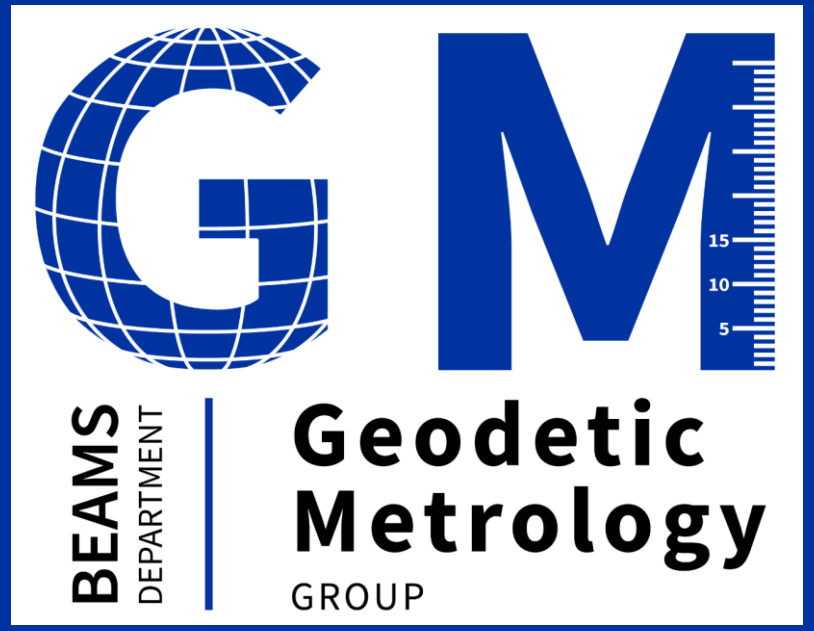


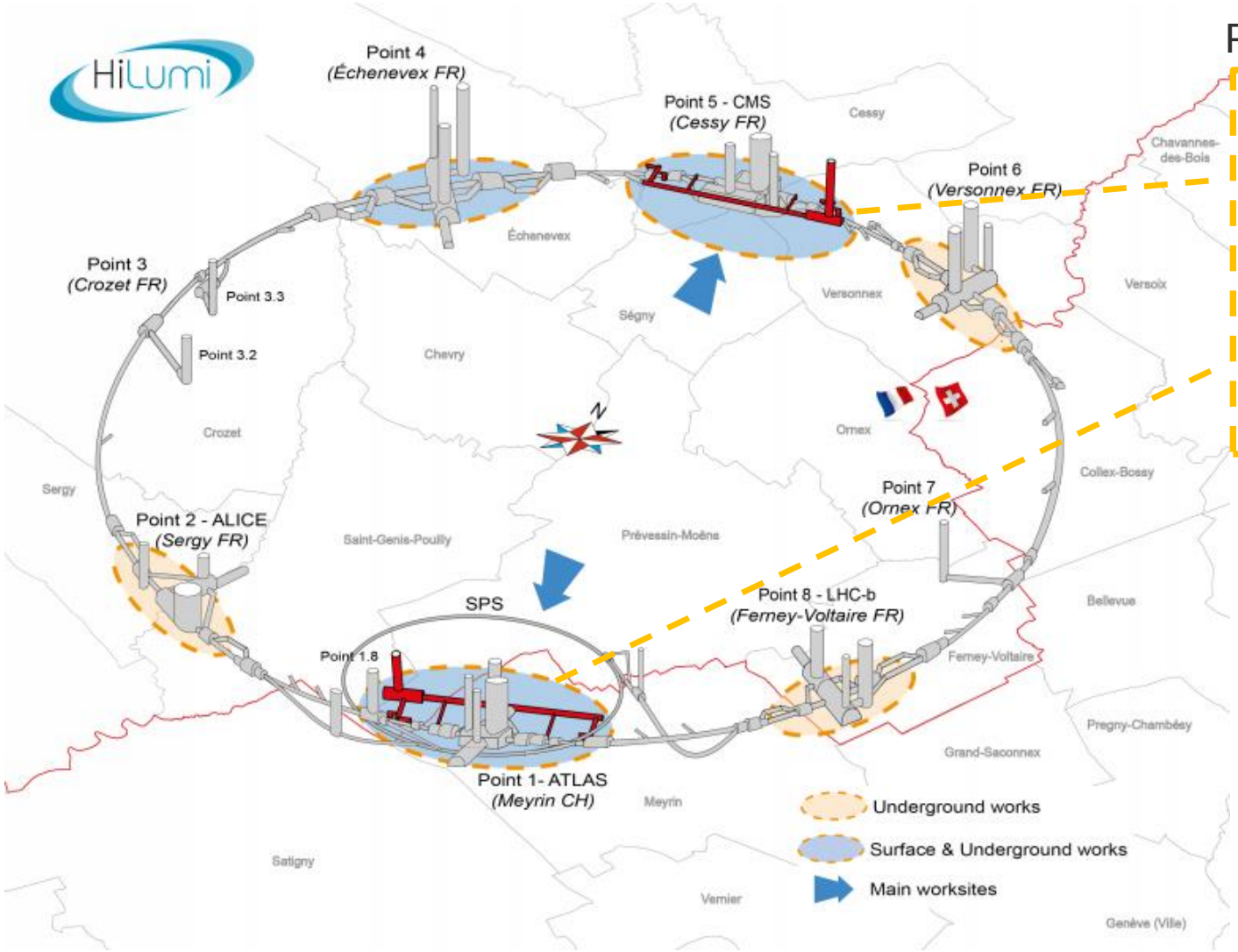
Development of robust, low-cost, sensors and adjustment systems for micrometric alignment

Mateusz Sosin, BE-GM-HPA

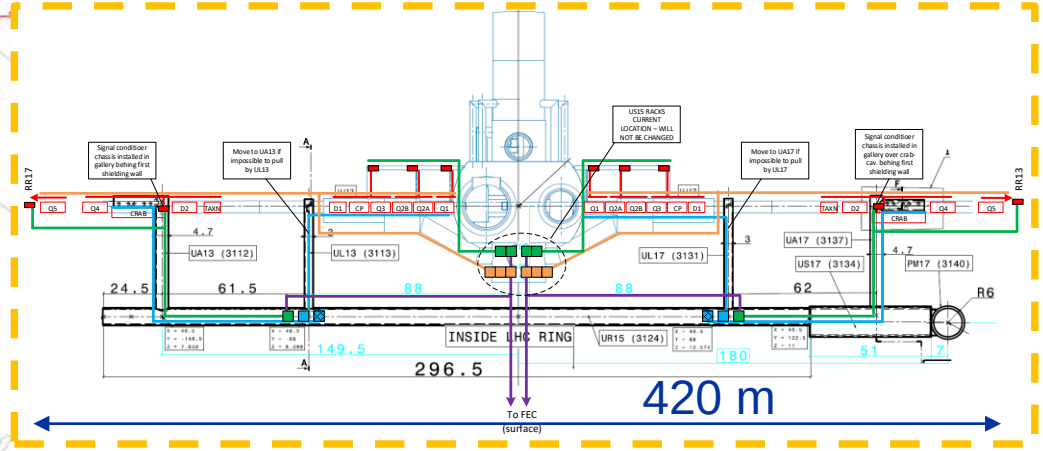
Outline

- High-Luminosity LHC (HL-LHC) and Full Remote Alignment System
  - **Need of simple, robust and maintenance free systems**
- Multi Target Frequency Scanning Interferometry (MT-FSI)
- Wire Positioning System – capacitive sensors
- Position adjustment systems and precise electro-mechanics

HL-LHC Full Remote Alignment System (FRAS)



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



Requirements:

- Alignment of components → **< 0.1 mm (150 m); < 0.5 mm (420 m);**
- 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
- Remote alignment of collimators, masks, magnets

FRAS – Scale of the system

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

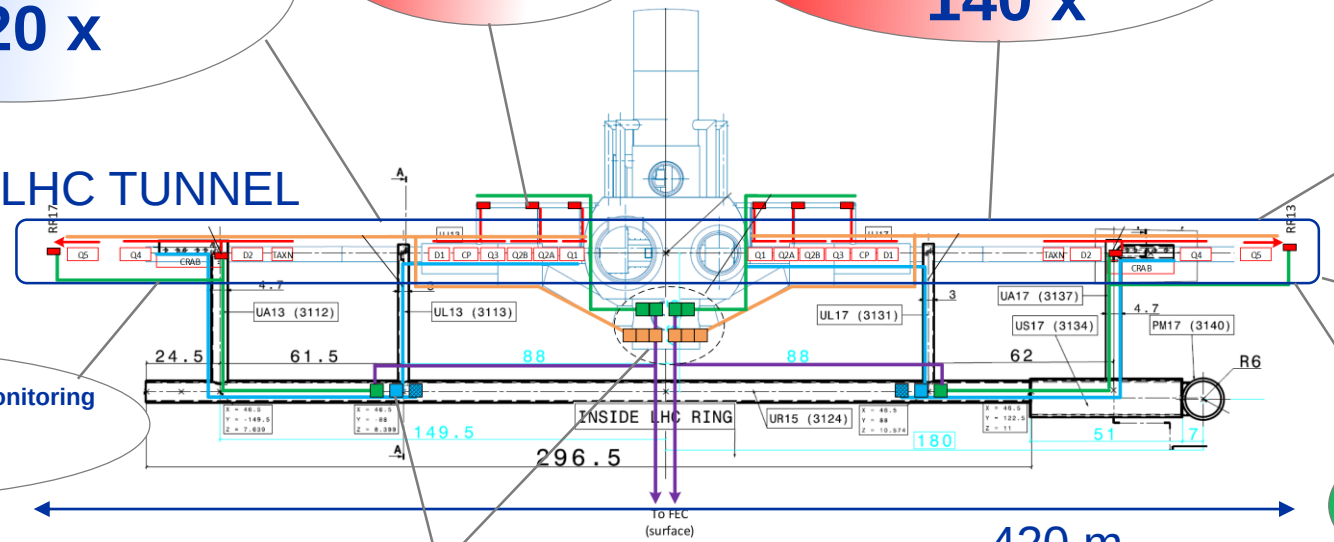
Capacitive sensors electronics (rad-tol)

