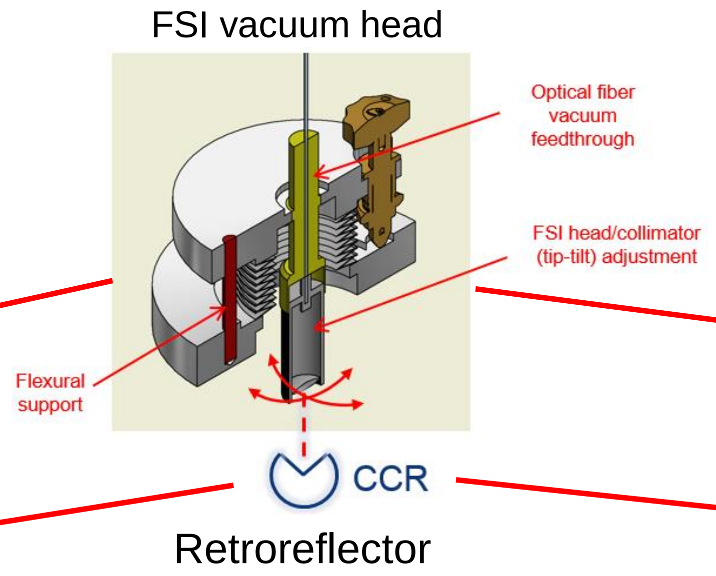
- Uncertainty (95%) = 0.5 µm/m
- Measurement distance: 0.2 – 20 m
- Double sweep laser – dynamic FSI
- Gas cell traceability

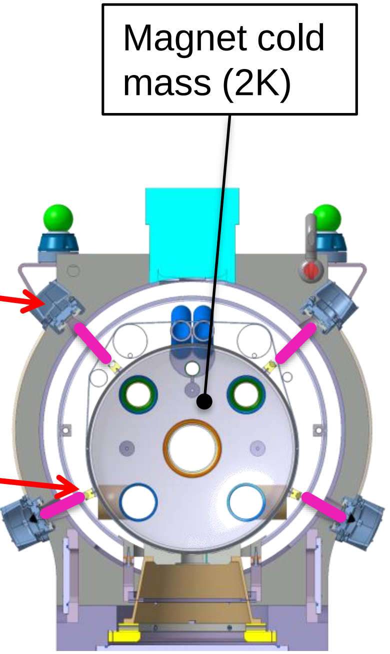
(www.etalon-gmbh.com)

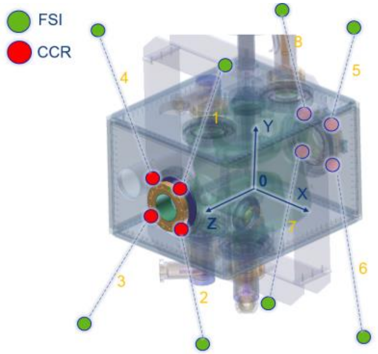
FSI for internal monitoring of cold objects inside cryostats

- **First FSI application – crab cavity position monitoring**
- **2016 .. 2018**

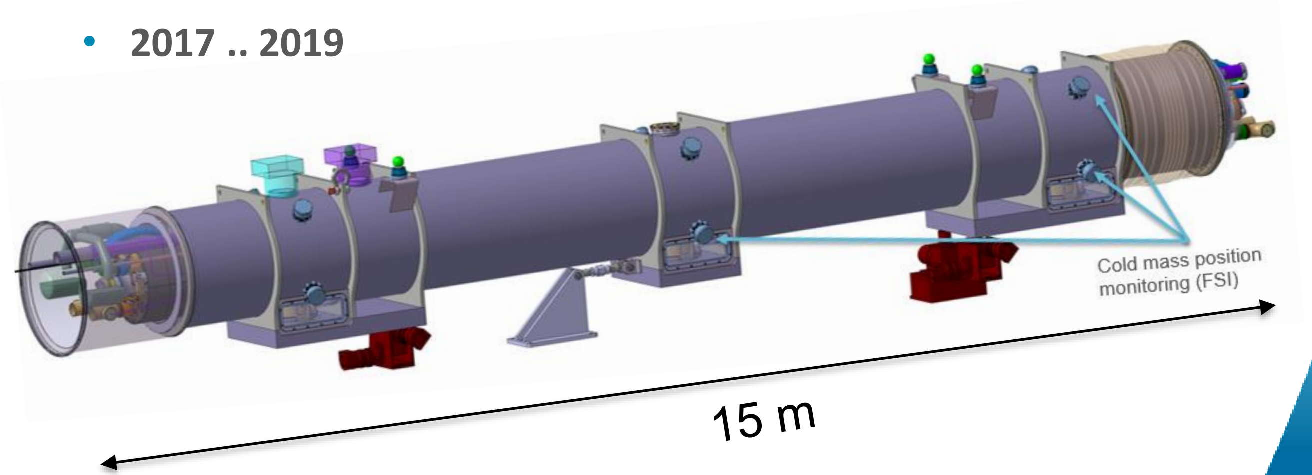








- **Second FSI application – inner triplet cold mass position monitoring**
- **2017 .. 2019**



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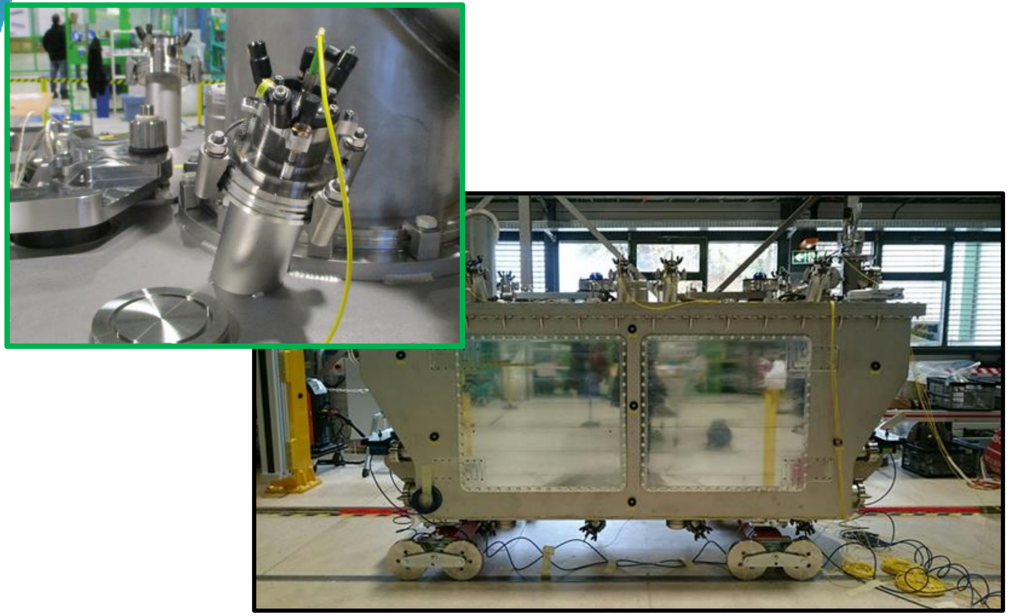
Internal monitoring (classial FSI) – first conclusions

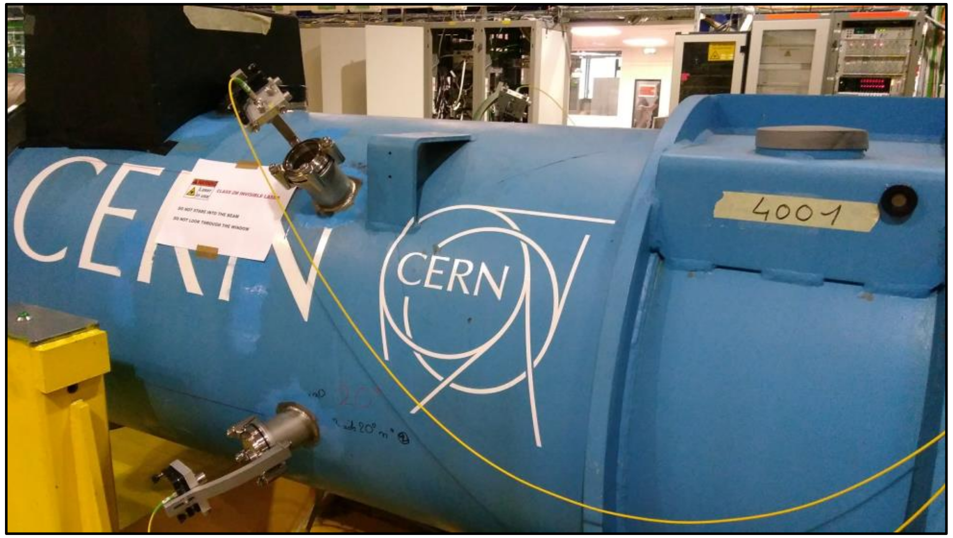


INNER TRIPLET:

