# Frequency Scanning Interferometry and its application for the internal monitoring of the cold mass position inside the cryostat

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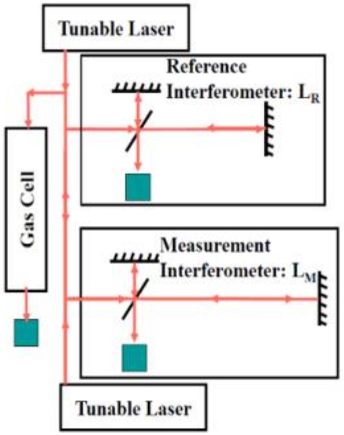
HL-LHC MQXF Workshop 2019.10.19

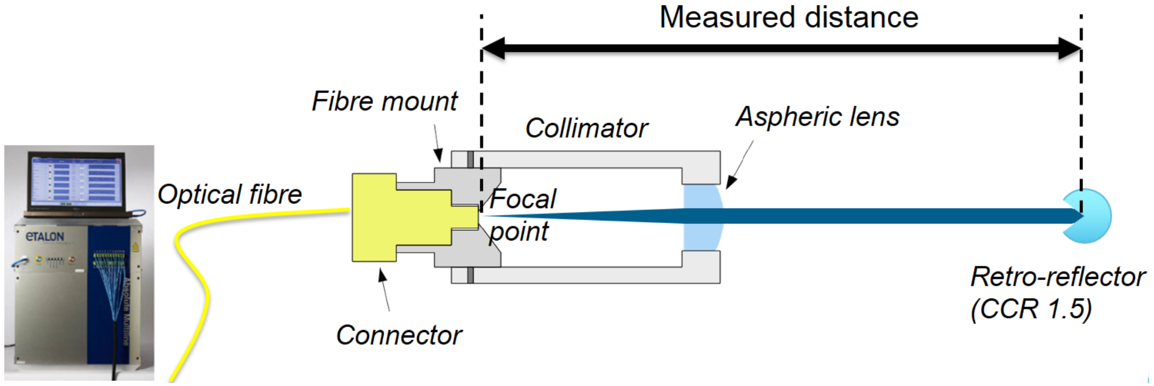
# Outline

- FSI ETALON system to monitor HL-LHC cold mass position
  - FSI – short reminder
  - Crab-cavity FSI system and performance
  - Inner-triplet FSI system
- Dipole test
  - Integration of FSI instrumentation
  - Initial cool down tests
  - Survey results
  - Insulated prism concept, initial tests
  - Heat in-leak optimization, insulated prism design, test results
- FSI interface design, HL-LHC triplet integration
- Other tests and validations
- Summary