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

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

LHC TUNNEL

TID ~1MGy
T=20..25 °C



Inclinometer
70 x

Magnets longitudinal position monitoring
48 x

Remote adjustment (motorized platforms and jacks)
>300 motors

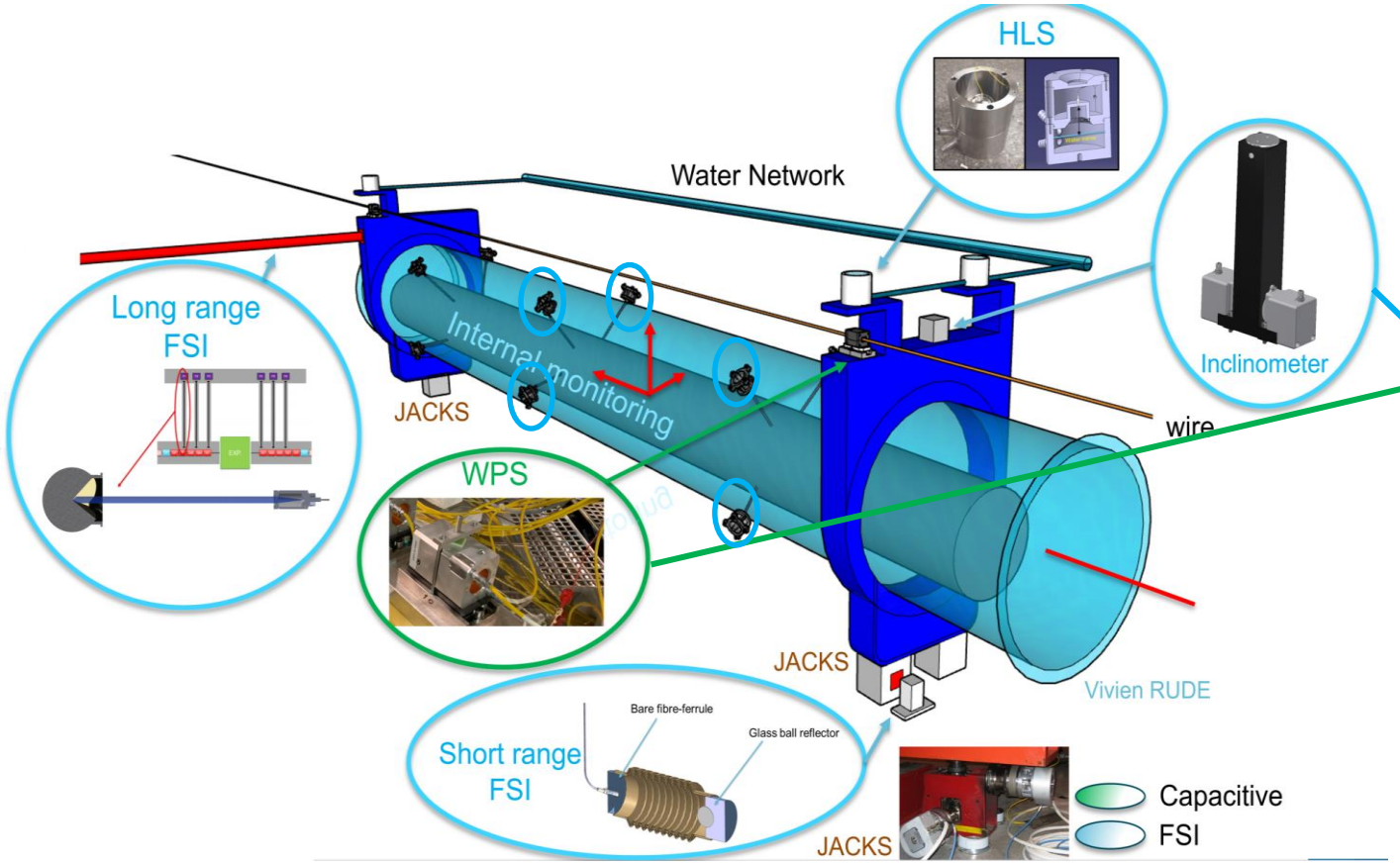
Interferometers /motors electronics

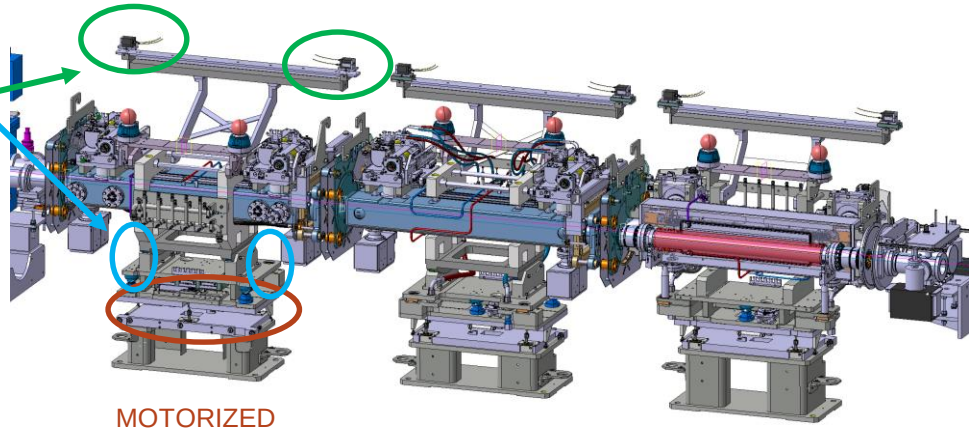
Capacitive

Frequency Sweeping Interferometry

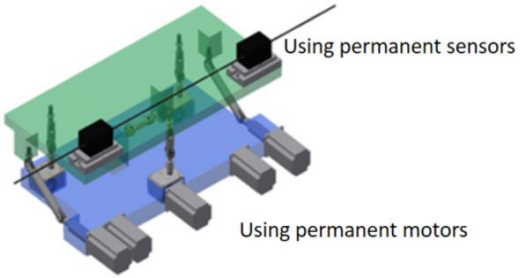
Adjustment mechanics

FRAS – Sub-components of the system

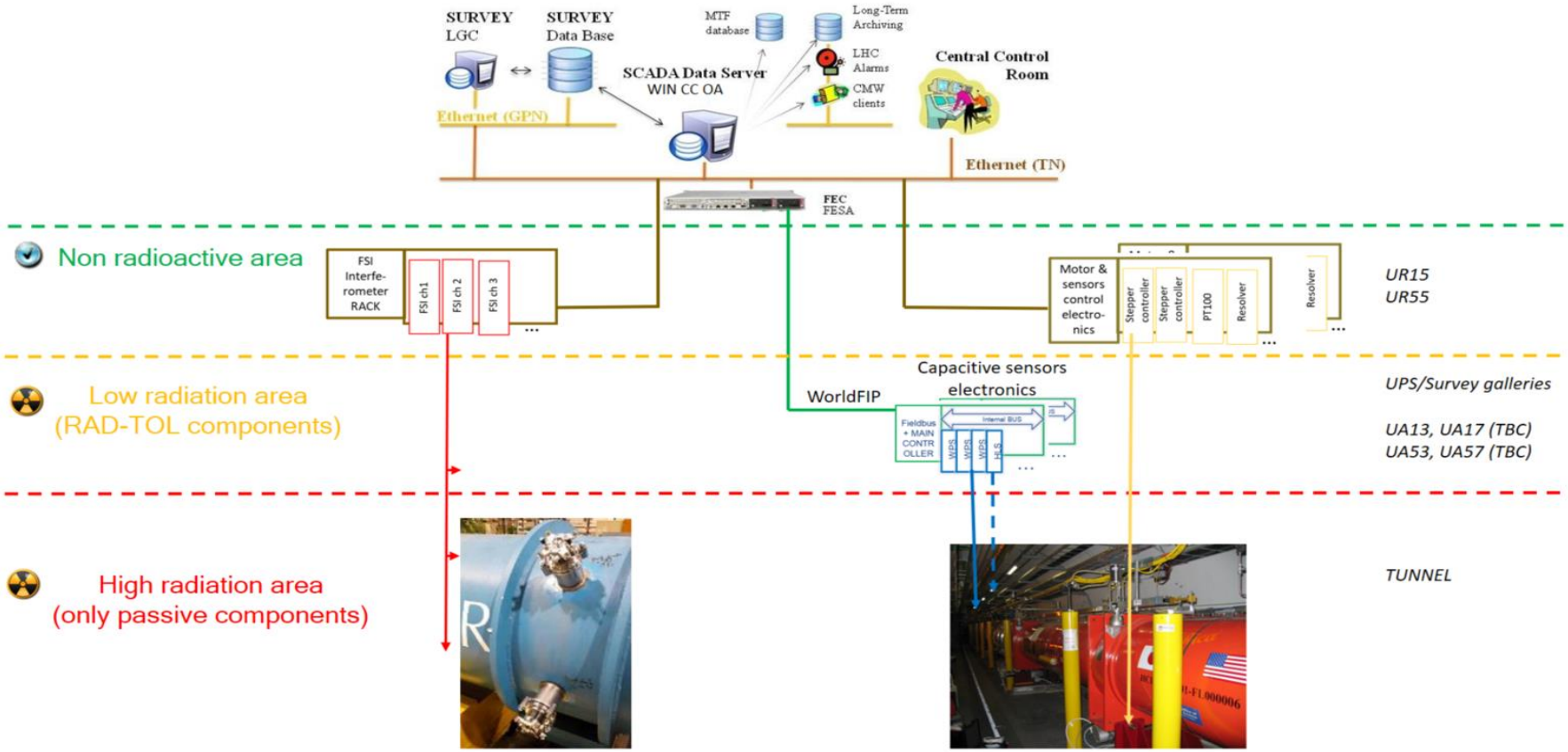




MOTORIZED
PLATFORMS



FRAS – Controls / data acq.



FRAS – Optimization

Simple, robust and maintenance free systems needed !!!

Frequency Sweeping Interferometry as position monitoring „workhorse”

- Absolute measurements, uncertainty (per ch) better than 10 µm / 10 µrad required
- EM immunity, cheap sensors and fibres, robust

Capacitive Wire Position Sensors – streatched wire (radial alignment)

- Only technology allowing for X-Y micrometric alignment w.r.t. stretched wire
- Sensitive to dust and EM noise (short cables required)

Remote adjustment

- Standardization of motorized jacks and Universal Adjustment Platforms

Electronics and controls located in non radiaiton or low-radiation areas

Multi-target Frequency Scanning Interferometry (FSI) Instrumentation

MT-FSI introduction

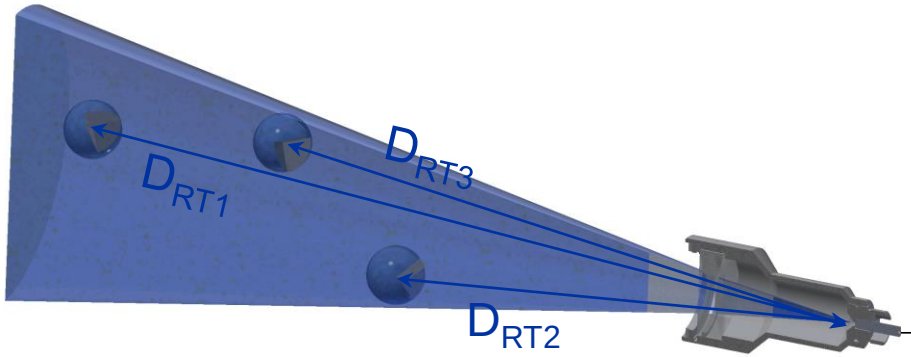
Retroreflective targets

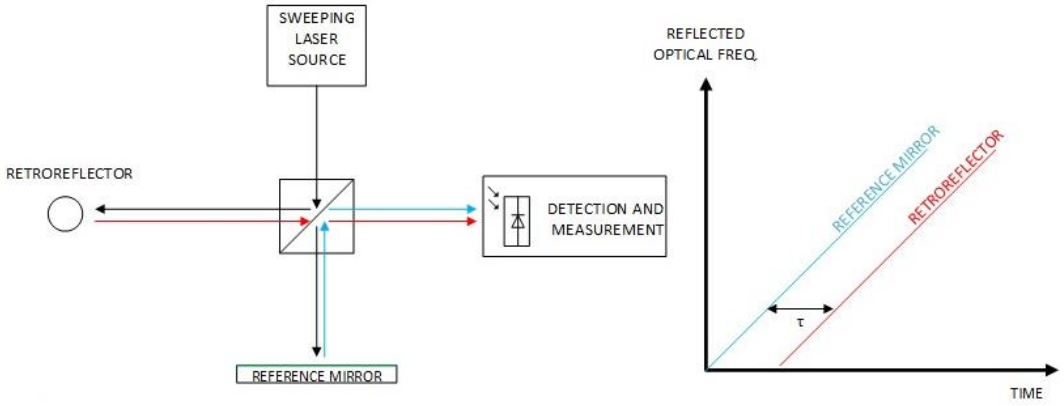
Triplet and crab cavity internal monitoring

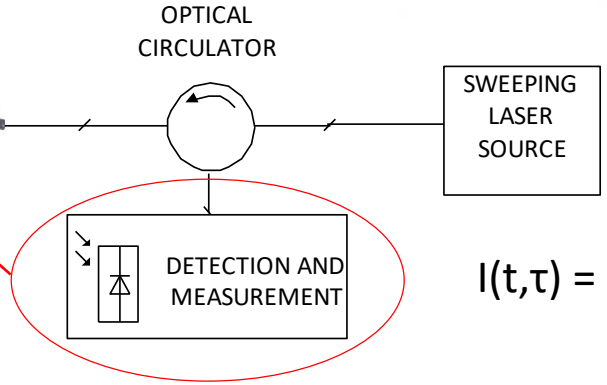
Sensors

- Interferometric iHLS sensor
- Inclinometers for magnets, masks and collimators
- Short/Long distance sensors

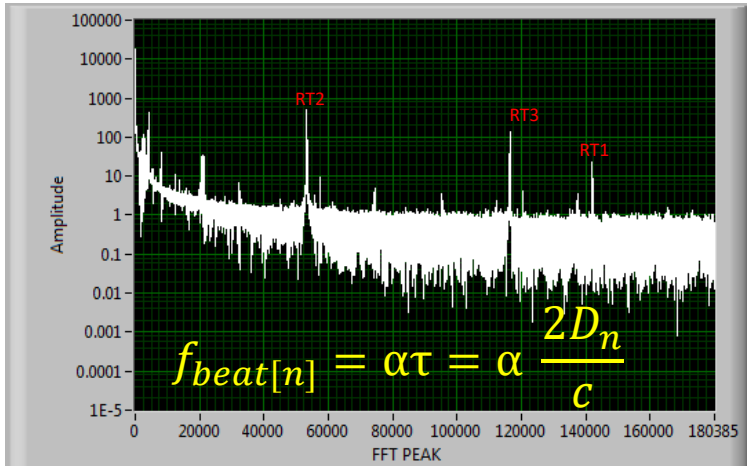
Multi-target FSI







FFT



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

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

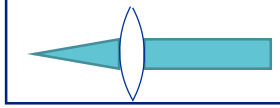
α – is a sweep rate of the laser ($\alpha = \frac{d\nu}{dt}$ - laser frequency change in time); c – speed of light; n – refractive index of light transmission medium; τ – time of flight of laser to the target