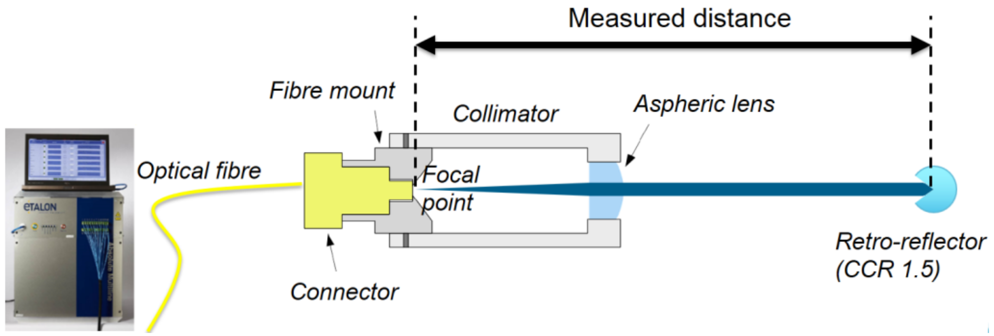
- Big lateral shifts of reflector caused by thermal contraction not allow to follow full cool-down cycle of the magnet
    - Tip-til adjustment of optical head needed
- Cryocondensation is an issue for reflector visibility
    - Solved by special design of reflector support
- Micrometric resolution of objects movements achieved

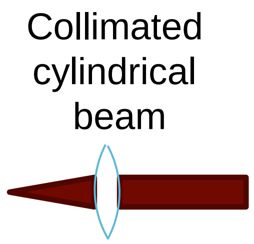
CRAB CAVITY:

- System allows to follow the cooled crab cavity position/orientation
- Micrometric resolution of objects movements achieved
- Continuous measurement by over 6 months
- However! 2 targets visibility lost during measurements (Cryocondensation? Lateral target displacement?)



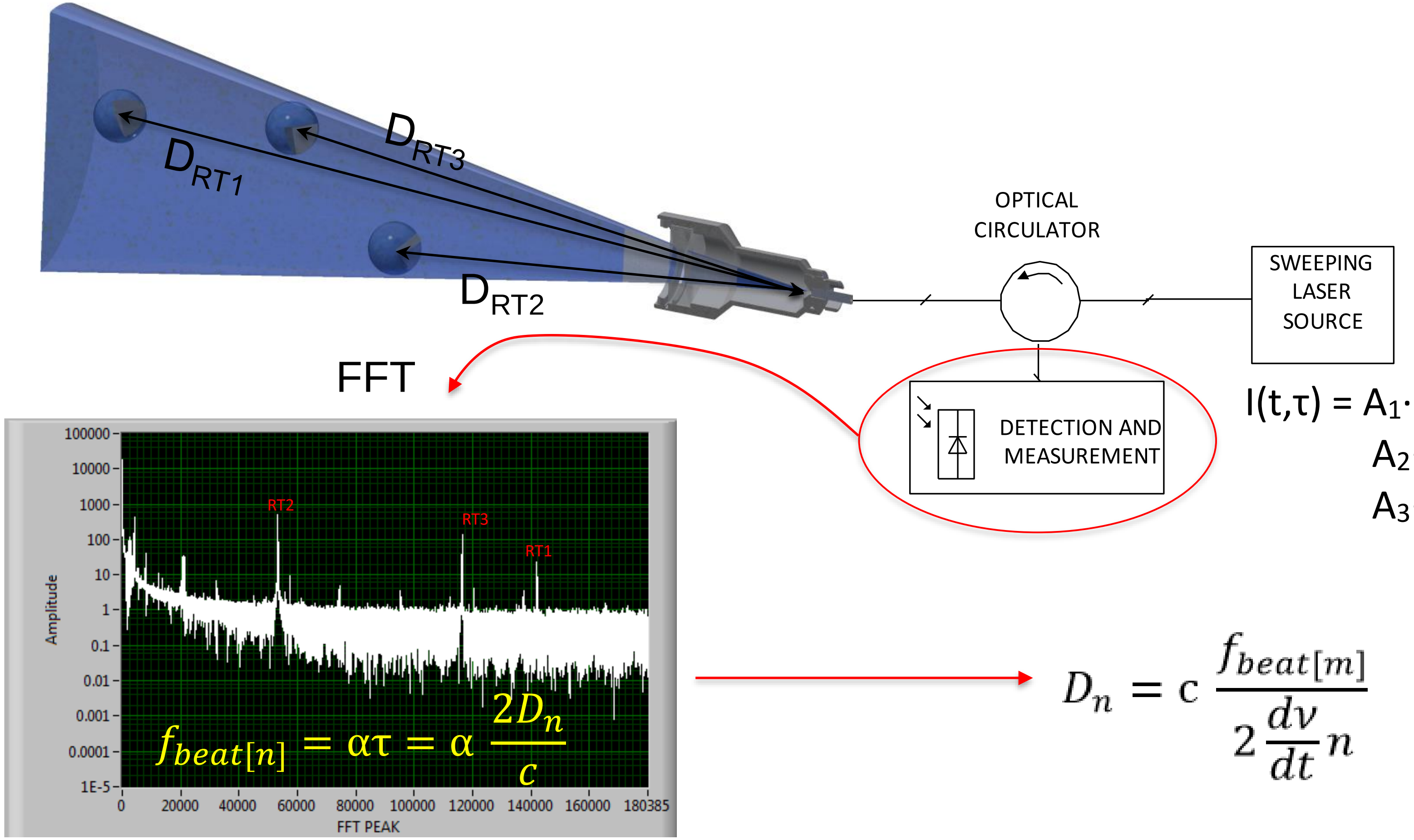
Classical FSI – summary





- **System is sensitive to return signal intensity level (beam alignment important)**
  - Reflectors lateral position or dust on the reflectors have big impact on measurement performance
- Beam diameter defines transversal movement range of the target
- Optical feedthroughs needs to include tip-tilt adjustment functionality for initial beam position targeting into retroreflector (higher cost of feedthrough, need of adjustment after cool down)
- Only collimated beams and observation of single target

Multi-target FSI (Fourier analysis based)



$$f_{beat[n]} = \alpha\tau = \alpha\frac{2D_n}{c}$$

$$I(t,\tau) = A_1\cdot\cos[2\pi(\alpha\tau_1 t + f_0\,\tau_1)] + A_2\cdot\cos[2\pi(\alpha\tau_2 t + f_0\,\tau_2)] + A_3\cdot\cos[2\pi(\alpha\tau_3 t + f_0\,\tau_3)]\ldots$$

$$D_n = c\,\frac{f_{beat[m]}}{2\frac{d\nu}{dt}n}$$

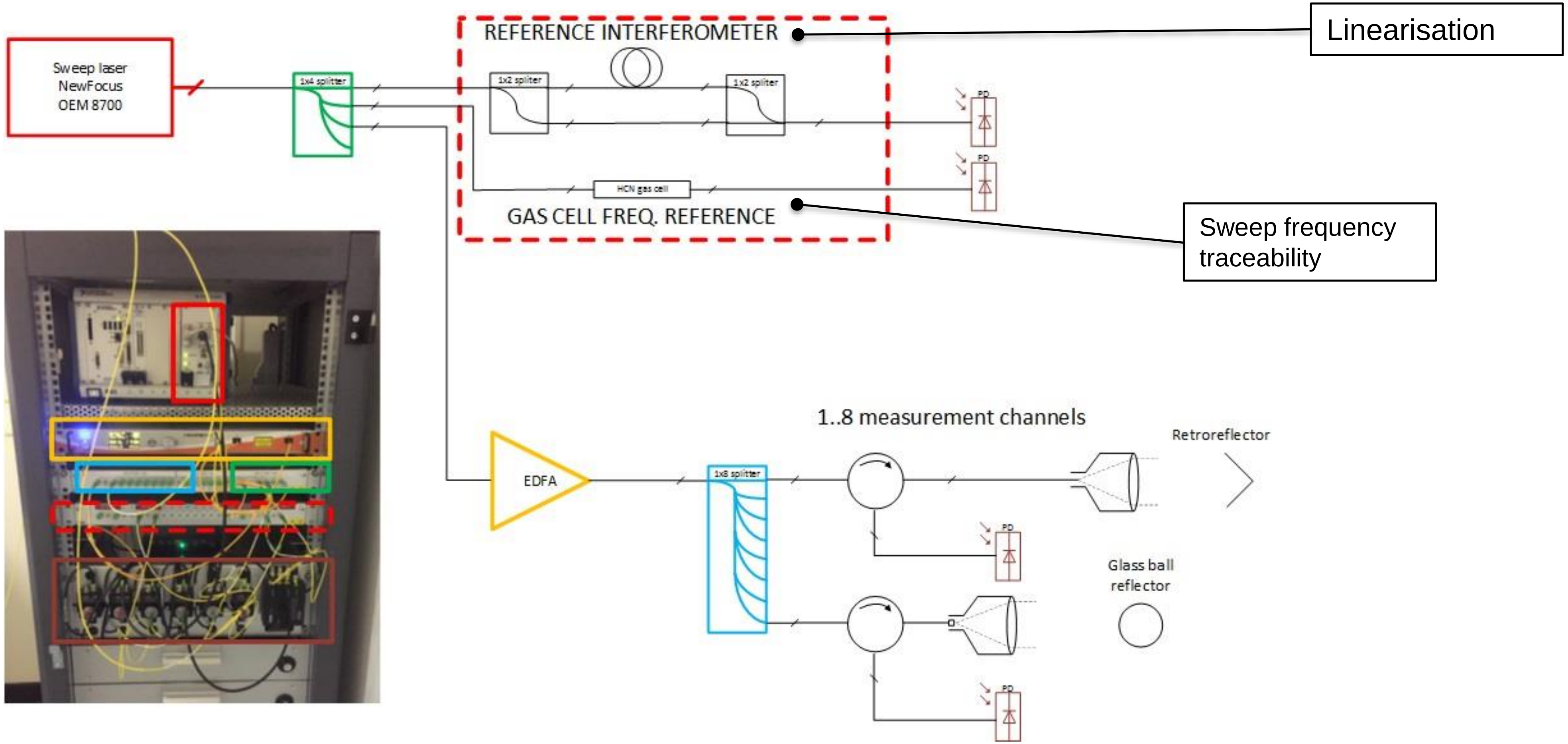
α – is a sweep rate of the laser ($\alpha = \frac{d\nu}{dt}$ - laser frequency change in time);