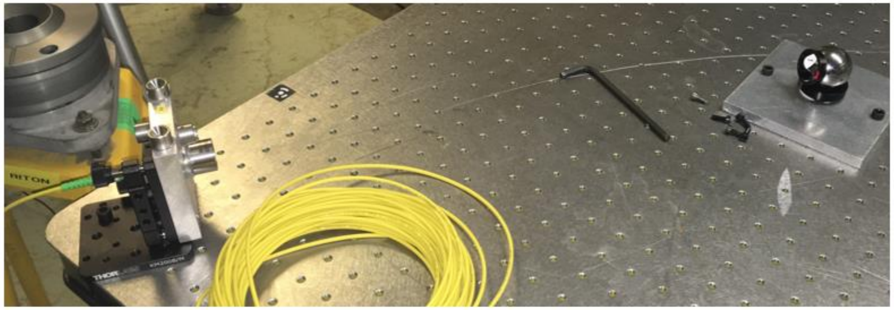
# Reminder – FSI ETALON system

**FSI – absolute interferometric distance measurement**



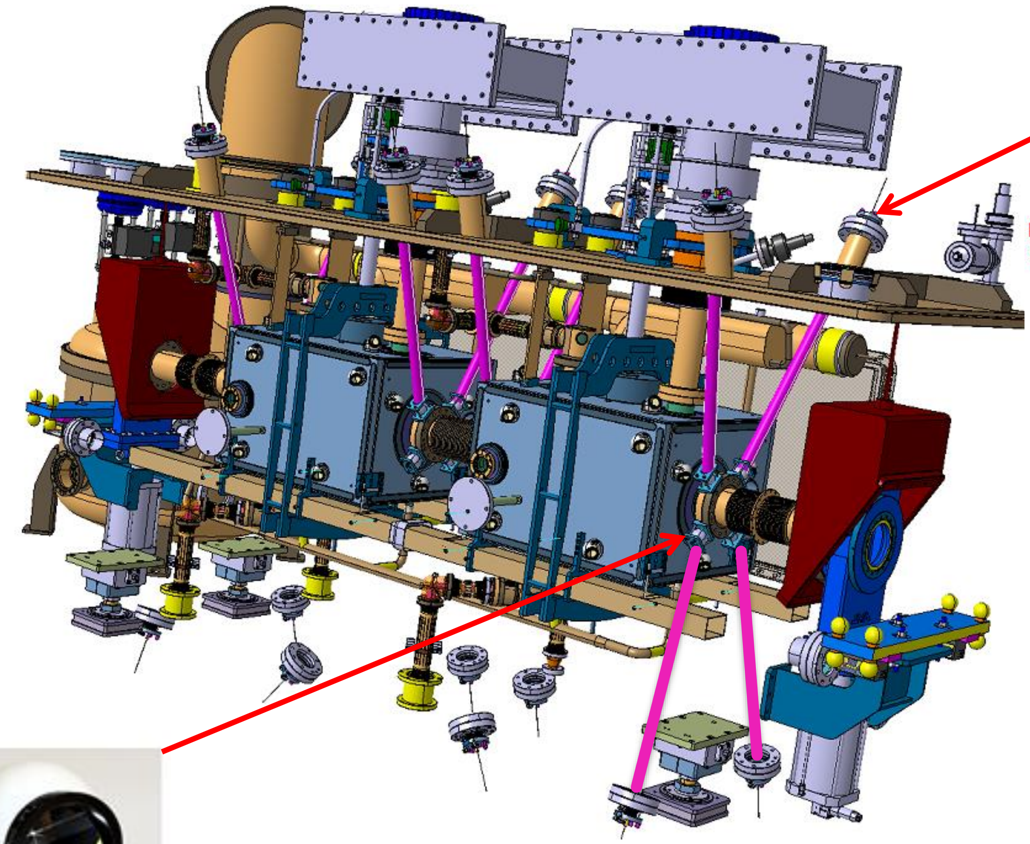



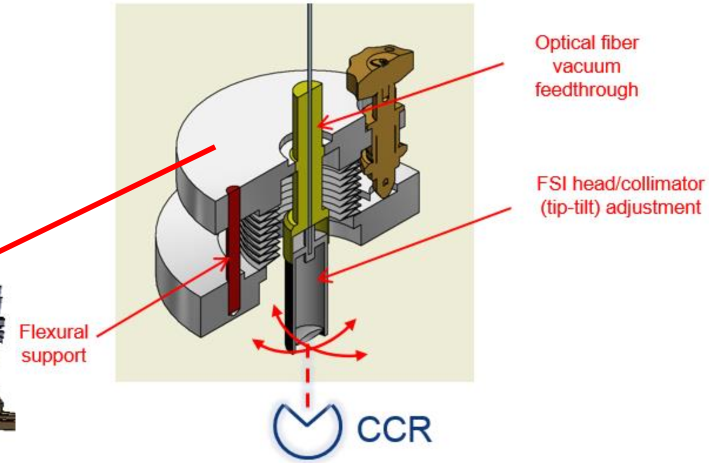

- Absolute distance measurement
- 8 channels expandable to 100
- Uncertainty (95%) = 0.5 µm/m
- Traceable
- Measurement distance: 0.2 – 20 m
- Fiber length – up to several hundreds meters
- Length given by the ratio of measurement interferometer to reference interferometer fringes

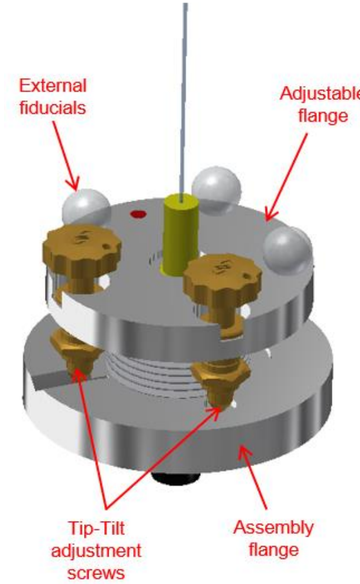


# Crab cavity FSI monitoring system

**FSI solution – cryo-module implementation (DQW)**



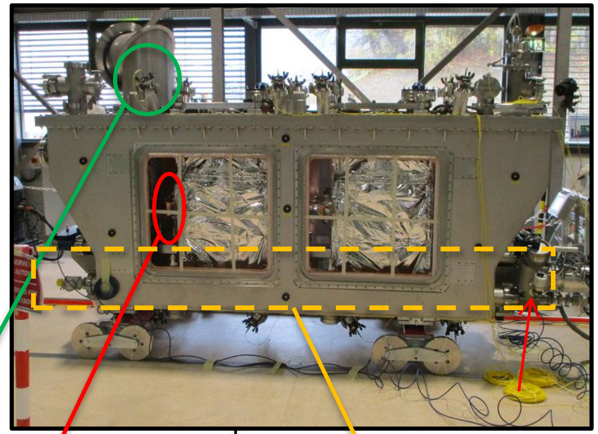