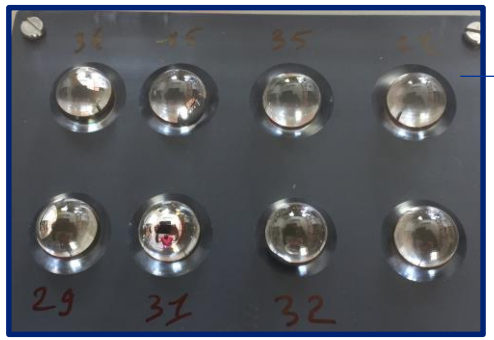
Multi-target FSI – laser radar

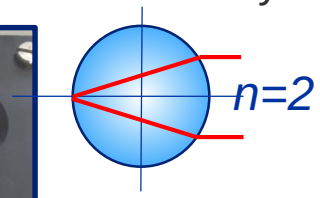
- **Very robust measurement method – almost insensitive to the light intensity (high and very small power reflections visible over the noise background**
  - Possible to use cheap glass balls as a reflectors
  - Possible to measure reflection from various surfaces
- Measurement uncertainty <5 µm (single laser configuration, no vibrations)
- Measurements of distance to multiple targets within single laser scan
- Collimated and divergent beams compatible
- Simple beam delivery optics
- Optical system allows easy increase of channel number

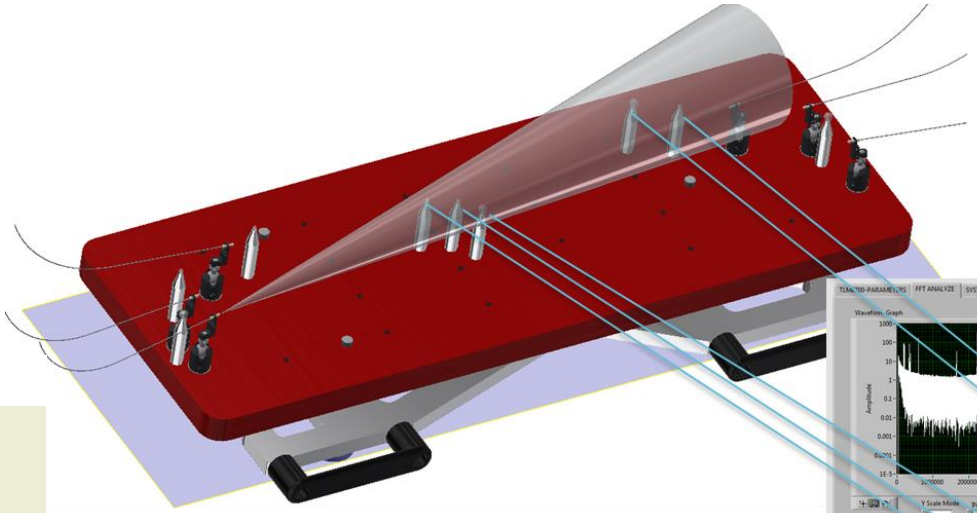
Divergent beam

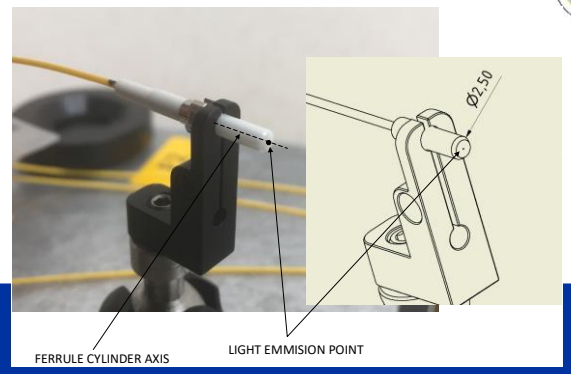
Collimated cylindrical beam

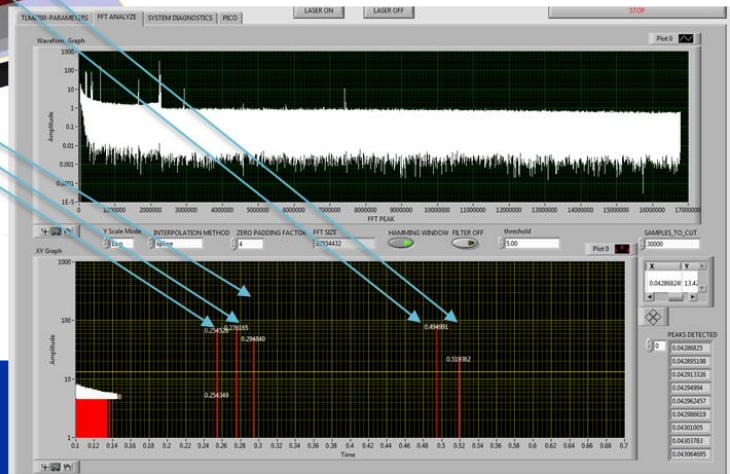










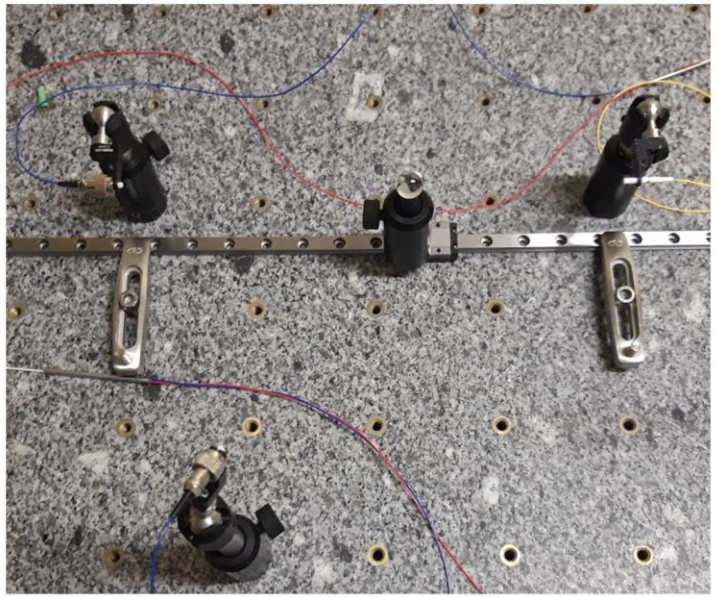


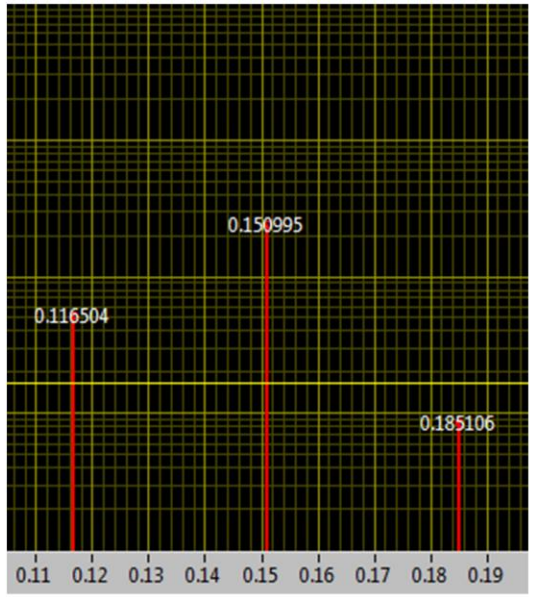
Multi-target FSI - optical systems applications

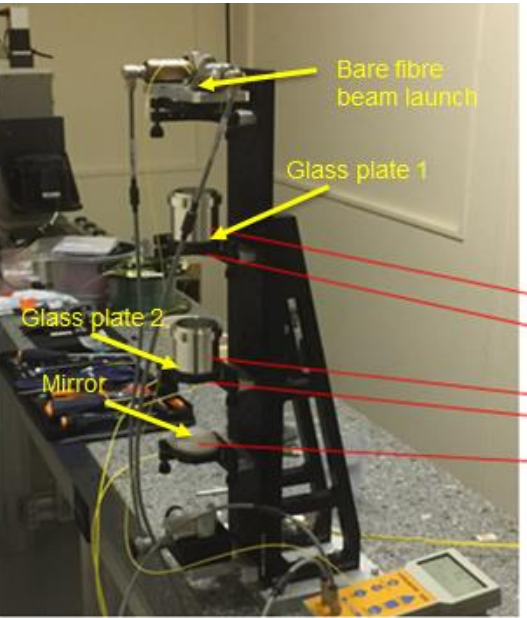
Multiple reflection applications

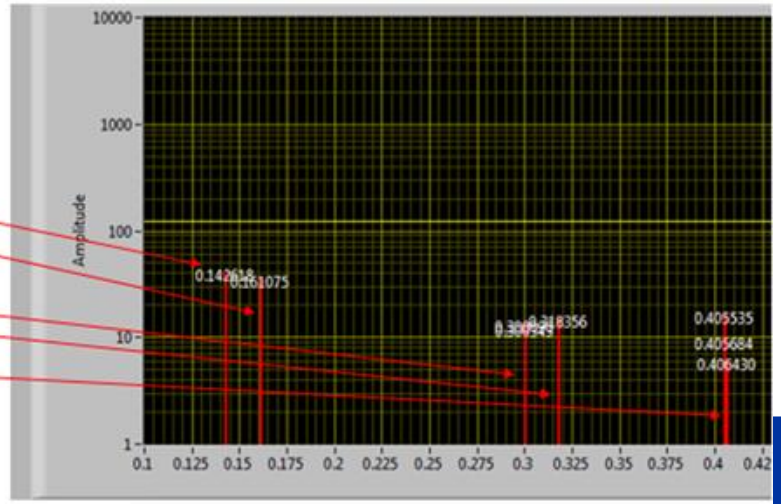
Multi-reflection sensors

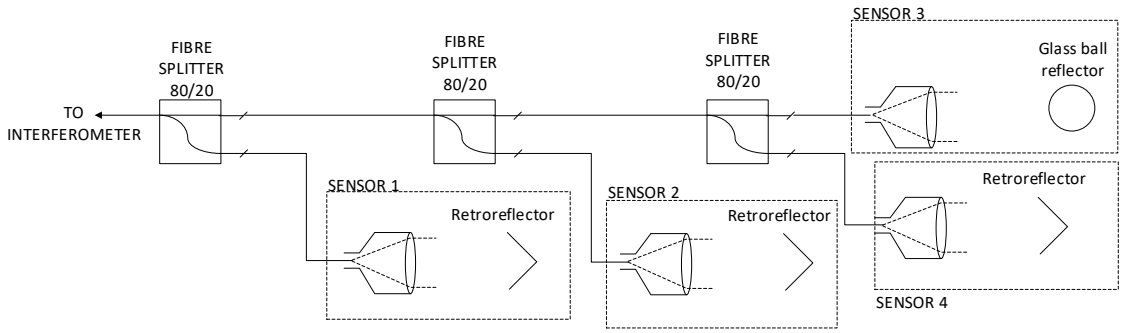
Multi-sensor solutions (serial connection of sensors)