c – speed of light; n – refractive index of light transmission medium;

τ – time of flight of laser to the target

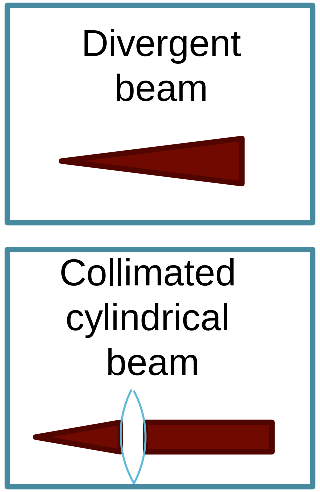
Multi-Target FSI – simple measurement setup

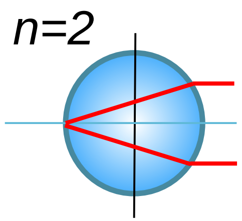
- Allows for flexible optical connections and scalability of the interferometer channels number
- Single laser (simple, but vibration sensitive) or „dynamic” - dual laser/sweep – FSI (complex, more expensive)

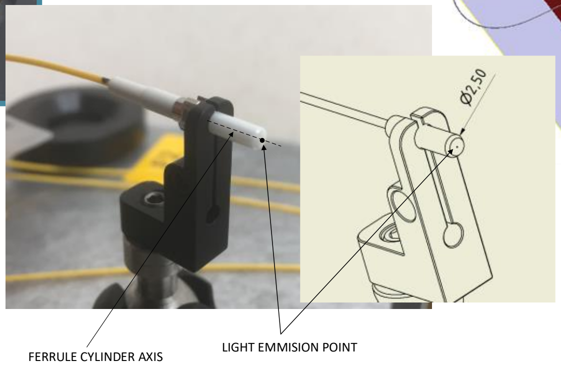


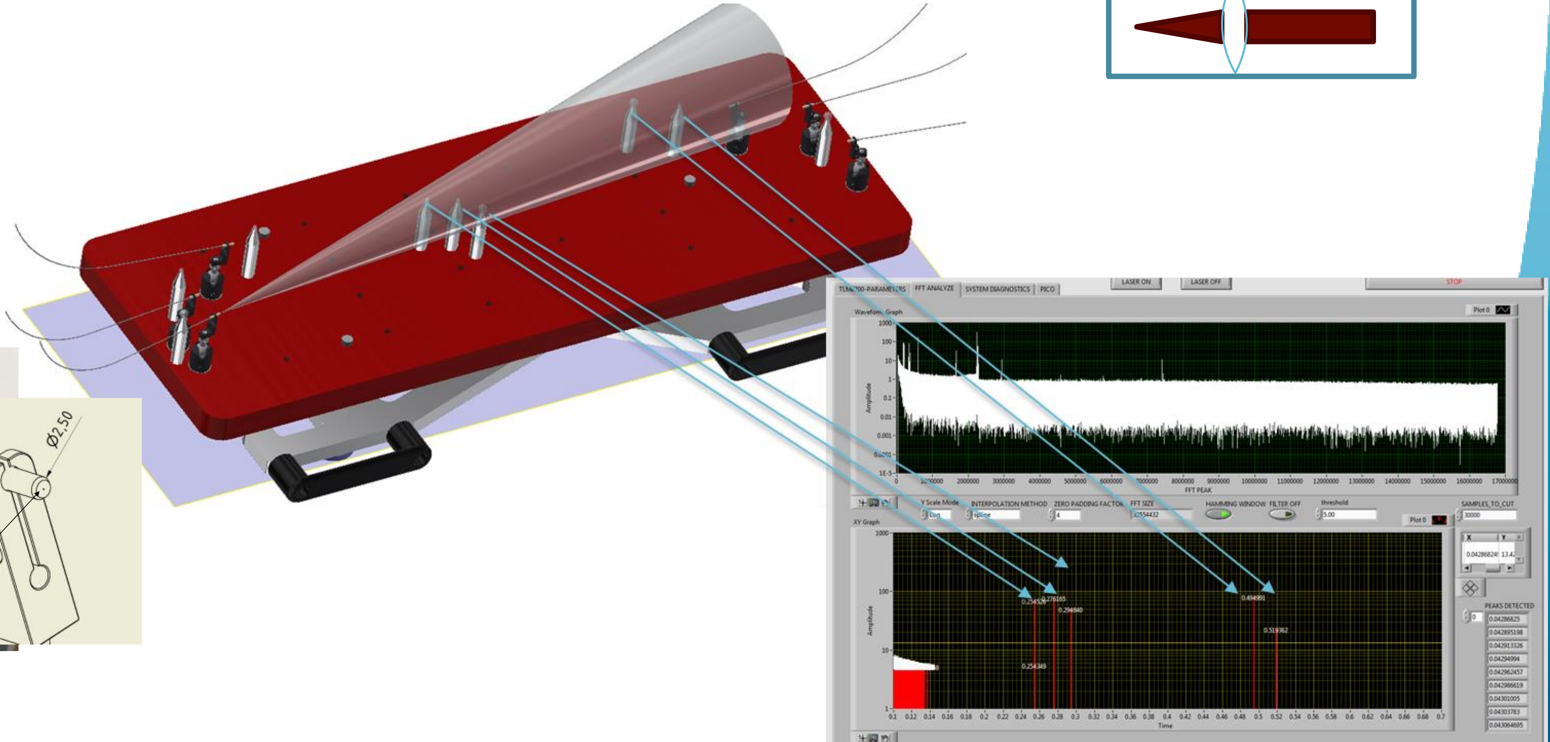
Multi-target FSI – advantages

- **Very robust measurement method – almost insensitive to the light intensity (high and very small power reflections visible over the noise background**
  - Possible to use cheap glass balls as a reflectors
  - Possible to measure reflection from various surfaces
- Measurement uncertainty <5 µm (single laser configuration, no vibrations)
- Possible to measure multiple targets within single laser scan
- Possible to use with the collimated and divergent beams
- Simpe beam delivery optics