# Crab cavity position monitoring systems for SPS test

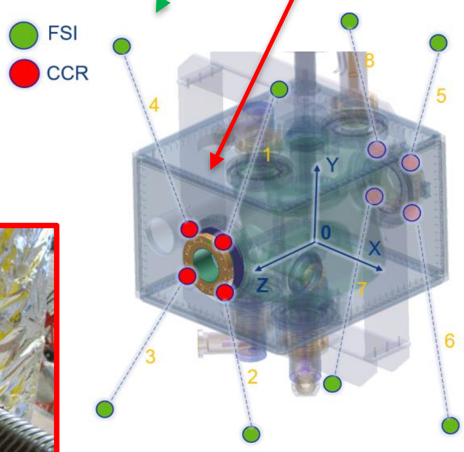
**Frequency Scanning Interferometry (FSI) – main system**

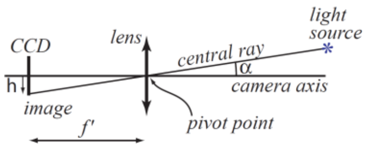
- Cavity position/orientation known thanks to absolute distance measurements between cryostat **FSI heads** and cavity **Corner Cube Reflectors (CCR)**
- System for HL-LHC use (cold, vacuum and radiation compatible)

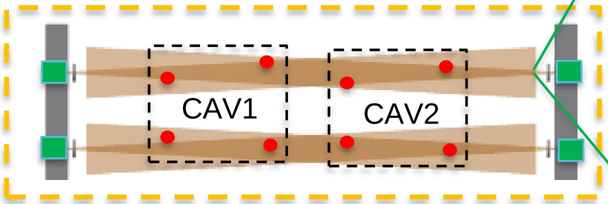


**Brandeis Camera Angle Monitoring (BCAM)**

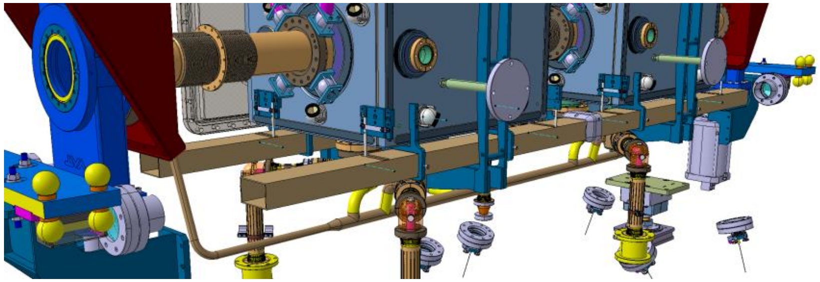
- Cavity position/orientation known thanks to **reflective targets** angular position measured by **BCAM cameras** (triangulation method)
- System used for FSI measurements crosscheck - only for SPS prototype alignment validation