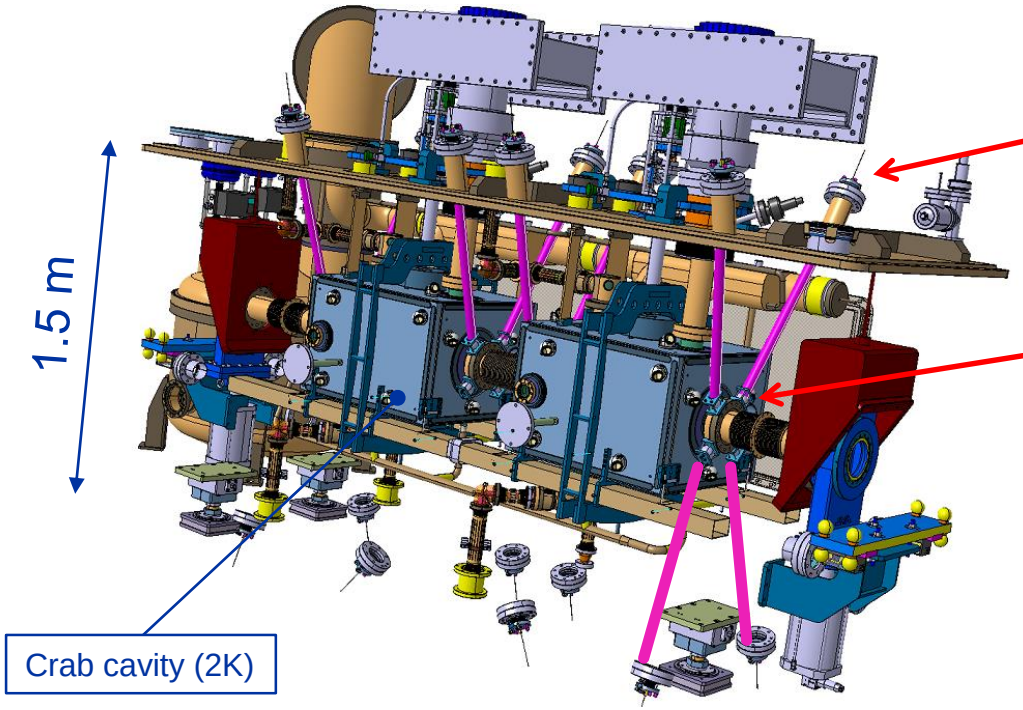


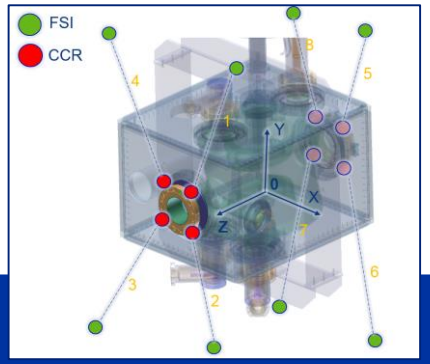


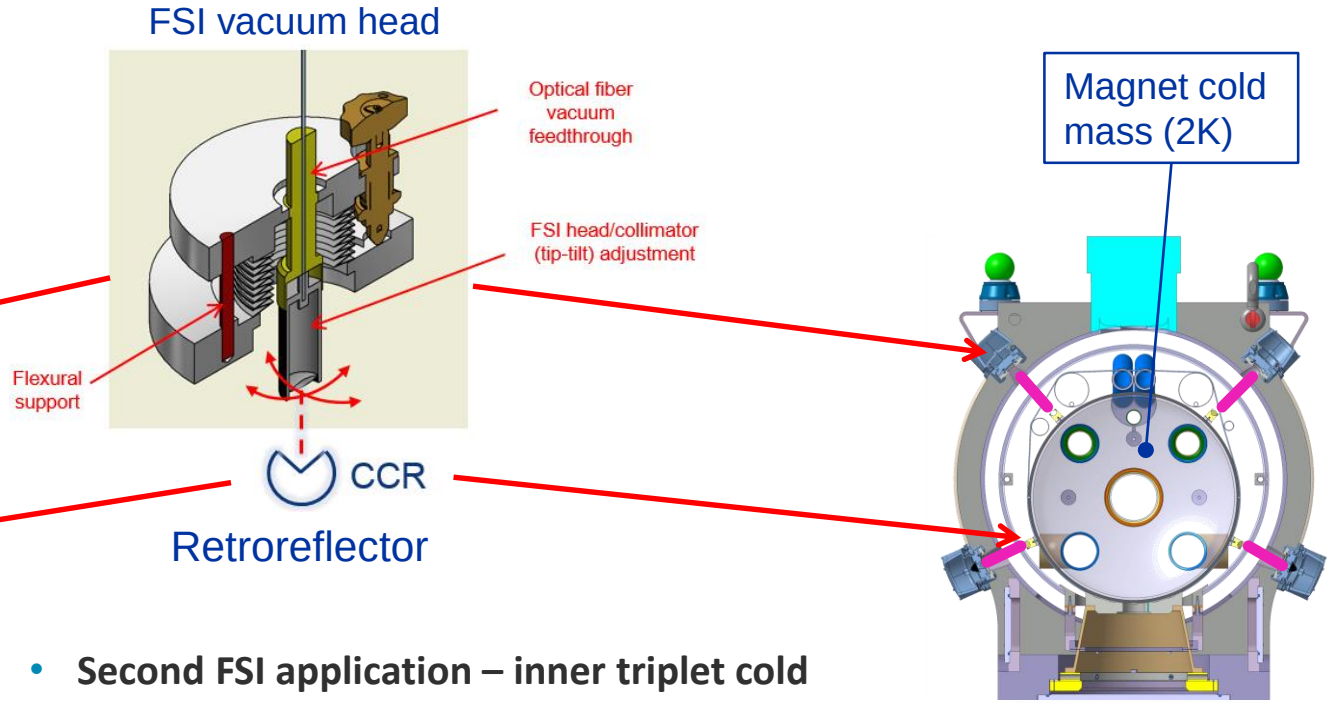


Internal monitoring of cold objects inside cryostats

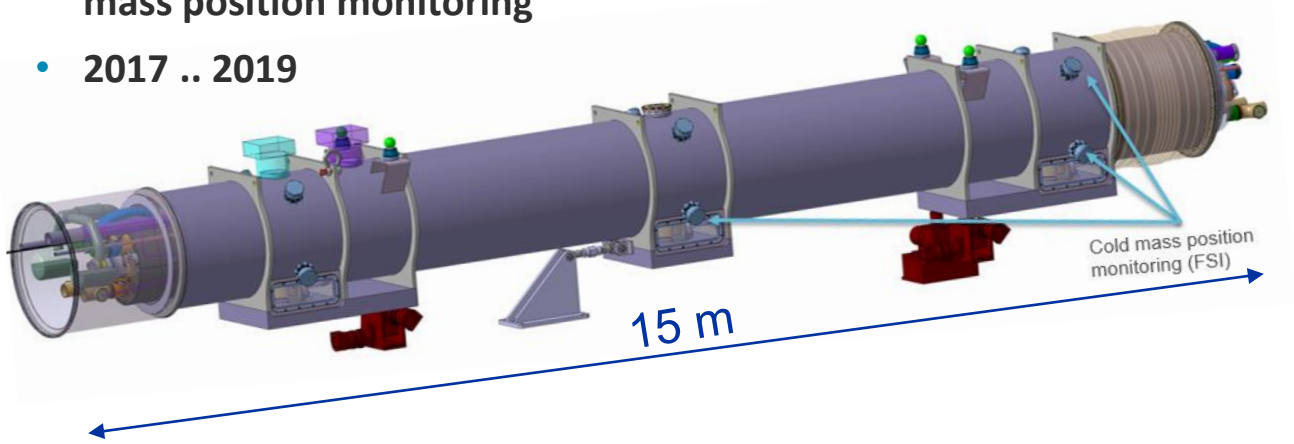
- **First FSI application – crab cavity position monitoring**
- **2016 .. 2018**







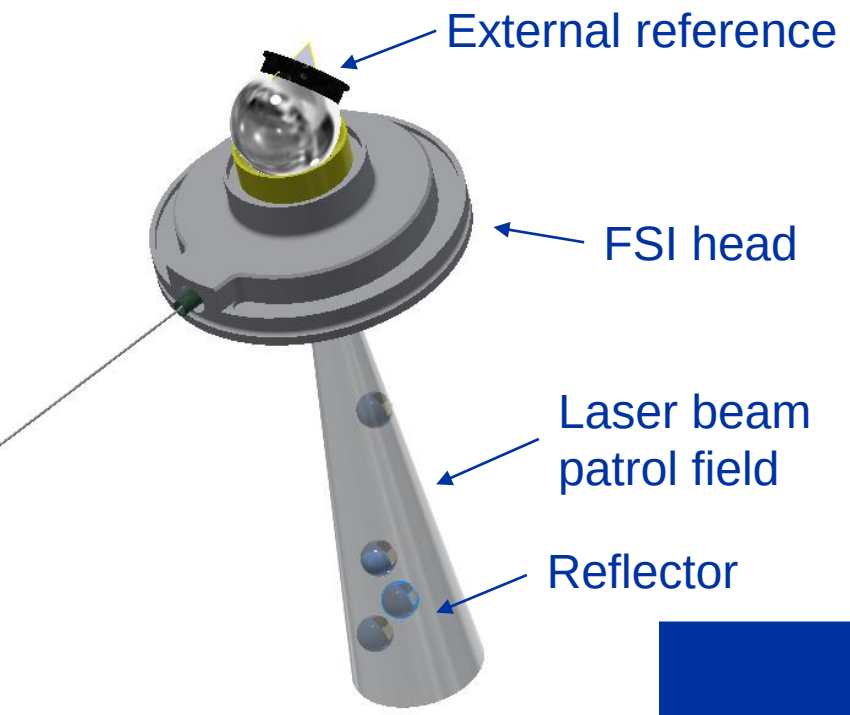
- **Second FSI application – inner triplet cold mass position monitoring**
- **2017 .. 2019**

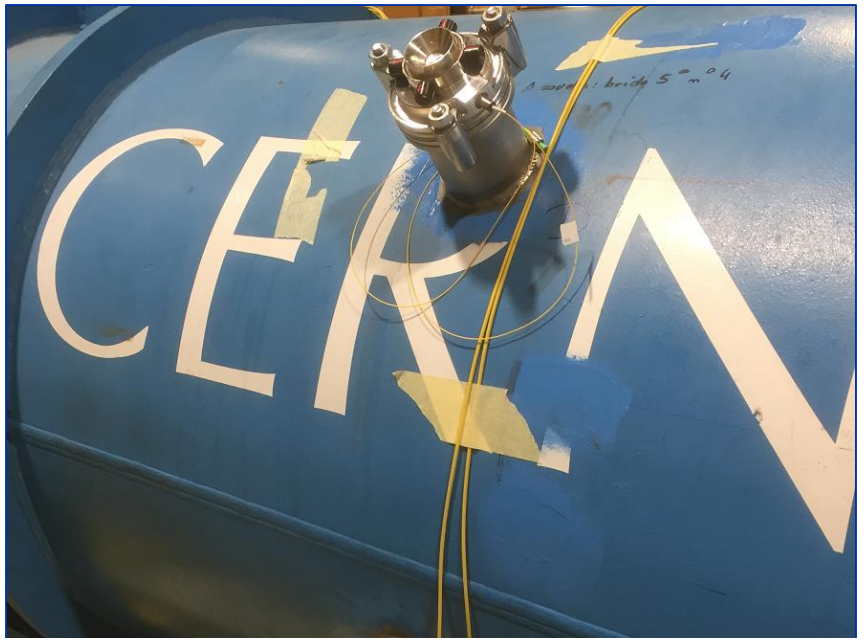


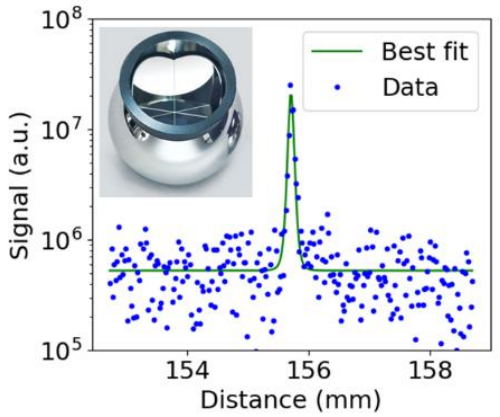
MT-FSI Instrumentation – vacuum heads & reflectors

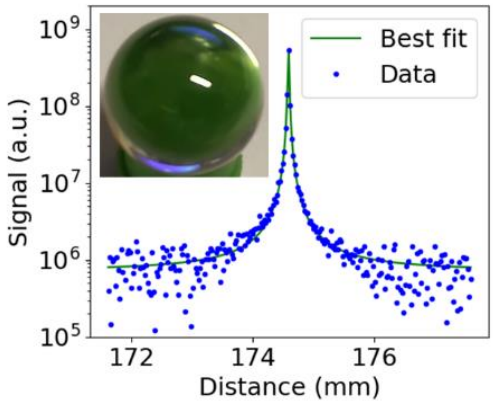
Simple vacuum FSI head for HL-LHC internal monitoring