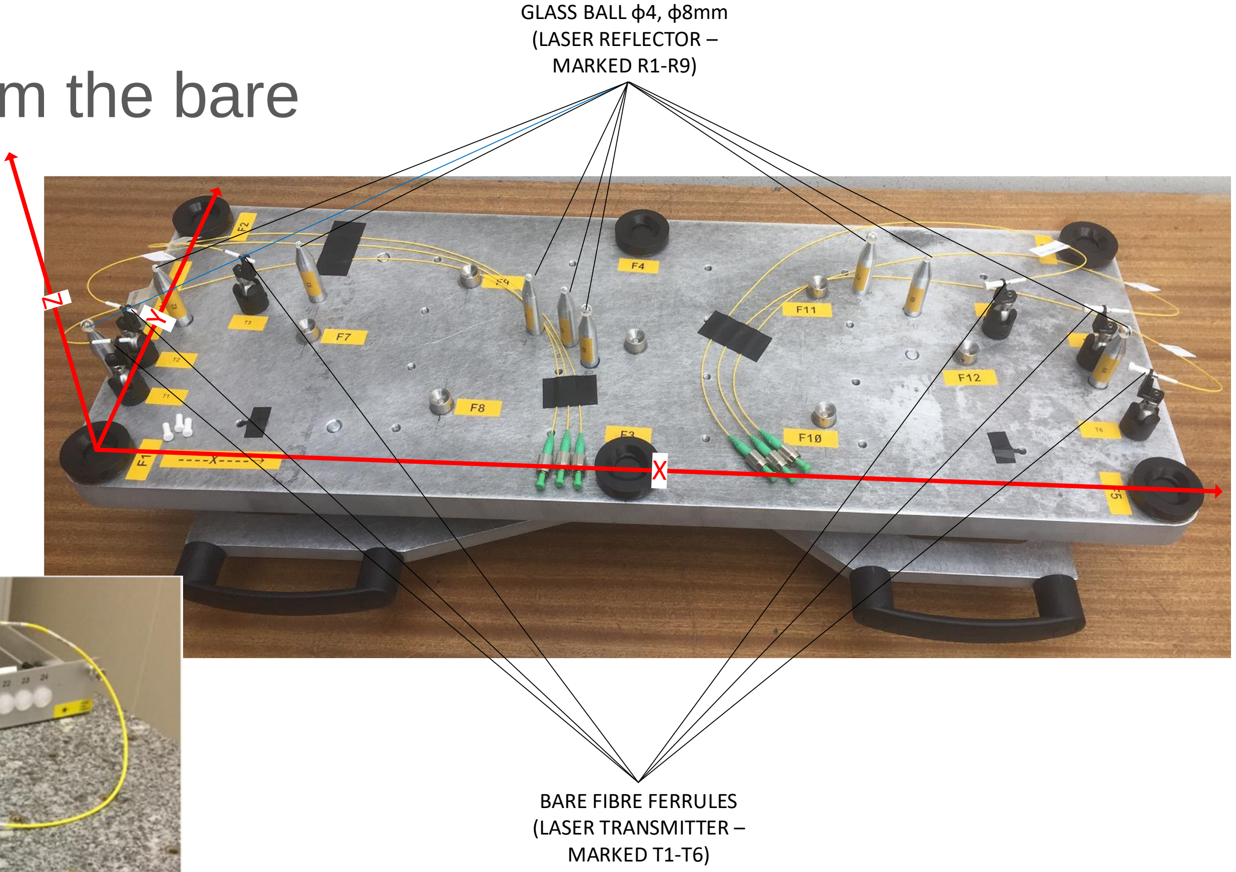


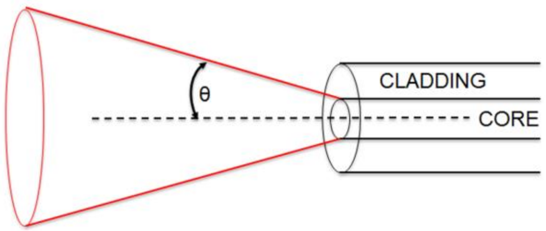


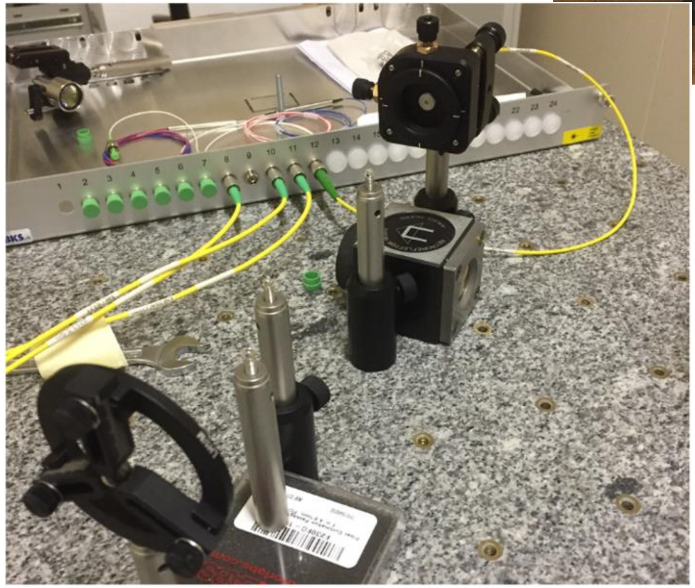
Multi-target FSI – applications

Launch of the divergent beam directly from the bare fibre ferrules as most optimized solution

- Divergence angle defined by NA
- Sufficient to measure distances up to 0.7m
- Easy to measure „interference origin” (ferrule tip axis using CMM)