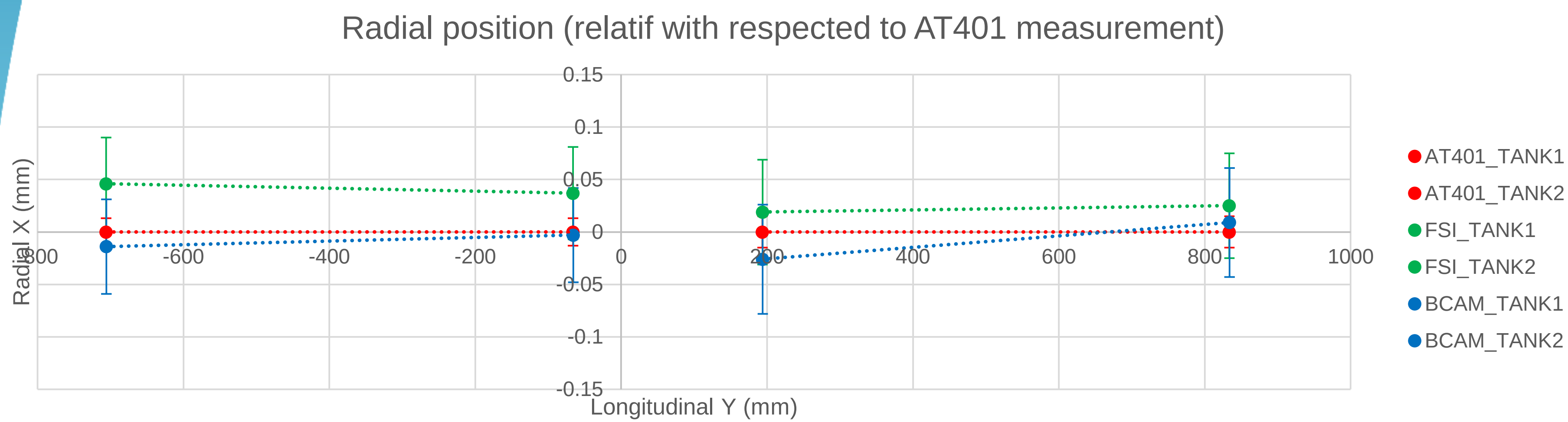



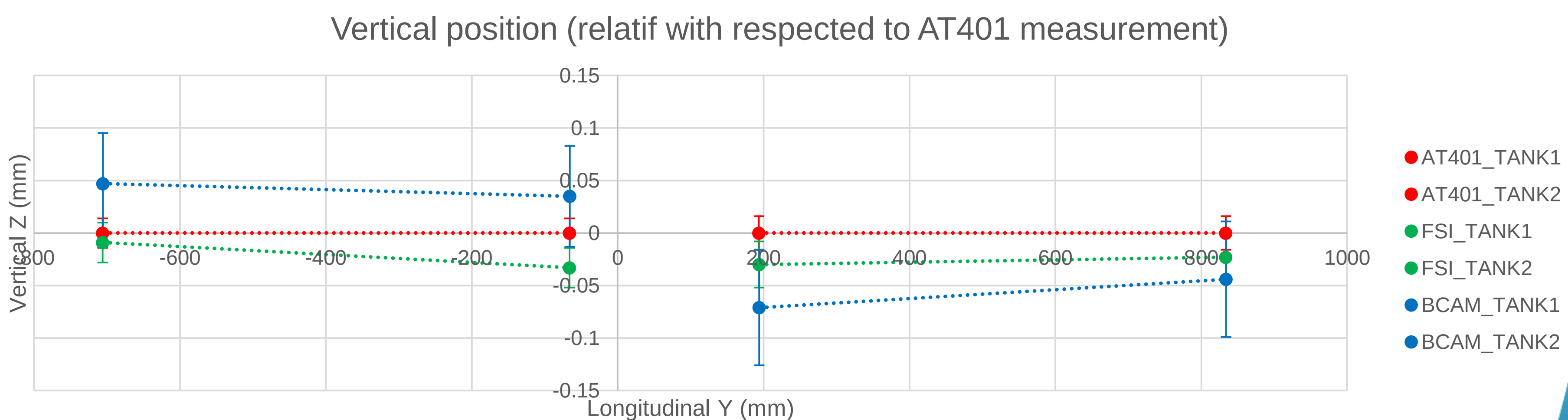

BCAM



# Crab cavity FSI performance at warm

- **FSI, BCAM systems precision better than 50µm (1σ), crosschecked with AT401 laser tracker measurements**

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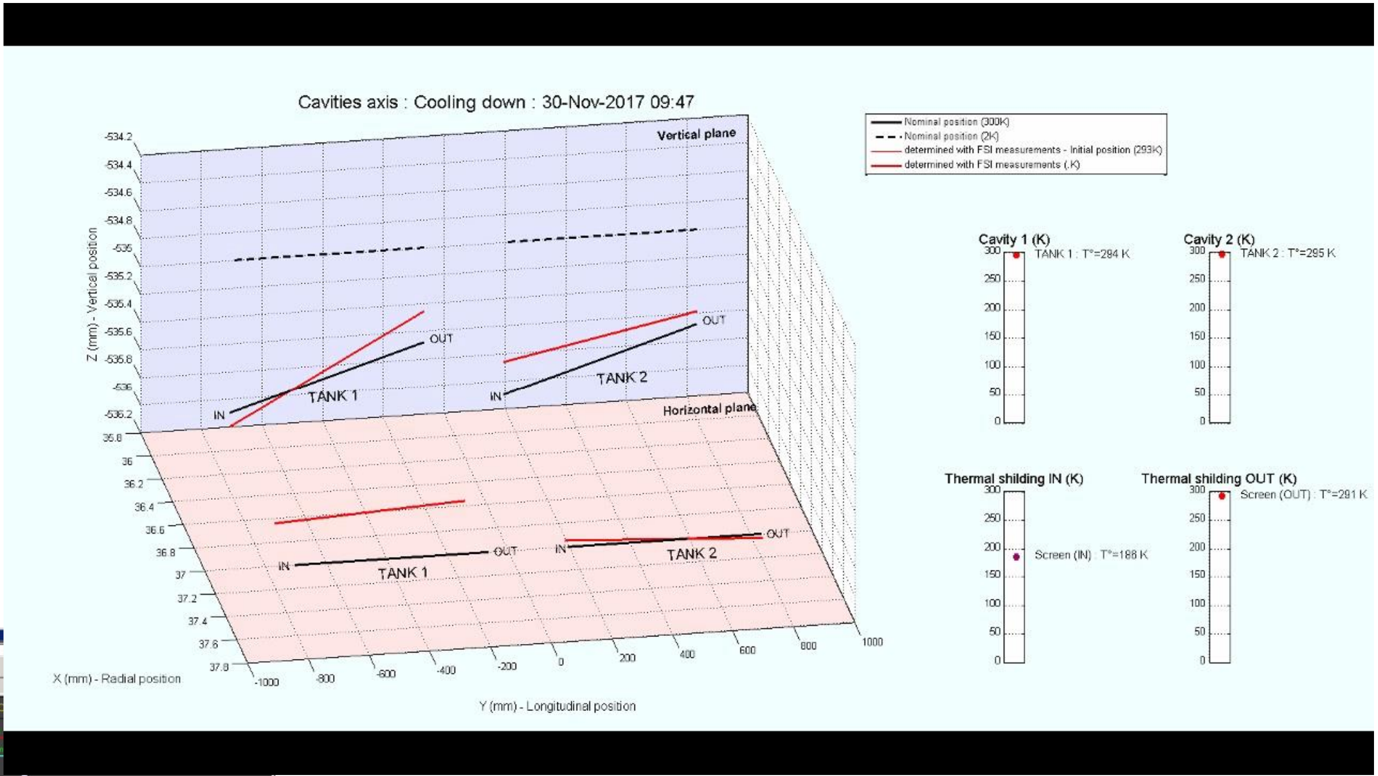
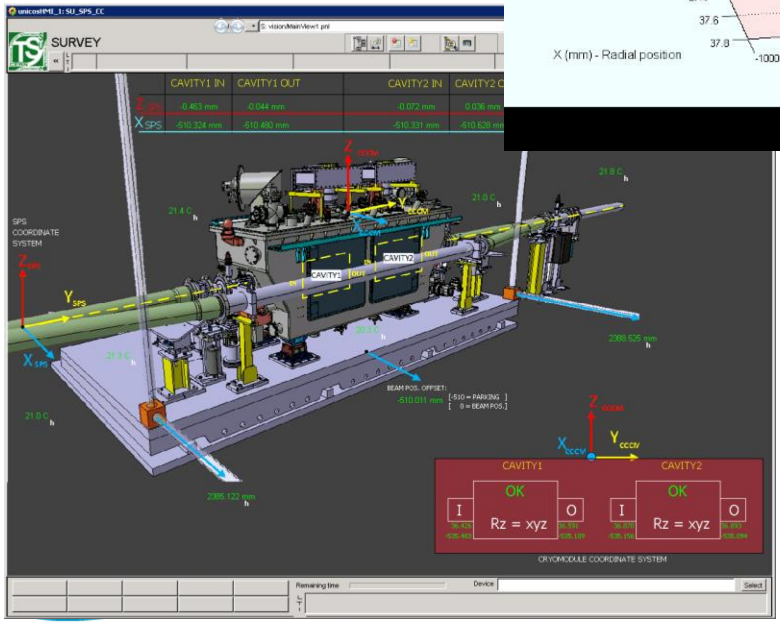
# Crab cavity FSI performance – cool down