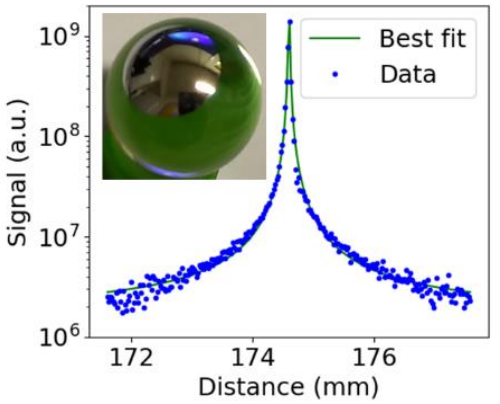
- **No moving parts, cheap, single steel body design**
- **Wide patrol field – big lateral reflector movement range**
- **Low cost (bare fibre ferrule beam launch)**







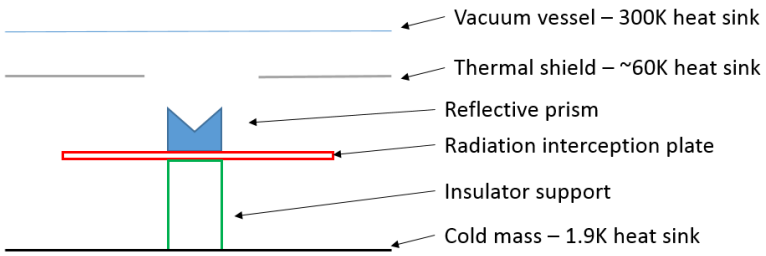




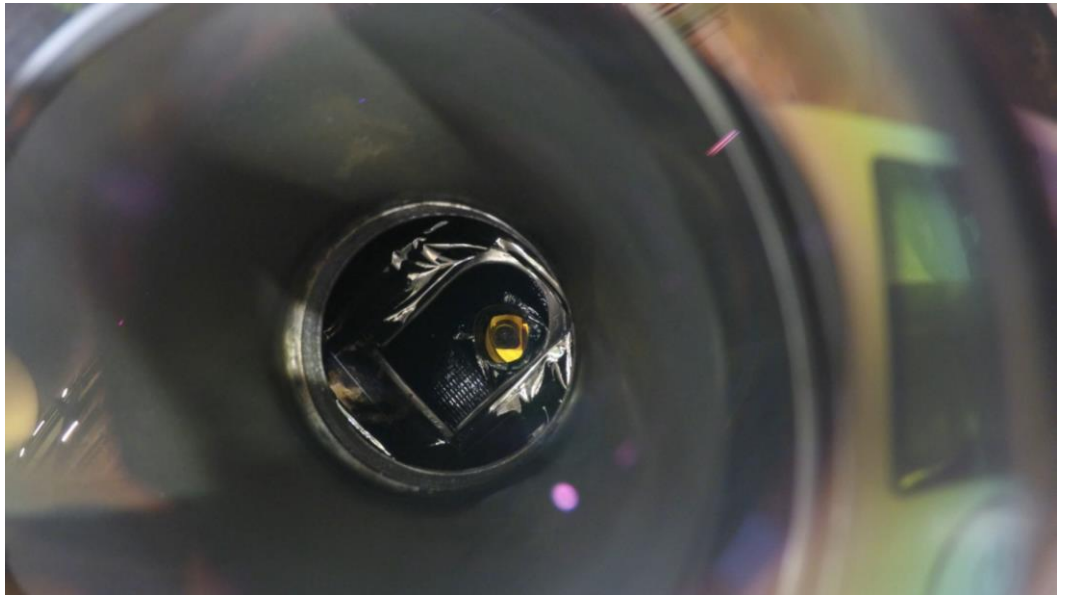
MT-FSI instrumentation - cryo-compatible reflector supports

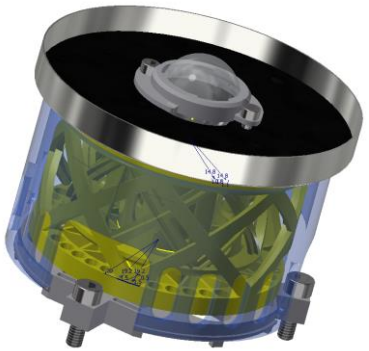
„Passive", SIMPLE design to suppress cryo-condensation effect

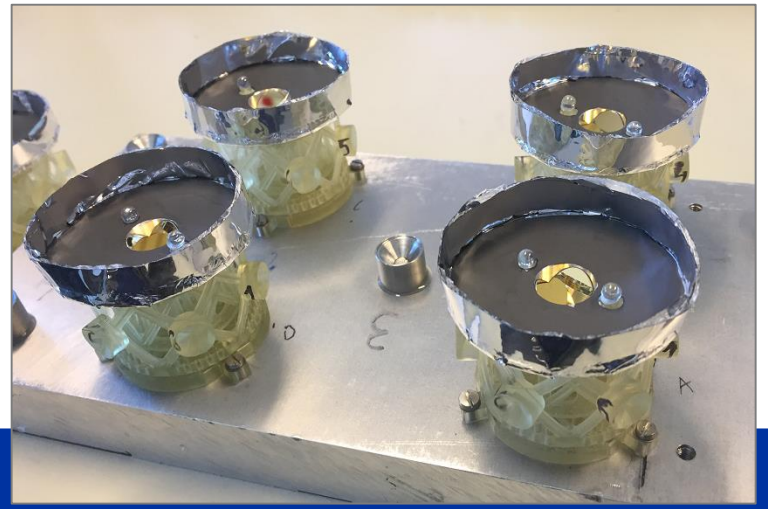
- **3D printed targets to provide complex insulator shape**
- **Graphite coated, heat interception plate**
- **MLI film to minimize heat radiation towards cold mass of magnet**

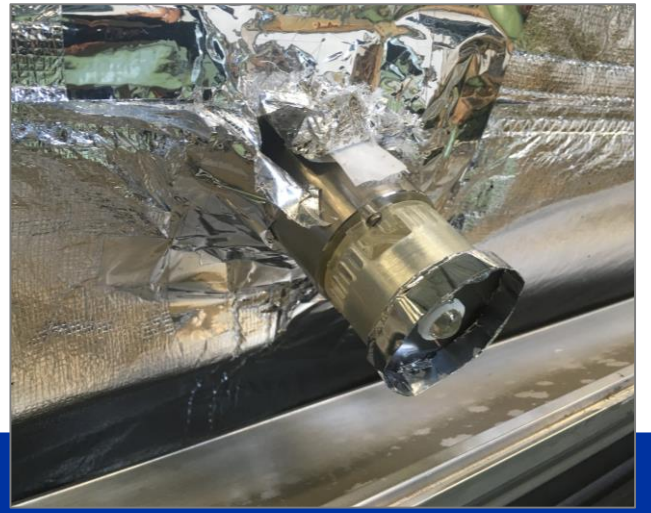


F. Micolon

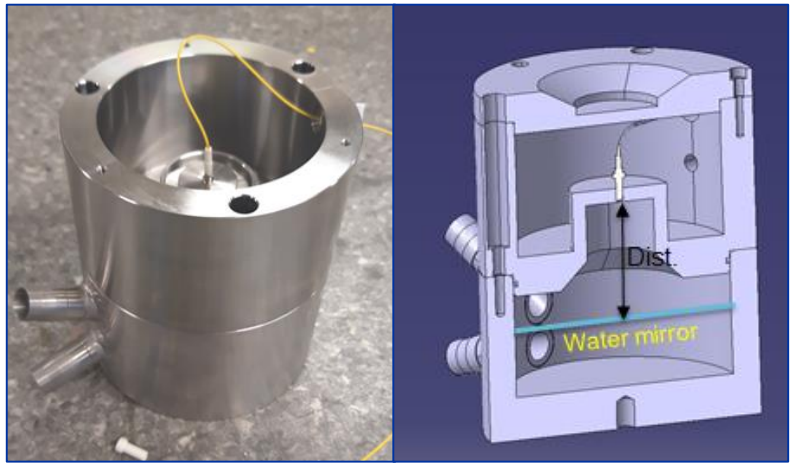






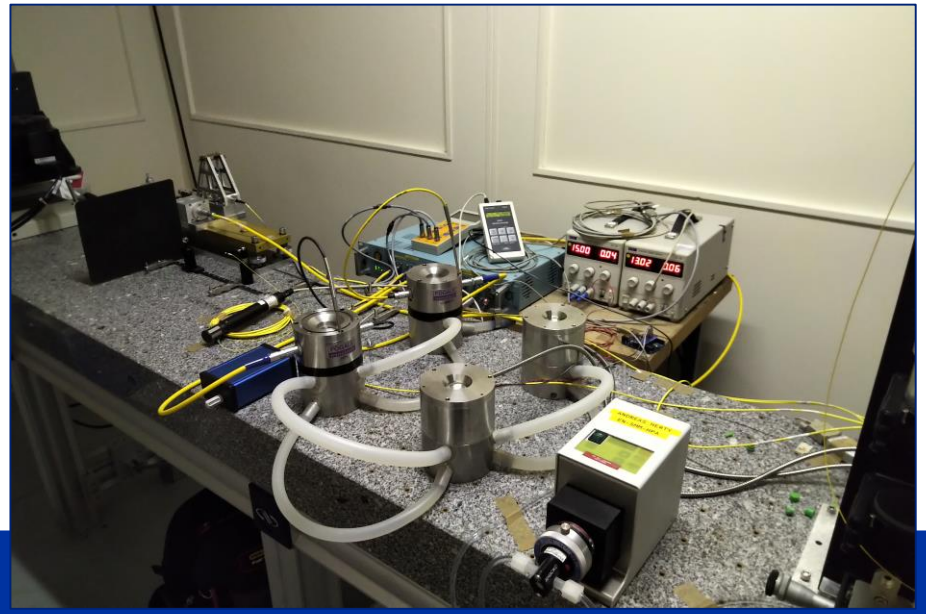


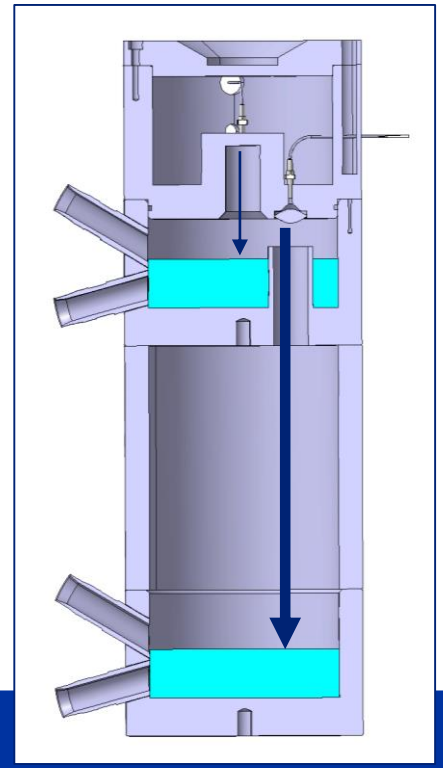
MT-FSI Instrumentation – interferometric Hydrostatic Levelling Sensor (iHLS)



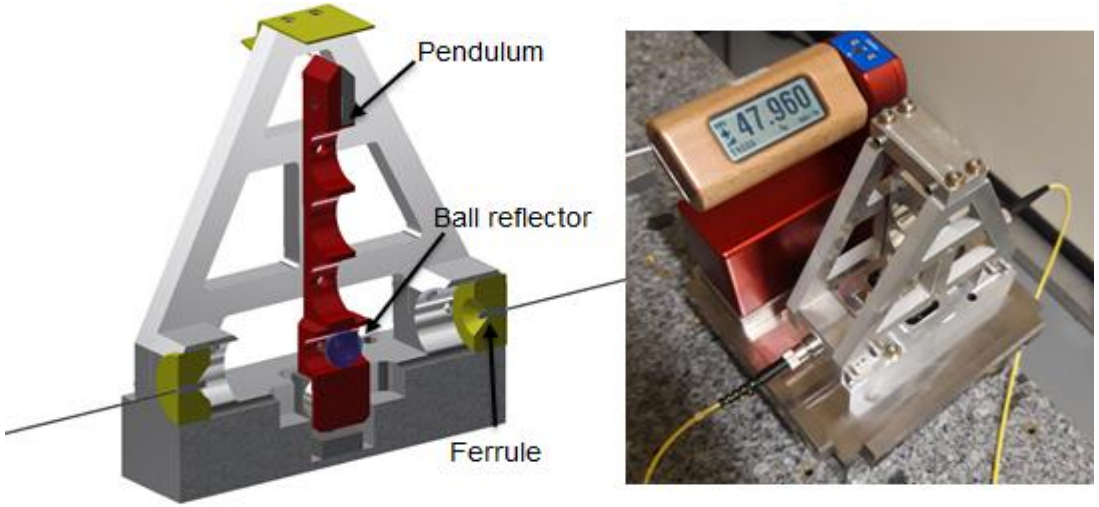
Cost optimized, divergent beam FSI HLS sensor for HL-LHC