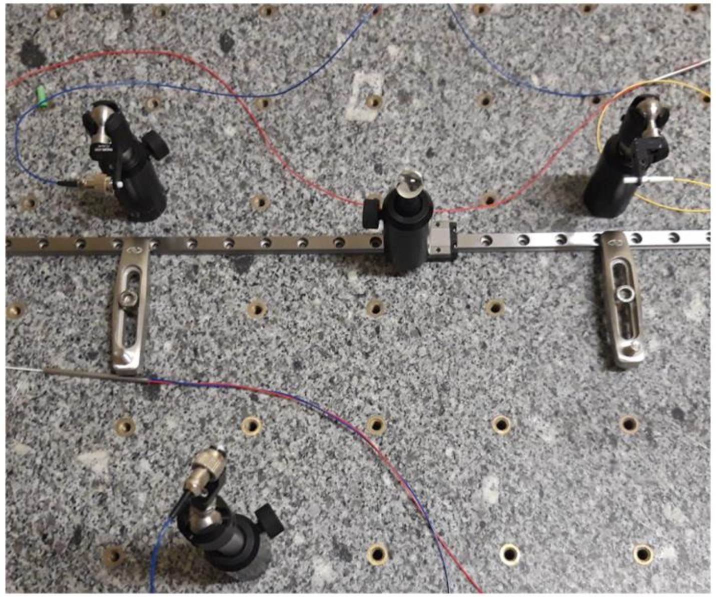


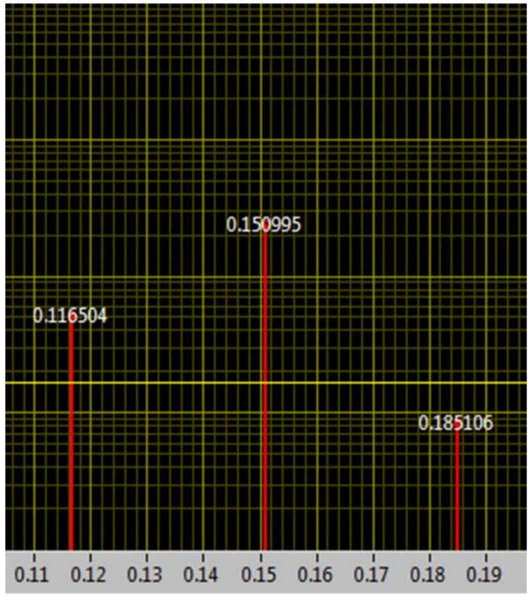


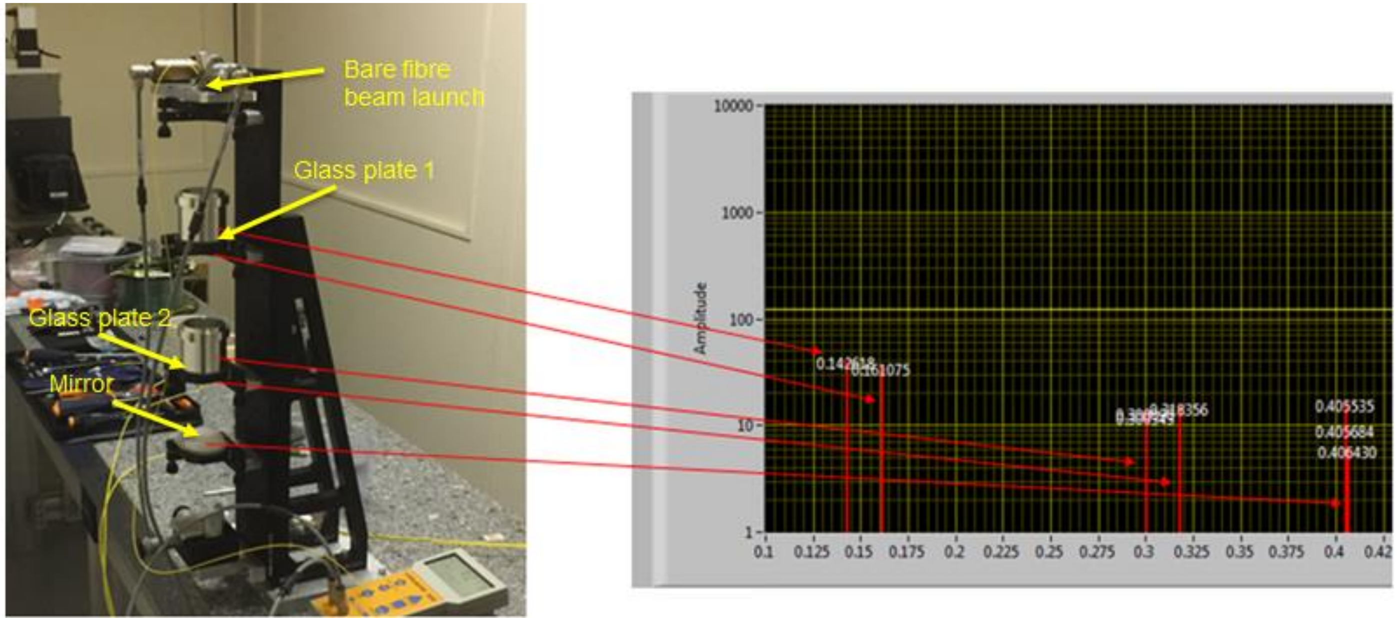
Multi-target FSI – applications

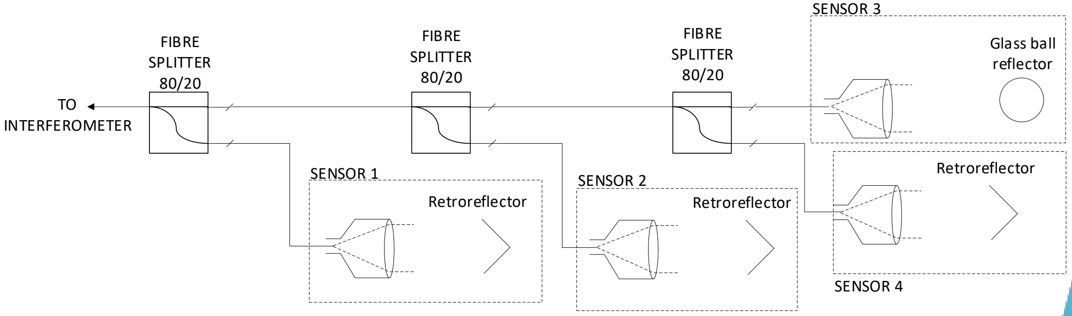
Multiple reflection applications

- Multi-reflection sensors
- Multi-sensor solutions (serial connection of sensors)
  - Different physical quantities measurement through measurement of length of cavities created within the fibre







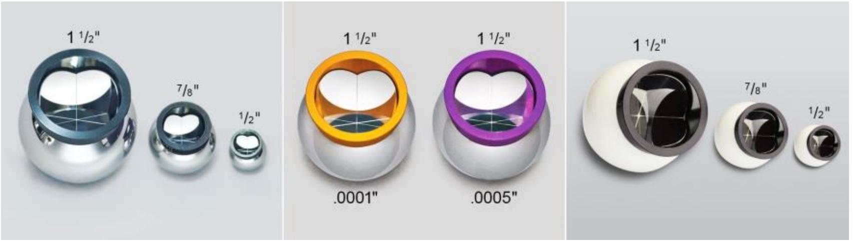


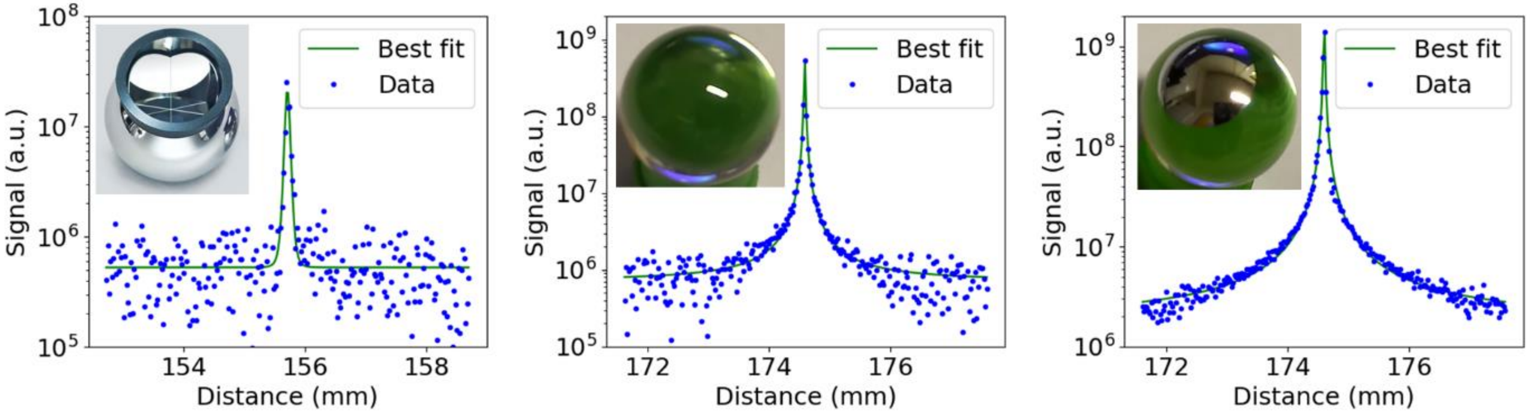
Multi-target FSI – drawbacks

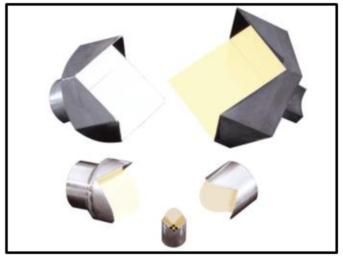
Frequency spectrum will show all the reflections including also the unwanted ones

- Internal parasitic reflections (e.g. circulators)
- Fibres Rayleigh scattering increase noise ratio
- Sensitive to parasitic reflections from shiny surfaces surrounding the measured reflectors/surfaces
- Multi-surface or multi-sensor – beat frequency peeks can not overlap