- System allows to follow the cooled crab cavity position/orientation
- Precision better than 50µm (1σ)

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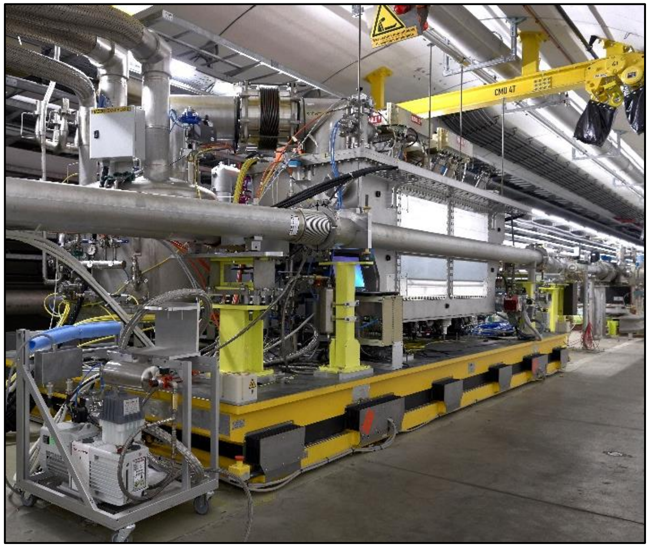
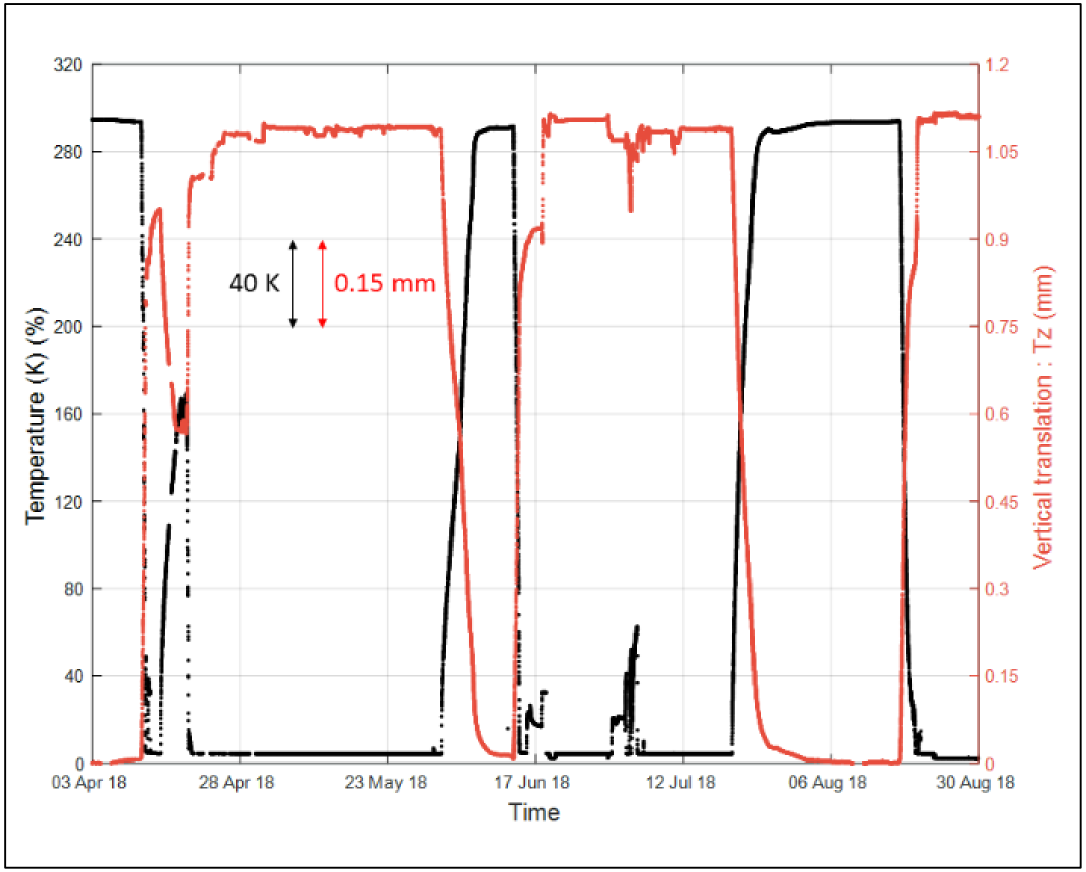
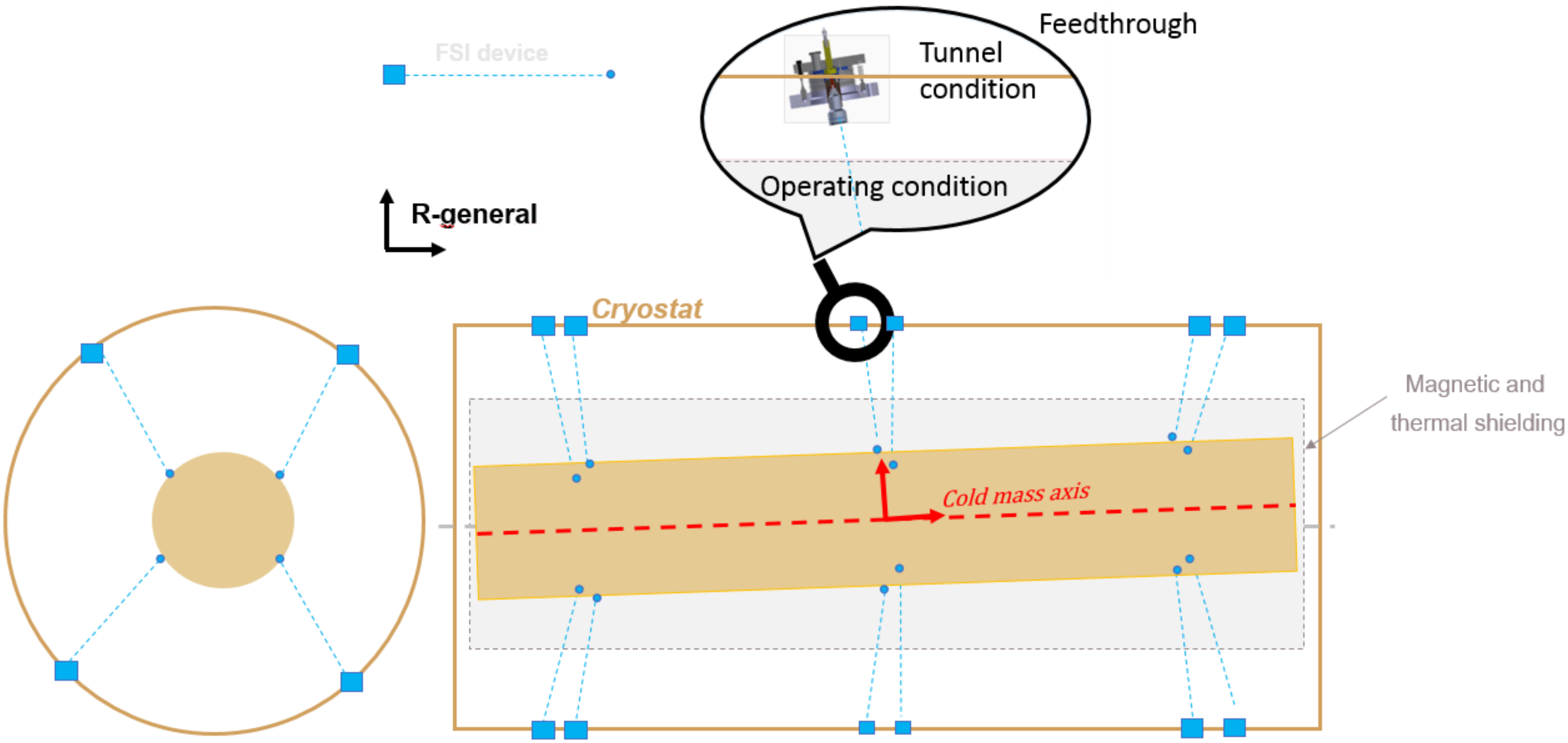
- Several cool-down cycles performed
- Micrometric resolution of objects moves observation (relative monitoring)
- FSI deployed in SPS crab cavity test stand