- Single metal body chassis, no movable parts, minimum amount of optical components
- Measurement uncertainty < 5µm, precision ~1 µm
- Multiple level iHLS sensor under design
- Long term measurements coherent with cHLS

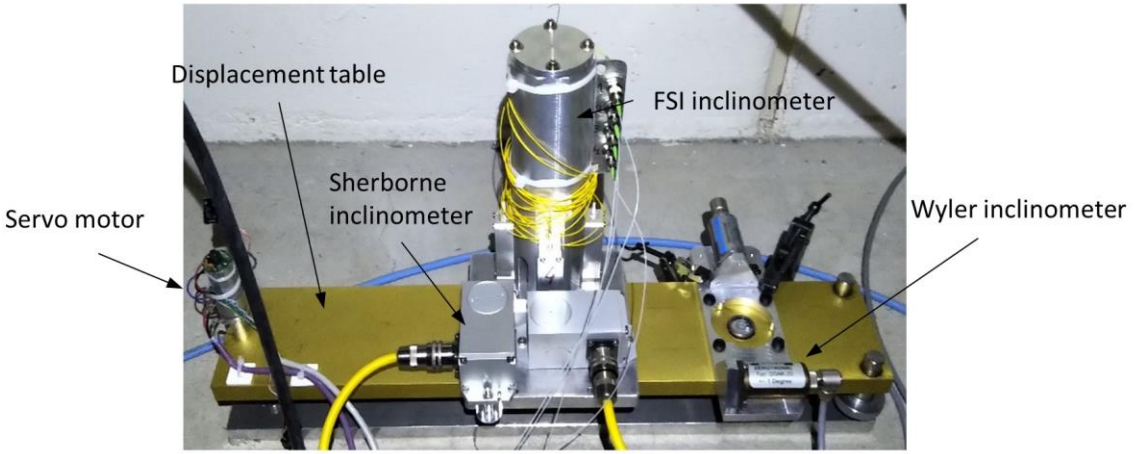




MT-FSI Instrumentation – optical inclinometer



1-st prototype (1-axis)

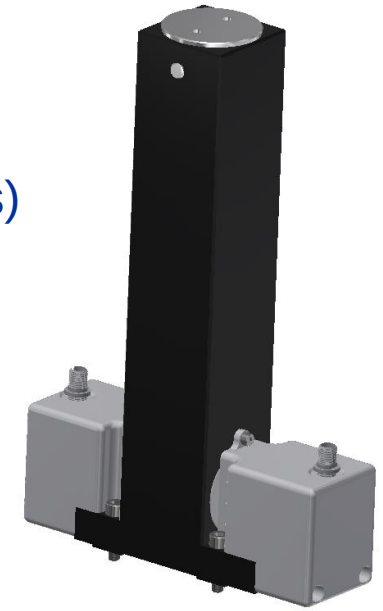


2-nd prototype (2-axis)

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

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

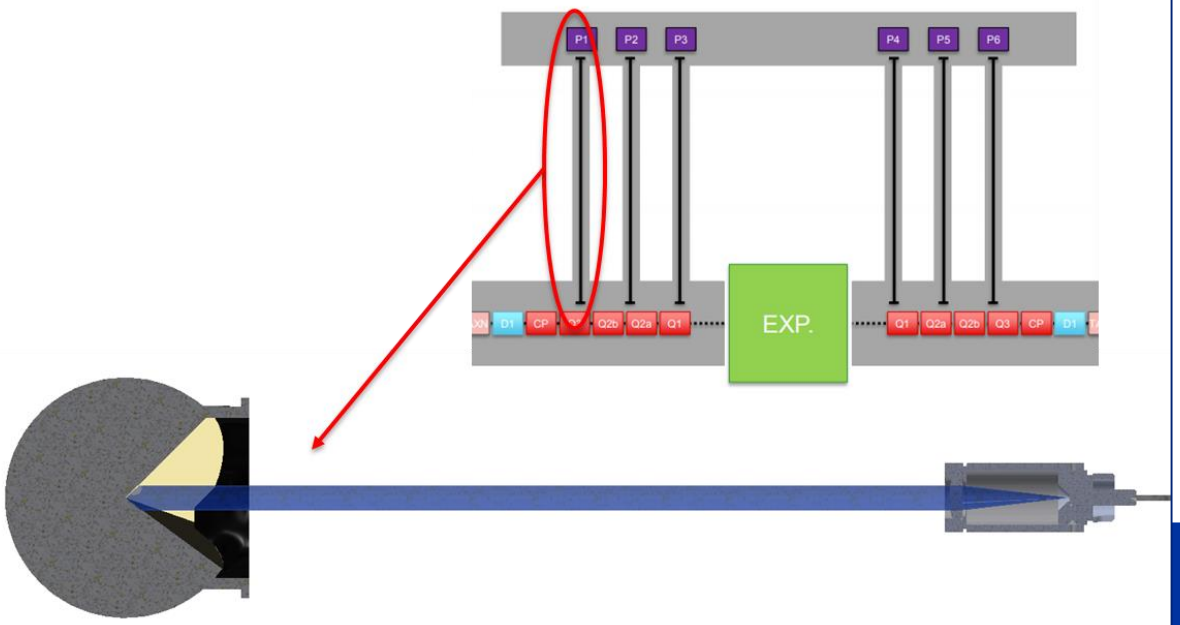


Multi-Target FSI – Long/Short distance measurement sensors

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



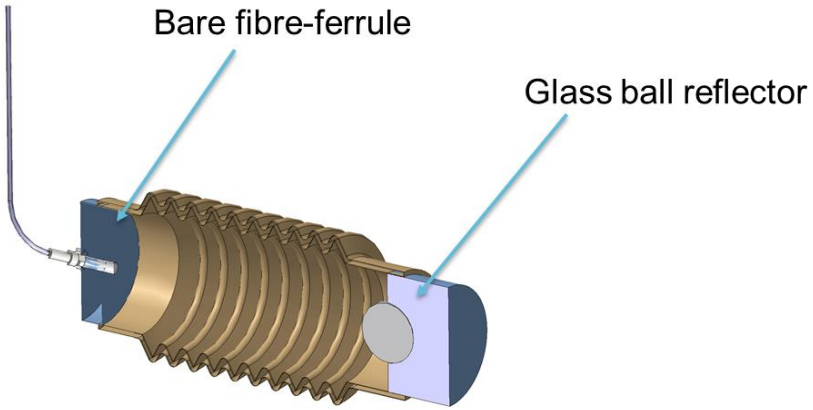
Short distance measurement sensor (range ±5 .. 10mm)

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

Expected measurement uncertainty < 5µm

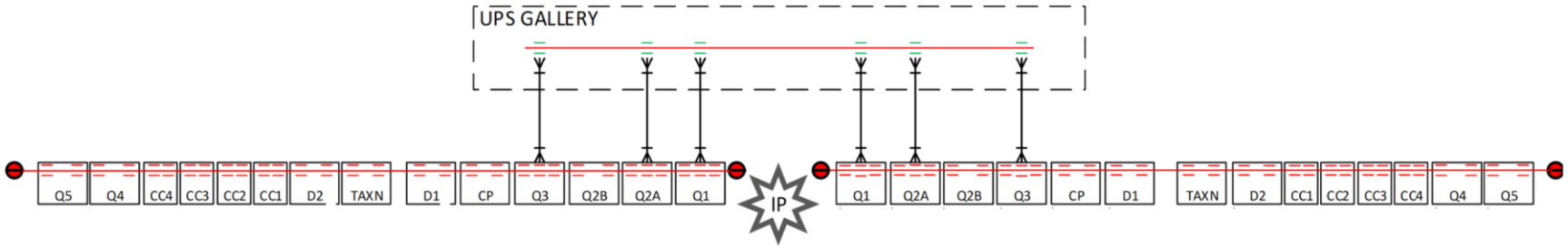
Precision ~1 µm

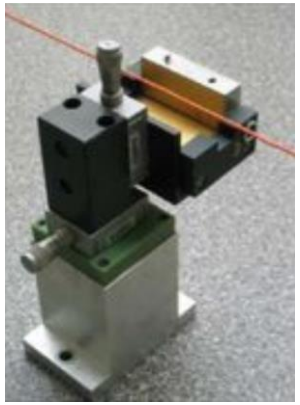
Maximally simplified (bare-ferrule + glass ball reflector) to increase reliability

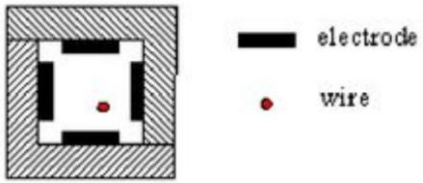


Low cost WPS sensor and RAD-TOL electronics

Wire Positioning System - Capacitive measurements

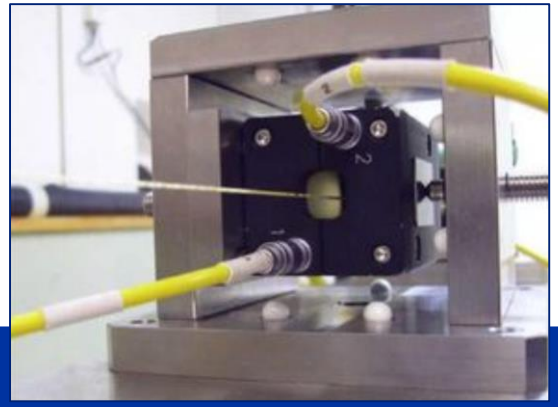






WPS sensor

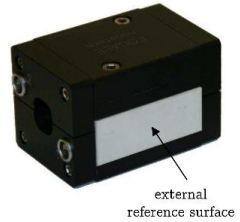
- X-Y measurement w.r.t. stretched conductive wire
- Accuracy < 5µm, Resolution < 1µm
- **Limited cable length (max. 30 .. 50 m)**
  - **Conditioning electronics need to be RAD-TOL**

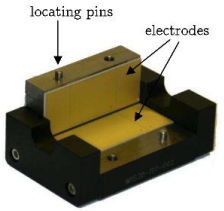


R&D on electronics and WPS sensors

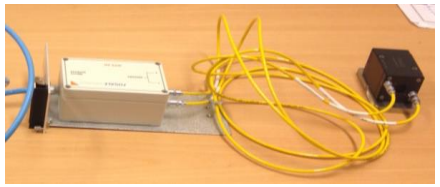
- Previous solution
  - „BLACK BOX” solution
  - Delivered in sets (sensor + conditioner + cable)
  - No remote diagnostic possibility
  - **Expensive (~4k EUR SET)**

Currently used sensor

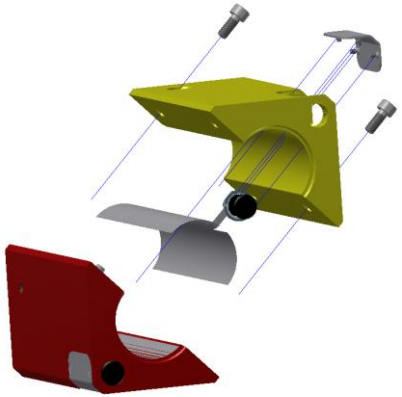


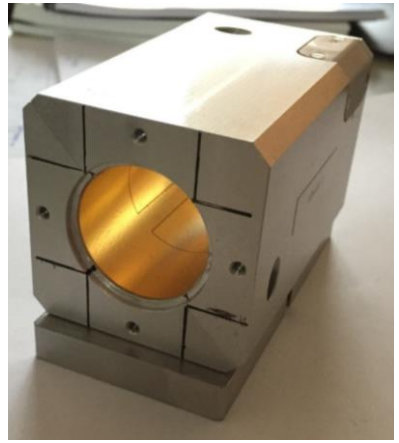


5 x 5 x 8 cm



- CERN P-WPS + universal capacitive sensor conditioner
  - Simple and cheap **(2x cost reduction)**
  - Compatible with current supports
  - Adopted to vacuum wire replacement system (round aperture) – **Broken wire replacement function**
  - Radiation tolerant
  - Provides remote diagnostics of electronics, sensor performance
  - Provides remote parameters tuning