MT-FSI Instrumentation – glass ball reflectors





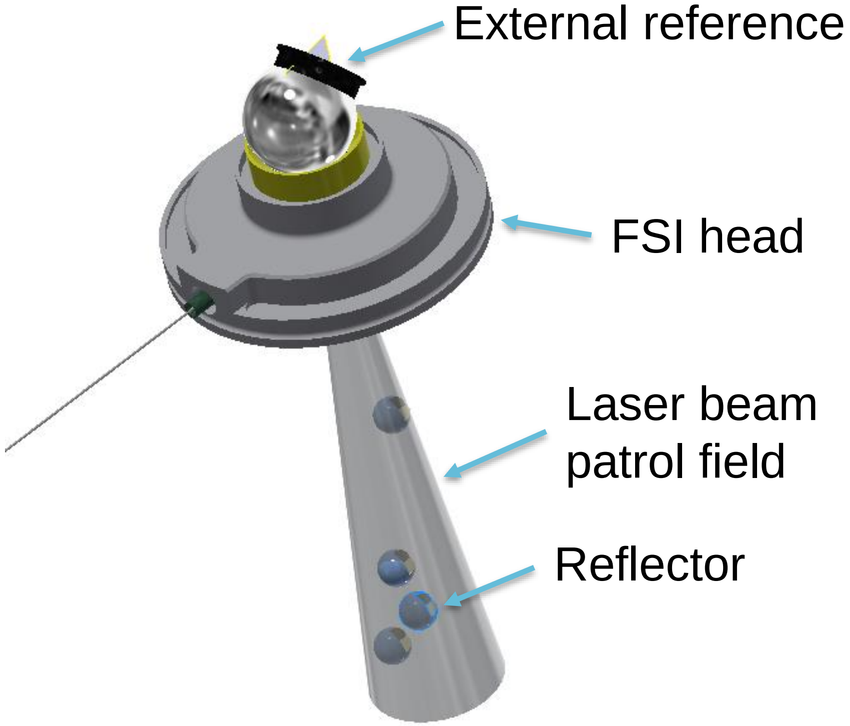


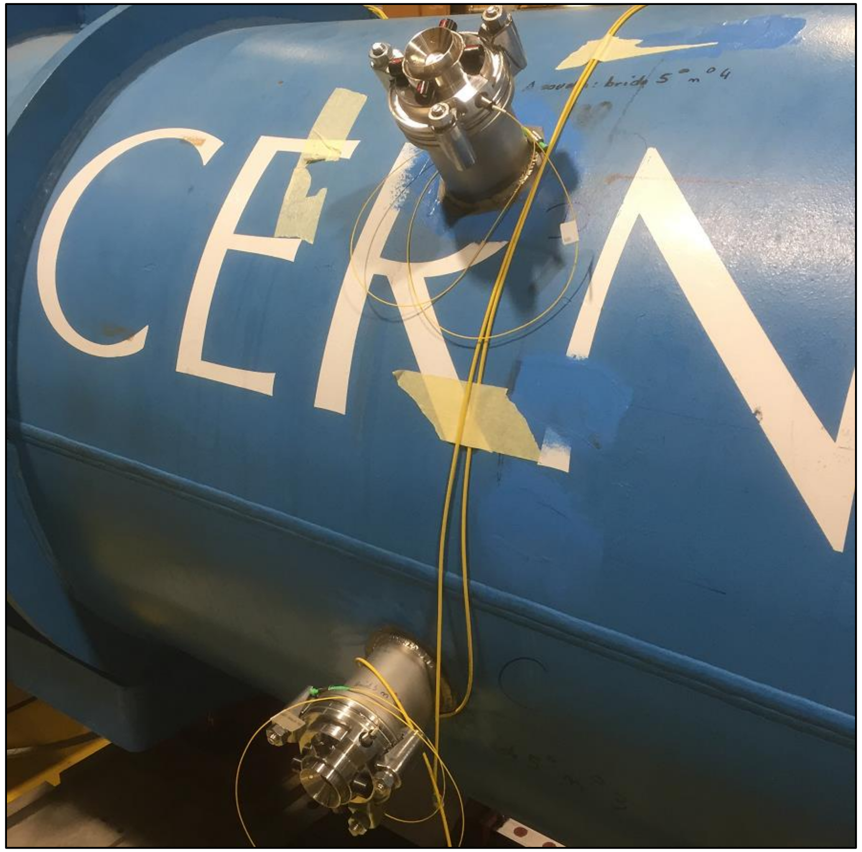
- Refractive index ≈2 glass ball used as an alternative to hollow retroreflectors or BMRs **(big reduction of installation cost!)**
  - 0.5” uncoated and coated reflectors manufactured and tested
- TAFD 55 and S-LAH79 ball reflectors radiation hard 5MGy, 10MGy samples under tests
- Coated glass ball reflector measurable by laser trackers

MT-FSI Instrumentation – vacuum heads

Simple vacuum FSI head for HL-LHC internal monitoring

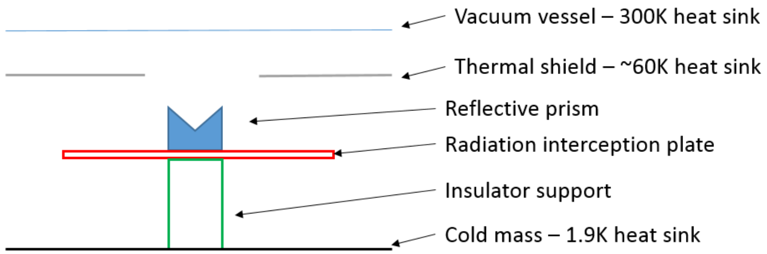
- No moving parts, cheap, single steel body design
- Wide patrol field – big lateral reflector movement range
- Low cost (bare fibre ferrule beam launch)



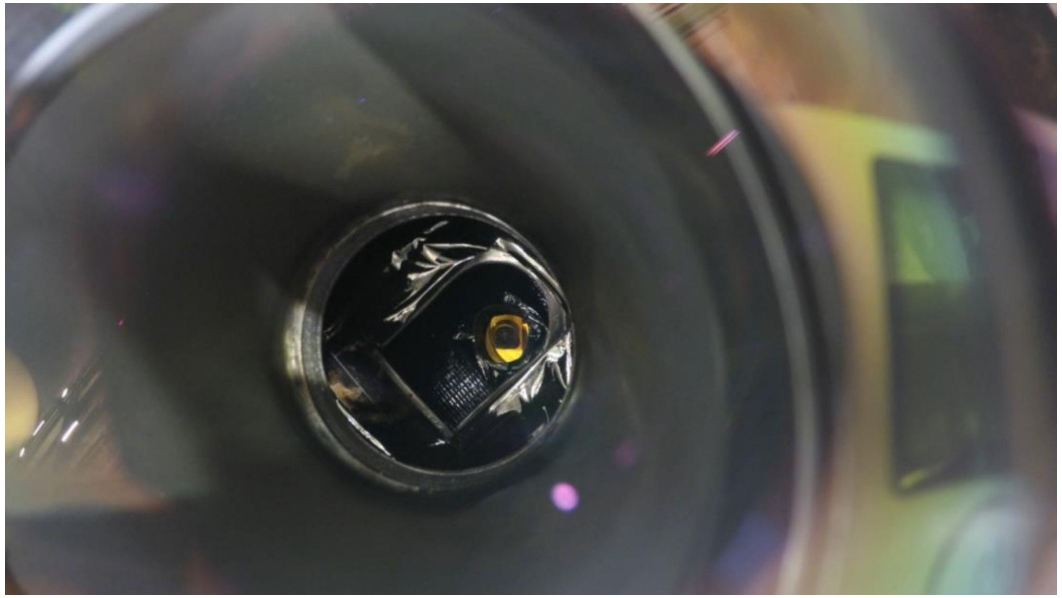


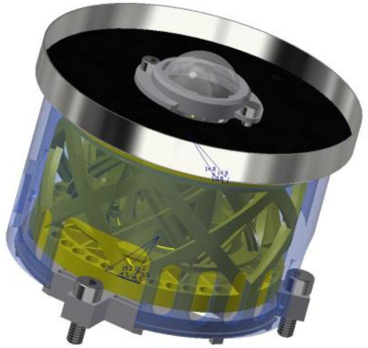
MT-FSI instrumentation - cryo-compatible reflector supports

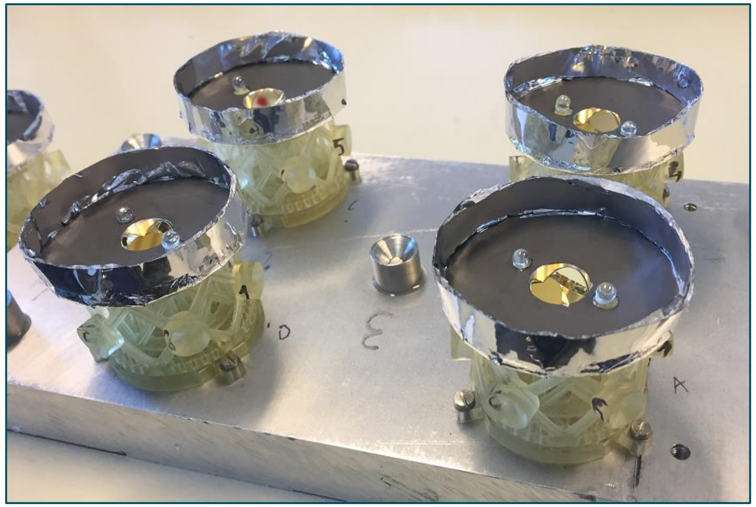
- „Passive”, SIMPLE design to suppress cryo-condensation effect
  - 3D printed targets to provide complex insulator shape
  - Graphite coated, heat interception plate
  - MLI film to minimize heat radiation towards cold mass of magnet