# Crab cavities – long term monitoring



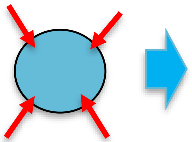


# HL-LHC Inner triplet – FSI integration layout

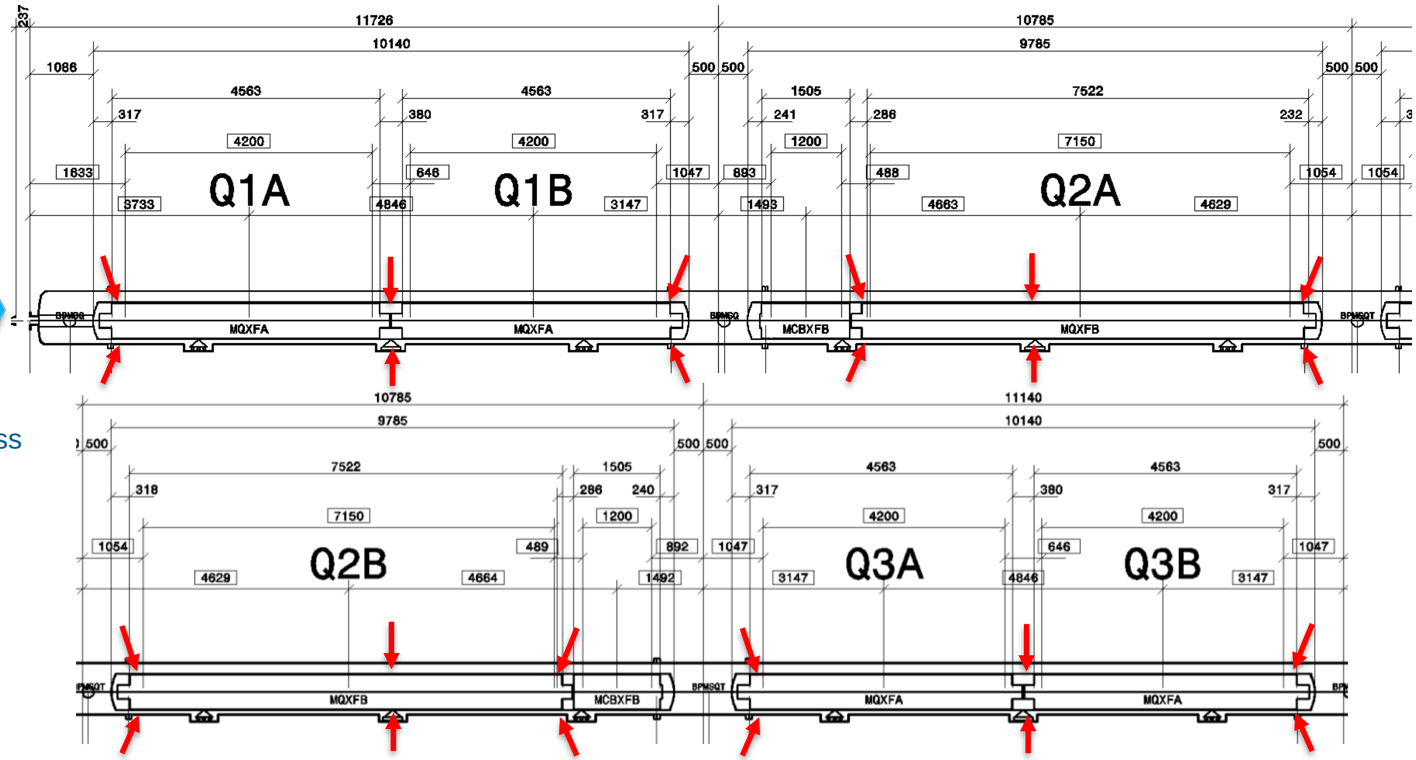


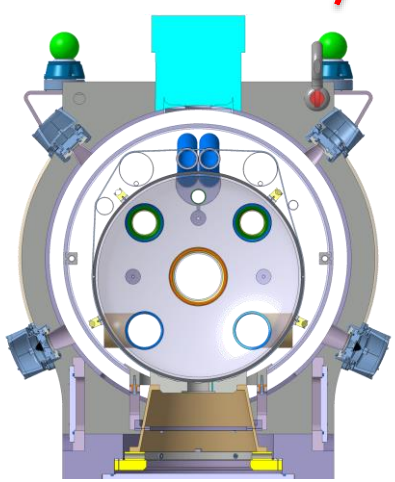
# HL-LHC Inner triplet – FSI integration layout