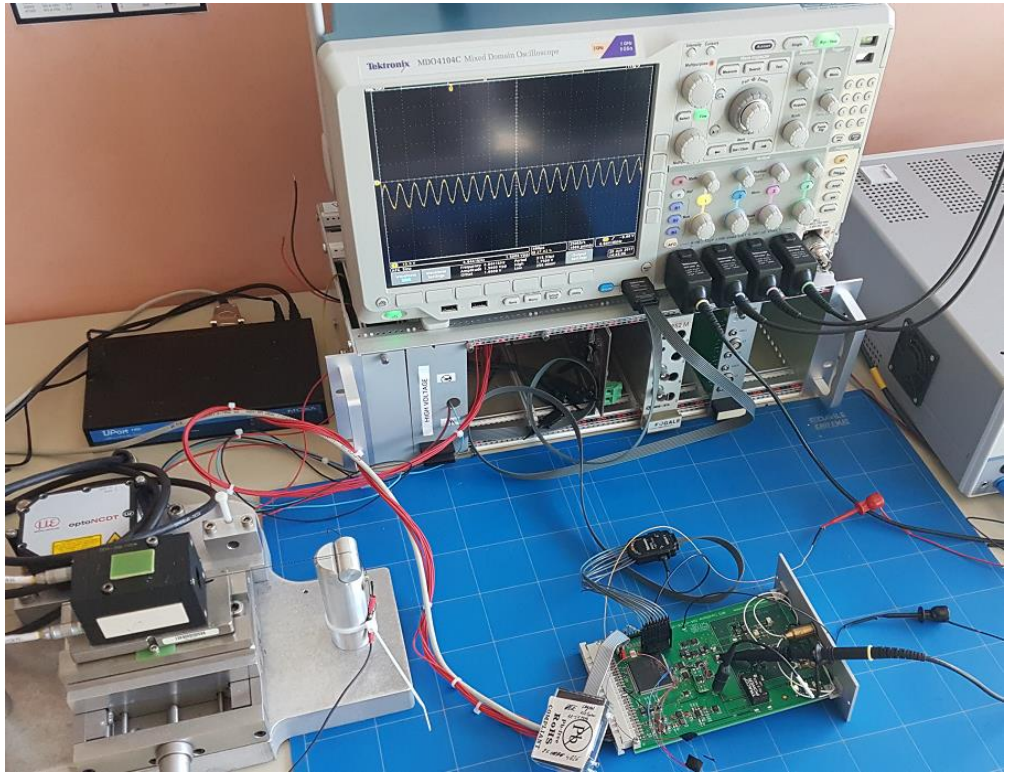


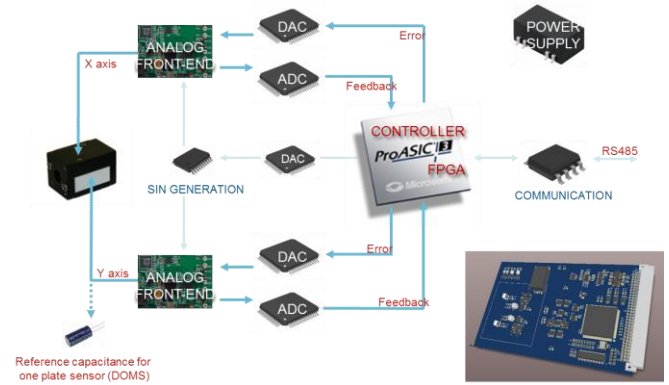


6 x 6 x 10 cm

CERN conditioning electronics – standardized modules

- Standardized capacitive sensors signal conditioner
  - ‚Deep' diagnostics of signals and sensing chain
  - RAD-TOL (200Gy)





Capacitive WPS design - Conclusions

- WPS is example of technology, which is difficult to implement in harsh environement due to technology limitations
- All fragile components of the WPS are evacuated from harsh environement
- Nevertheless ... appropriate approach of sensor and electronics design, makes it possible to create **cheap**, **simple** and **robust** sensors

Adjustment systems optimization

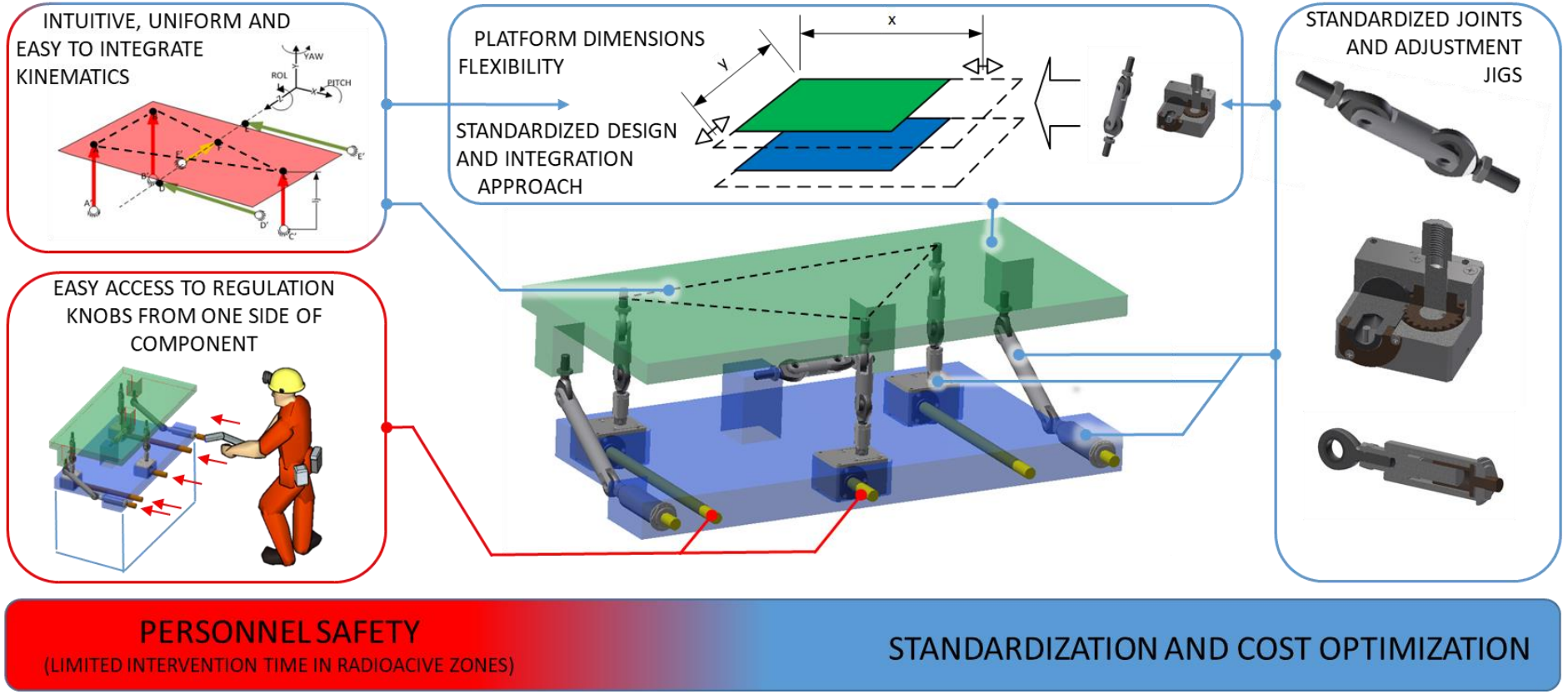
Universal Adjustment Platform (UAP)

Modular motorized adapters for jacks and platforms

Universal Adjustment Platform

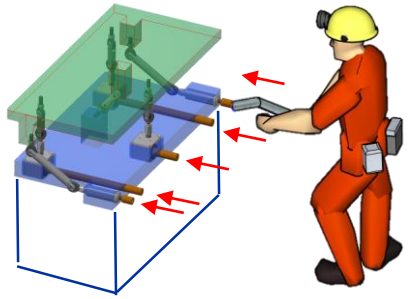
Definition of set of design rules and development of standardized and modular components to:

- increase safety of surveyors
- unify small (<2T) accelerator components adjustment systems
- decrease price of implementation of adjustment systems



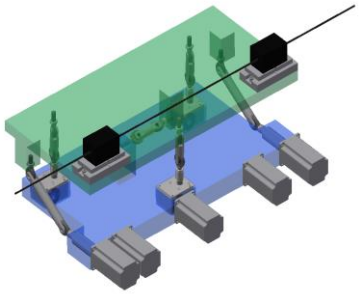
Universal Adjustment Platform

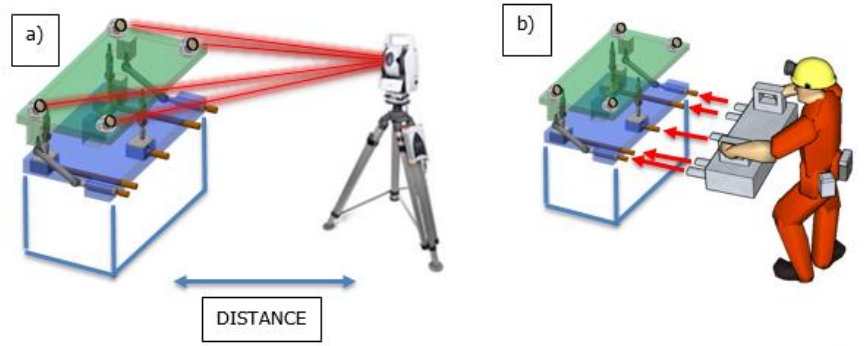
Allows for various operation use cases

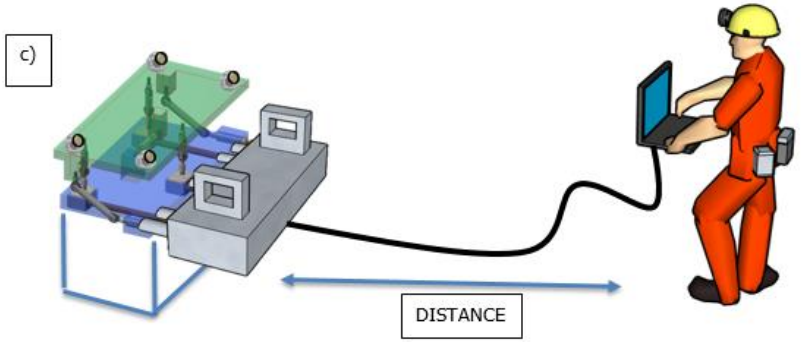


Universal adjustment platform – manual operation concept

Universal adjustment solution - permanent motors version concept. Platform equipped with WPS sensors





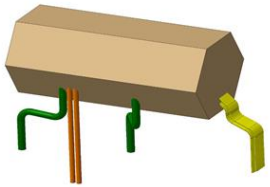


Universal adjustment solution – concept of use plug-in motors:
a) Platform measurement from distance using a laser tracker;
b) Installation of plug-in motors in less than one minute;
c) Remote adjustment from distance.

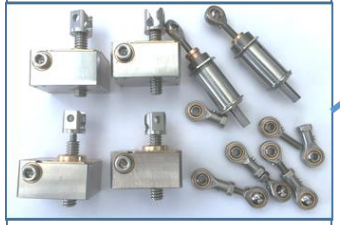
Plug-in motorized version - principle

UAP as a design FRAMEWORK

COMPONENT TO BE ALIGNED

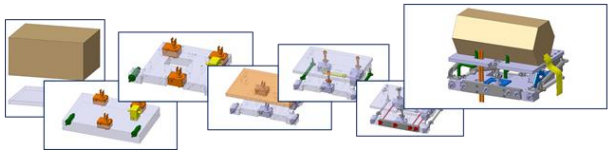


STANDARDIZED JIGS AND JOINTS



LHCGUPS_0001
LHCGUPS_0007

DESIGN PROCESS



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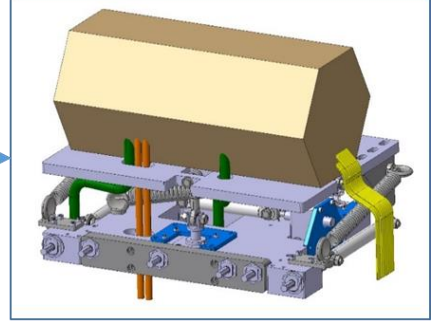
DESIGN GUIDELINES FOR SMALL UAP

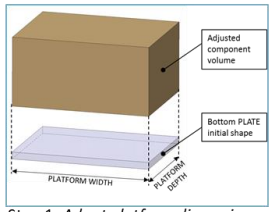
DEDICATED ADJUSTMENT PLATFORM



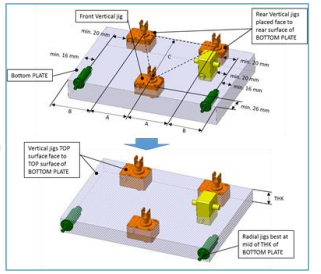
OPTIMIZATION OF:

- **Design time and resources**
- **Material cost (standardization)**

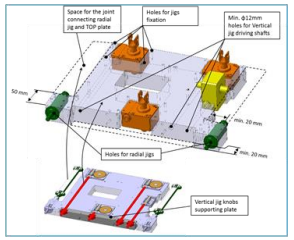
Engineers implements their own UAPs according to specific requirements, considering design guidelines and using standardized components („LEGO" blocks approah)



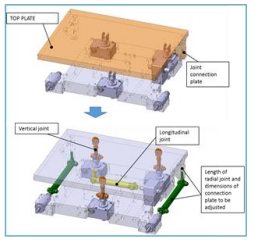
Step 1: *Adapt platform dimensions to supported component dimensions*



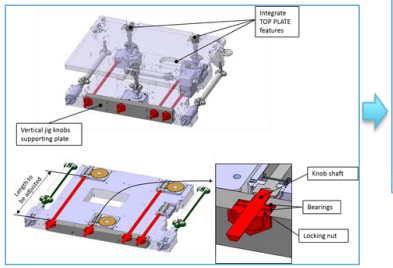
Step 2: *Arrange jigs pattern within Bottom plate volume (top)*; Step 3: *Adjust thickness of the plate and position of radial jigs (bottom)*



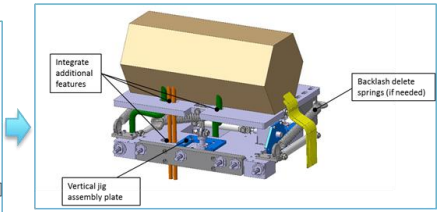
Step 4: *Prepare the space for the UAP functional sub-components*



Step 5: *Prepare the Top plate initial model and adjust the joints length*



Step 6: *Prepare the Top plate initial model and adjust the joints length*



Step 7: *Integrate all user specific features and vertical jig assembly plates*

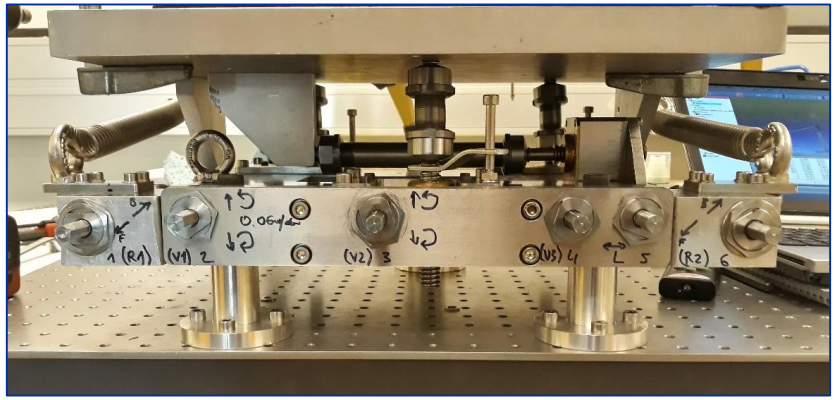
Universal Adjustment Platforms

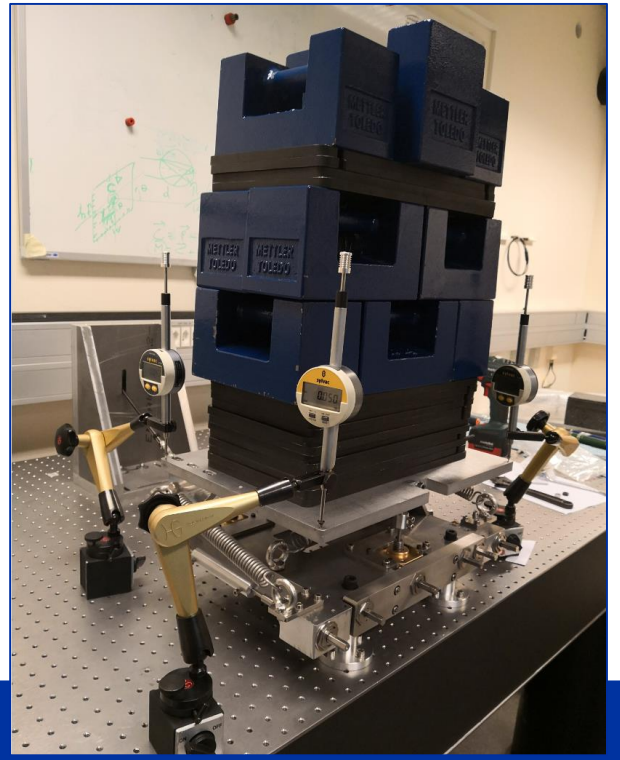
Two sizes of UAP assumed:

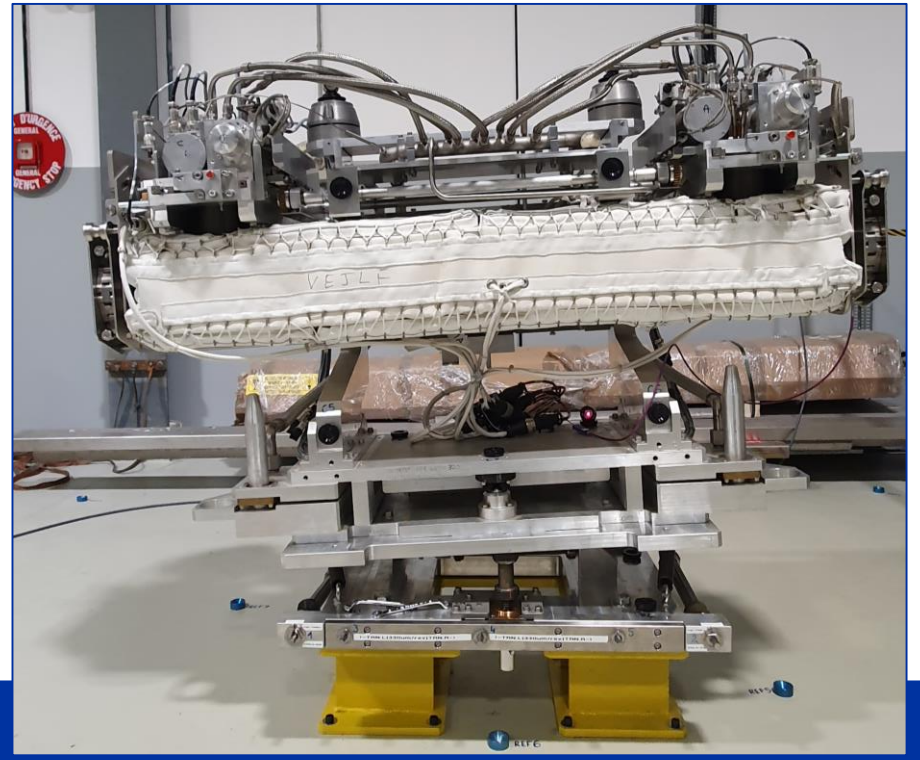
- SMALL UAP – for smaller components with max. weight of 300 kg
- BIG UAP - for bigger components, max. weight < 2 t

SMALL and BIG UAP design methodology is the same

Each platform will need different family of joints/adjustment jigs

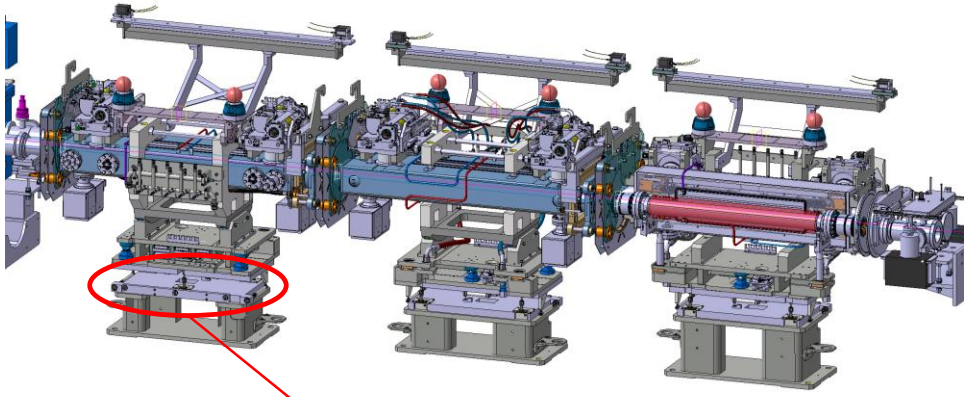


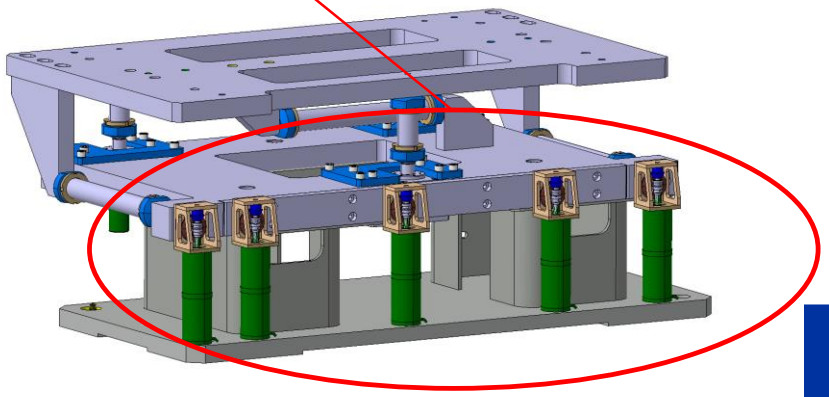


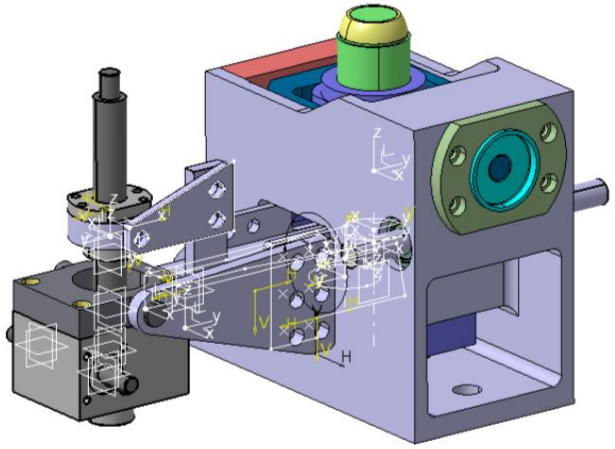


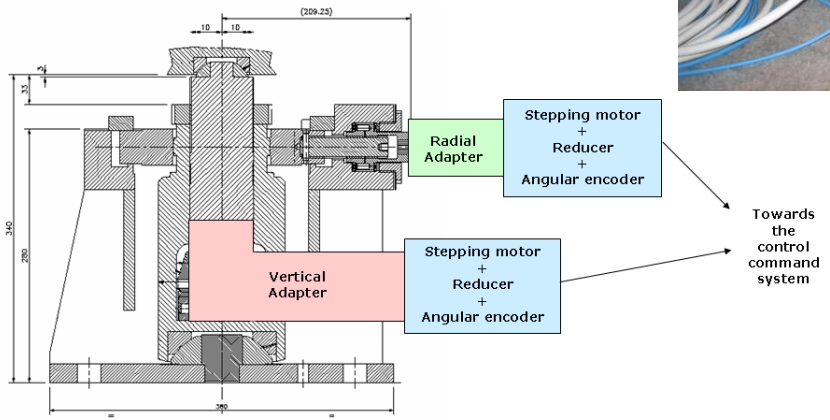
Motorized adapters for jacks and platforms

- 320 motorized axes operating in high radiation (1MGy TID), to be used for FRAS – optimization of motorized adapters cost is essential
  - Standarization and modular approach is the best solution to decrease overall costs
  - Three main designs considered: UAP motorized adapter; HL-lHC jacks vertical and radial adapters







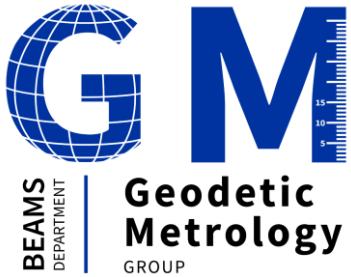


Conclusions and perspectives for future machines

- Current development on FSI technology demonstrates its utility for robust, cost optimized and immune solution for future accelerators and harsh environements. There is still big field for FSI applications and R&D

- Capacitive technology is example of fragile system, nevertheless appropriate approach of sensor and electronics design allows for integration of precise sensing networks in accelerator sector

- Uniform and modular approach to adjustement systems design, with use of standardized sub-components, provides best way for cost optimization of large-scale installations



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