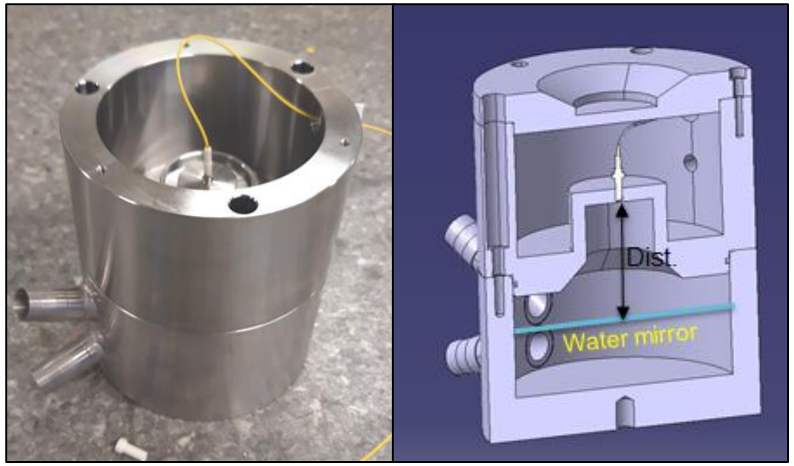
F. Micolon





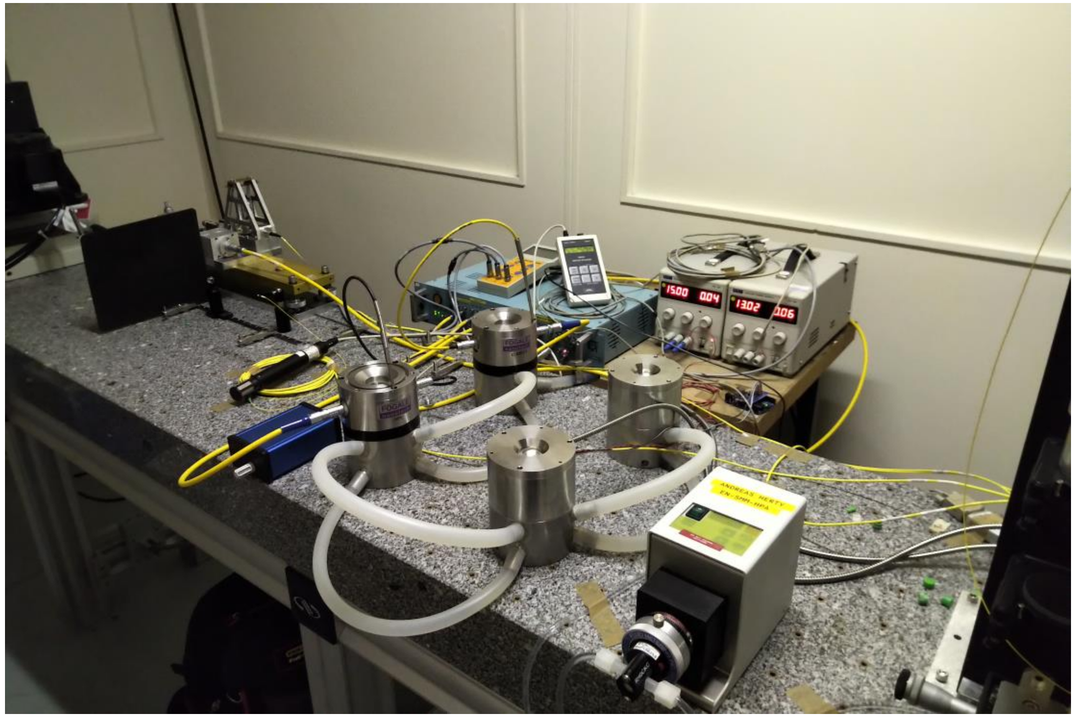


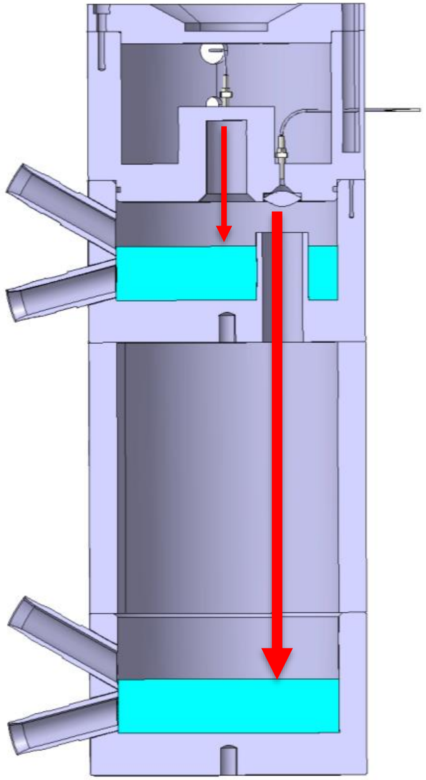
MT-FSI Instrumentation – interferometric Hydrostatic Levelling Sensor (iHLS)



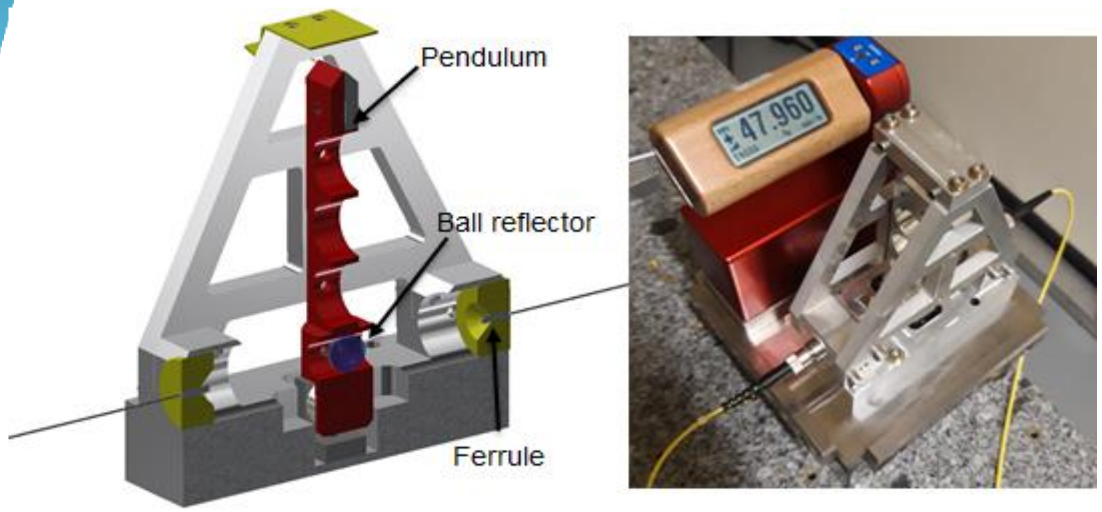
Cost optimized, divergent beam FSI HLS sensor for HL-LHC

- Single metal body chassis, no movable parts, minimum amount of optical components
- Measurement uncertainty < 5µm, precision ~1 µm
- Multiple level sensor under design

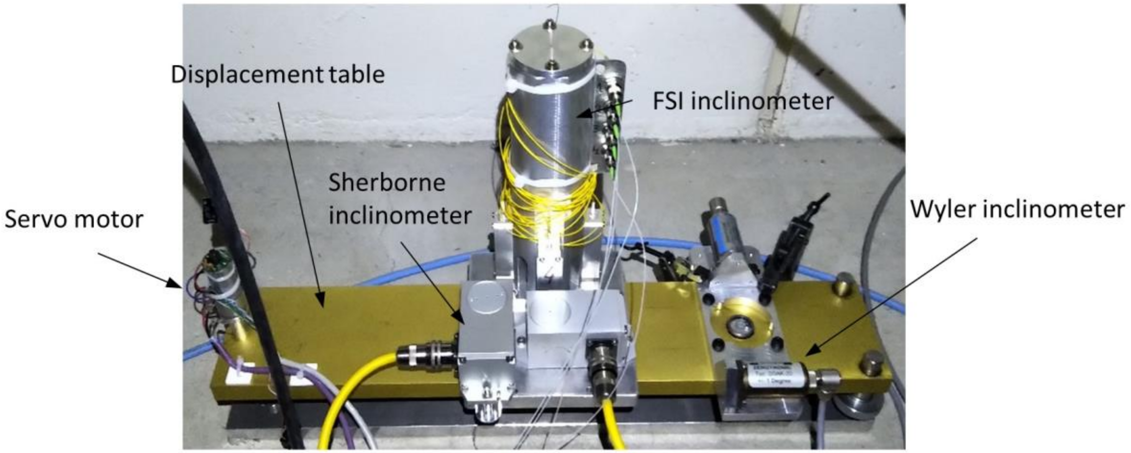




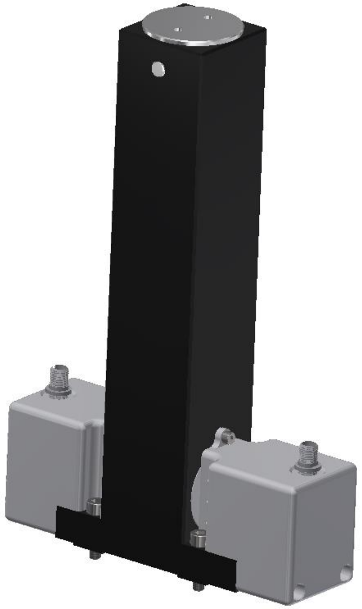
MT-FSI Instrumentation – optical inclinometer



1-st prototype (1-axis)



2-nd prototype (2-axis)



3-rd (final) prototype (1-axis)

Optical inclinometer for HL-LHC

- Resolution <10 µrad
- Differential pendulum measurement to anticipate thermal expansion effects
- Two generations of prototypes tested, allowed for final approach selection
- 3-rd – final generation of inclinometer under tests