IR5 right example:
LHCLSXH_0010

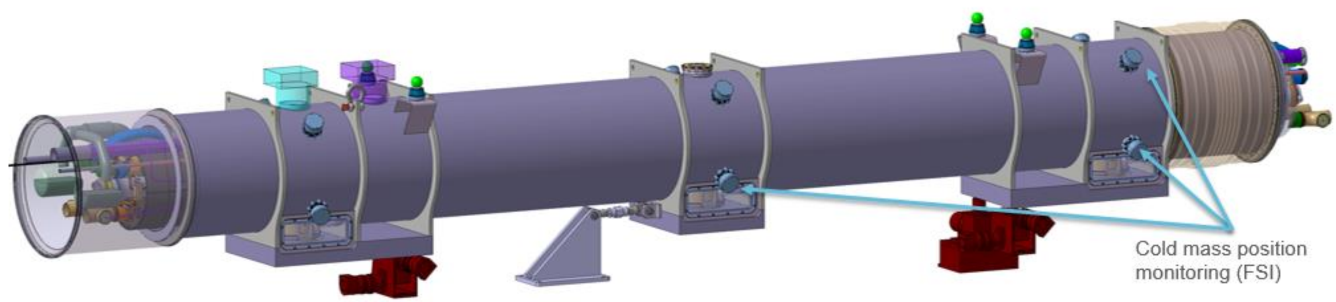


3 x 4 FSI heads
for each cold mass



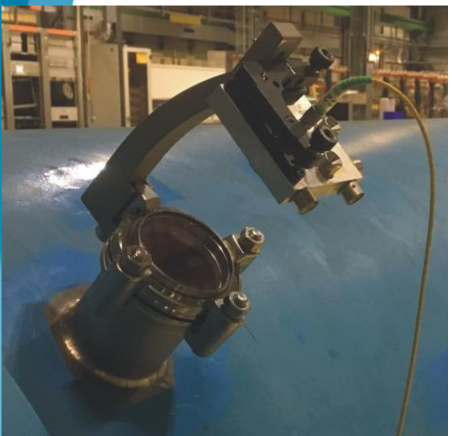



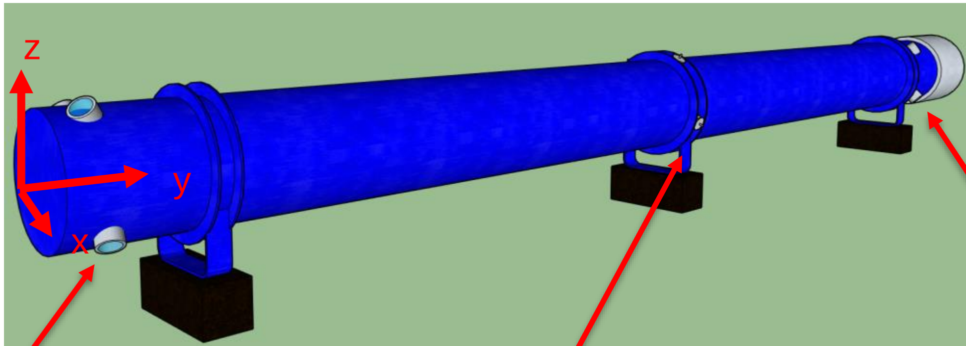
48 FSI heads per triplet needed

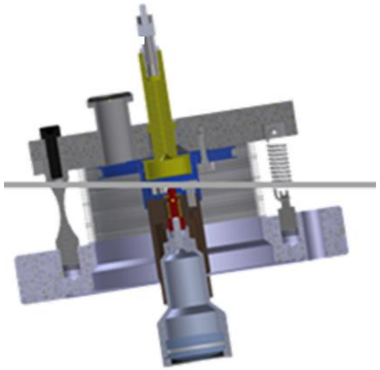



D. Ramos

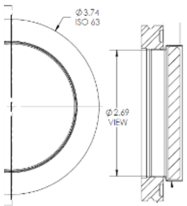
# Dipole test





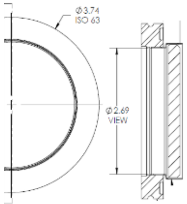



4 FSI mounts + collimators
+ 4 Viewports ISOK DN63
+ 4 Low-cost Alu reflectors

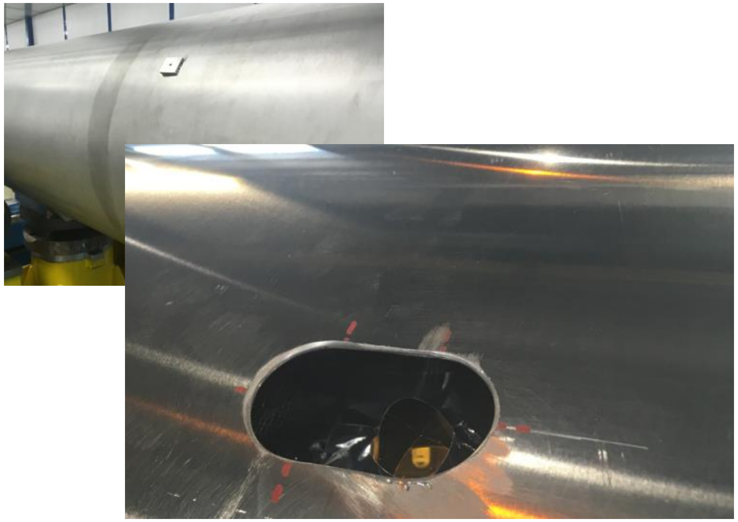


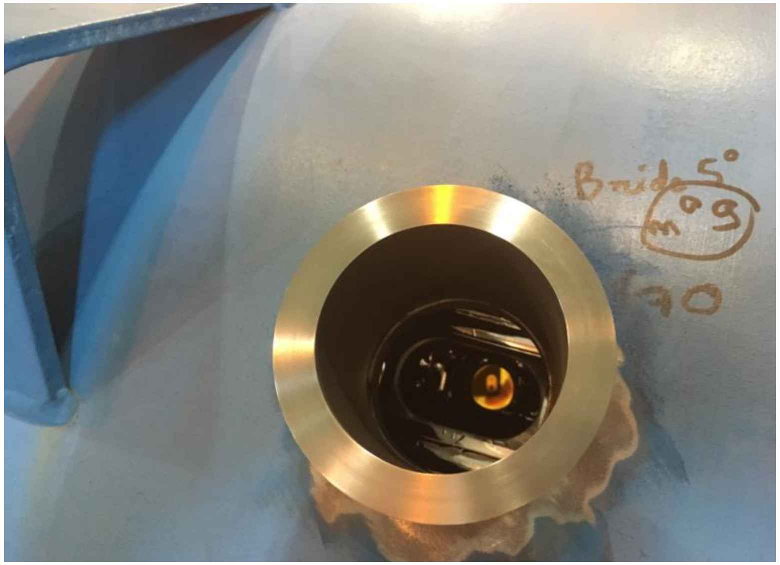
4 Crab Cavity Feedthroughs
+ 4 CCR targets

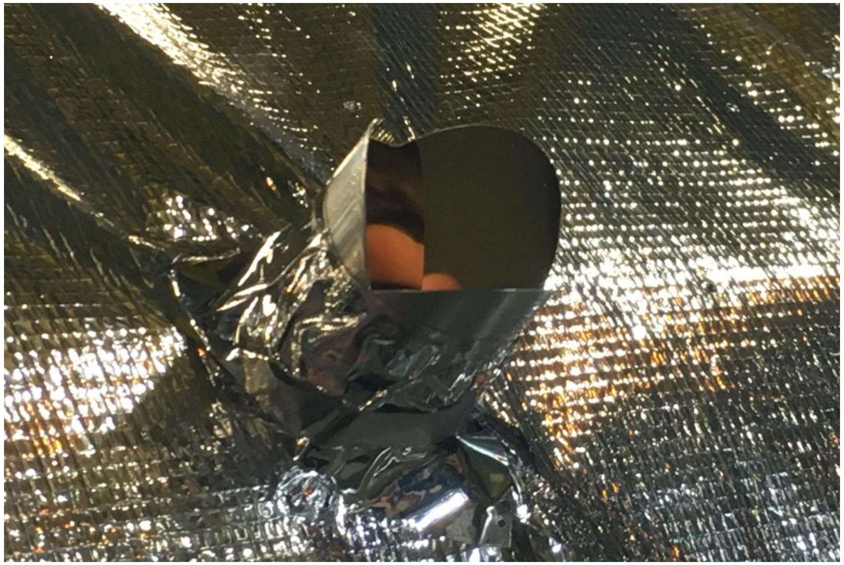
4 FSI mounts + collimators
+ 4 Viewports ISOK DN63
+ 4 Low-cost Alu reflectors