Multi-Target FSI – Long/Short distance measurement sensors

Distance measurement for UPS vs. Tunnel radial reference transmission

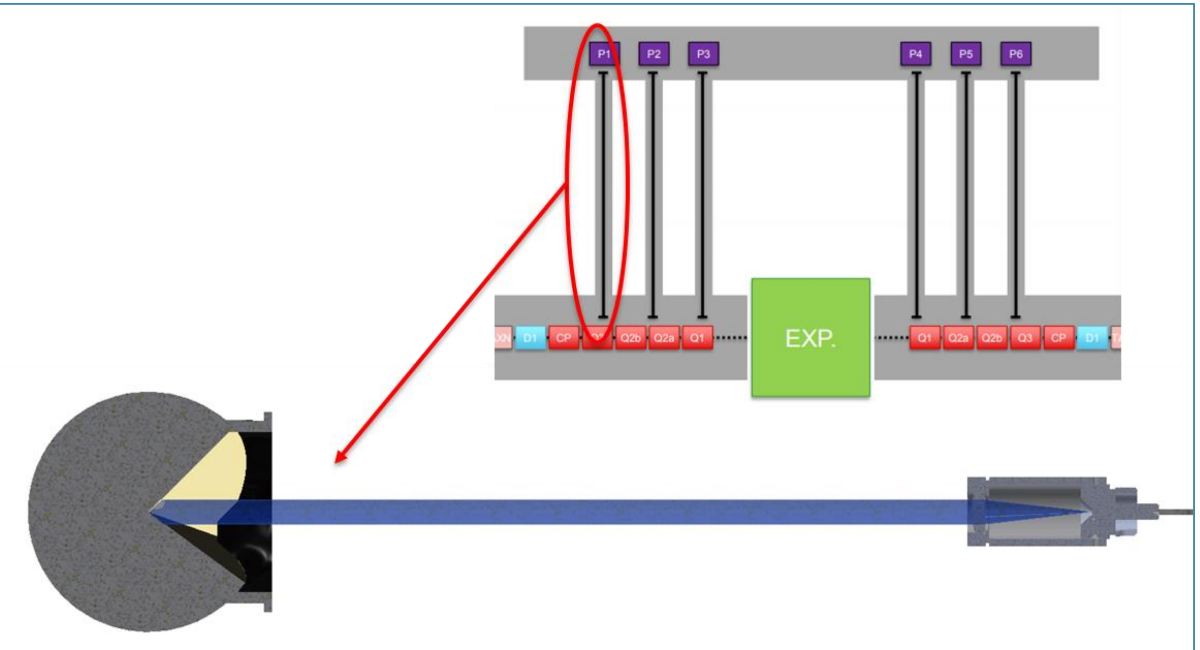
- ~15 m distance
- Standardized collimated optics to be used

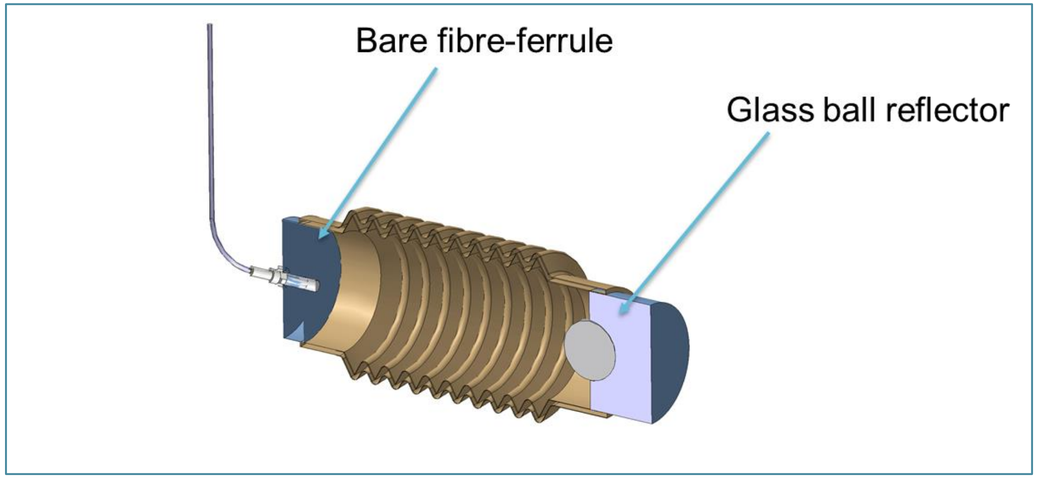
- Expected measurement uncertainty < 40µm
- Precision ~5 µm
- Under development

Short distance measurement sensor (range ±5 .. 10mm)

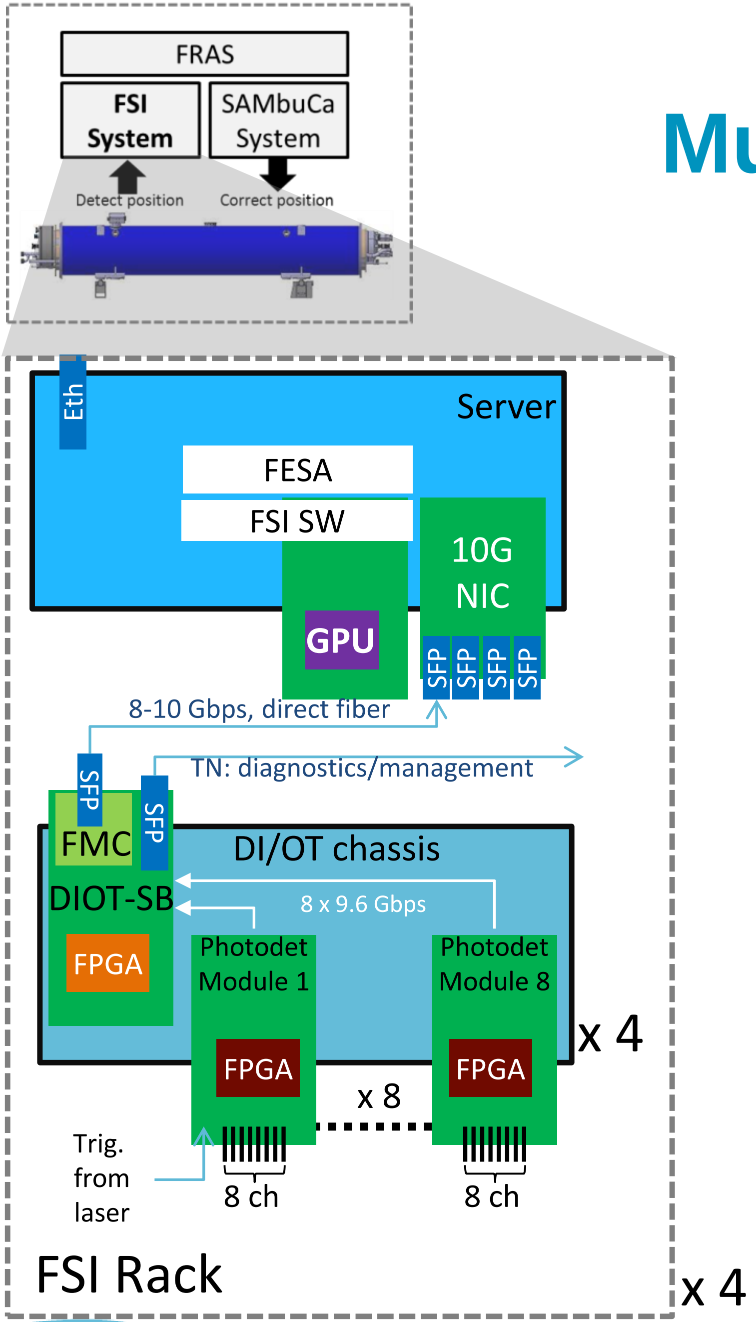
- To replace current capacitive sensor
- Design with thin wall bellow protection against the dust

- Expected measurement uncertainty < 5µm
- Precision ~1 µm
- Maximally simplified (bare-ferrule + glass ball reflector) to increase reliability



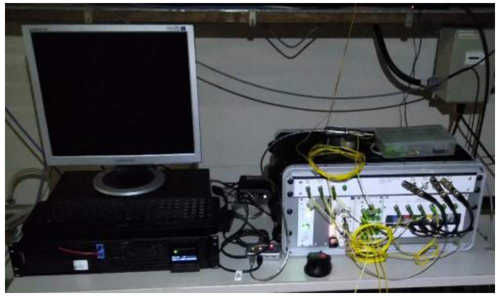


Multi-Target FSI – interferometers



Measurement setups:

- Proof-of-concept with **2 channels** by BE-GM in **2017**
- Portable measurement setups (16..24 multiplexed channels) in 2019/20



HL-LHC production setup(M. Lipinski – BE-CEM-EDL):

- Final system with **1000 channels** by BE-CEM for **LS3**
  - Based on **DI/OT**
  - Custom **photodetector acquisition module**
  - **10 Gbps Ethernet** links to GPU servers
  - **Advanced computations in GPUs** (FFT, linearisation, fitting)
  - Over **1 Tbps** of raw data produced by all channels
  - Over **3 GB** of data to be processed each second by 4 GPU servers
  - Demonstrator: end of 2021

FSI test setup

FSI photodetector module

Conclusions

- Fourier analysis based FSI allow to track distances to various types of reflectors or reflecting surfaces (with various intensities of interference beat signals)
- Appropriate approach to sensor design, combined with MT-FSI properties makes it possible to create very simple and robust sensors and sensor networks
- Reduction of the optics complexity, allowed to use absolute interferometry for big-scale installations

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Thank you for your attention