# Dipole test - instrumentation integration



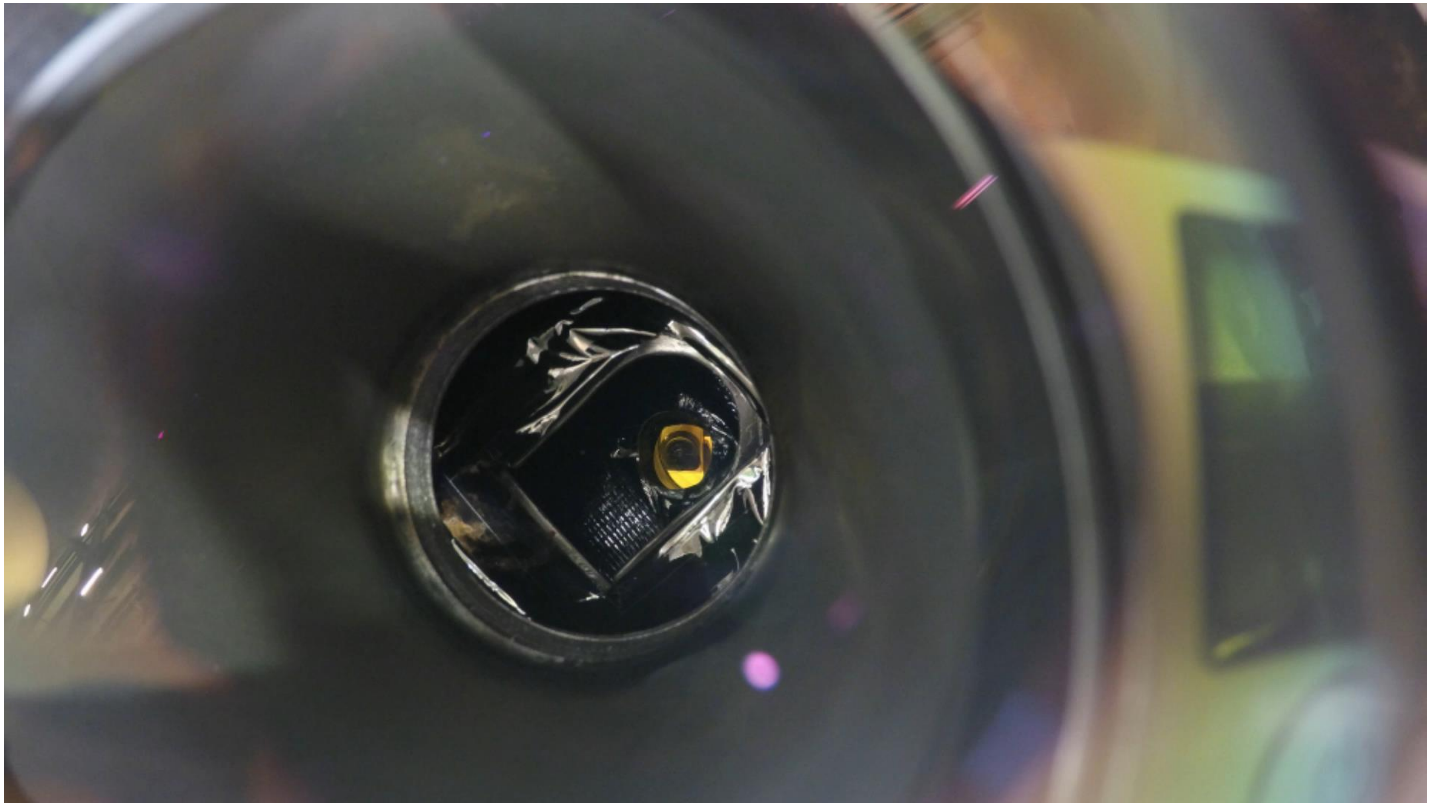





# Dipole initial tests (Phase 1)

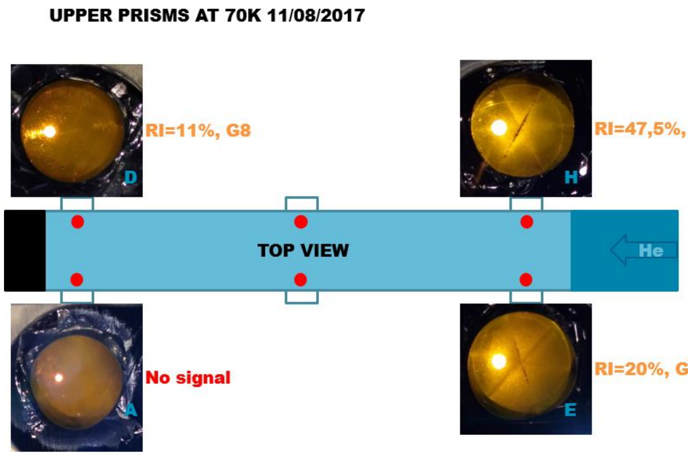
- Cooldown 1 (70K): 4-8/08/2017
- Cooldown 2 (70K): 10-15/08/2017
- Cooldown 3 (70K, 20K): 12/09/2017-11/10/2017

Several different approach verified:
- Nitrogen rinsing of cryomodule
- Cold mass/thermal shield -> different cooling order



# Dipole test – Aug-Oct 2017- conclusions

- FSI Etalon system use very sensitive to cryo-condensation effect
- Cryo-condensation strongly dependent on cryostat cleanliness/vacuum quality and cooling scheme

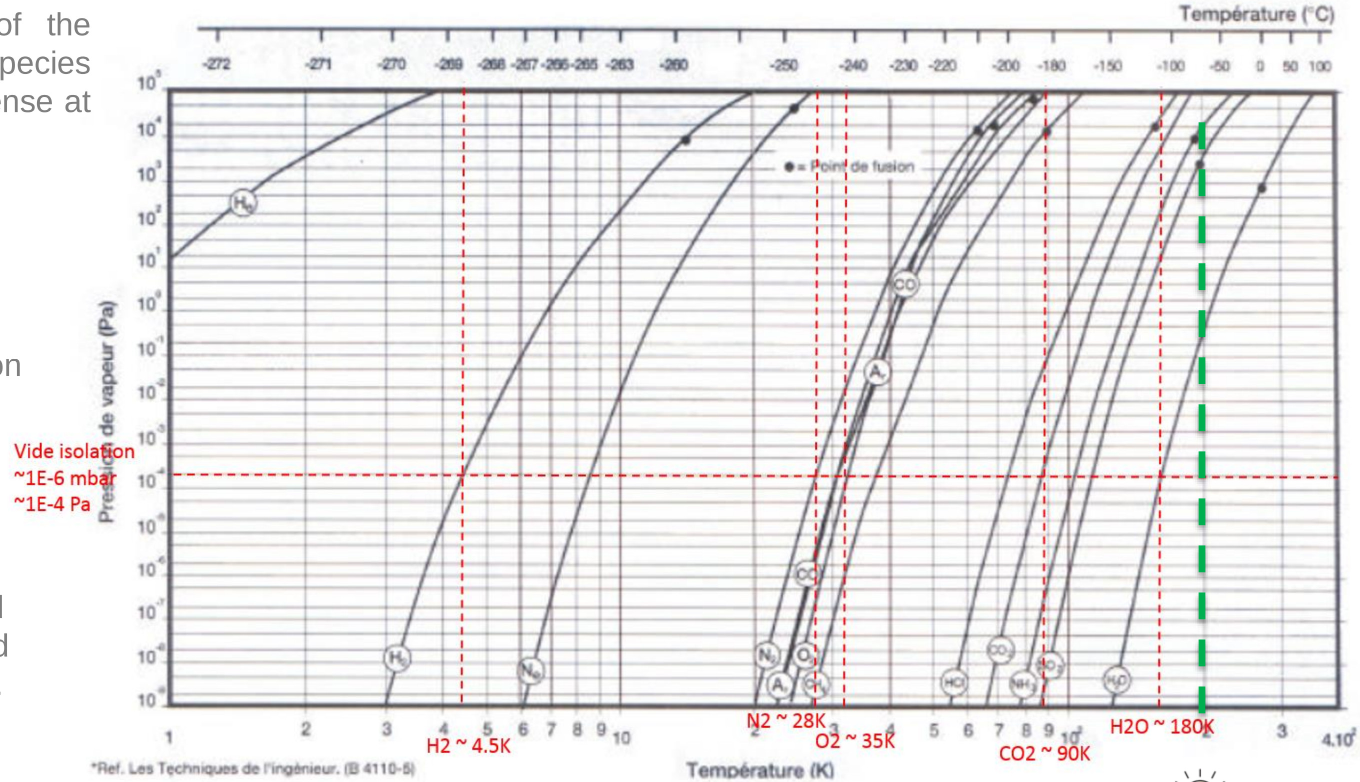


# Cryo-condensation - how to cope

At the residual pressure of the insulation vacuum every species naturally present in air condense at or below 180K.

→ If we manage to keep the reflectors at ~200K, no permanent cryo-condensation should occur! ☺

However the reflector should stay rigidly attached to a cold mass cooled down to 1.9K…




Hyp.: we assume that the vacuum vessel pressure is made of 100% of each specie to get the corresponding condensation temperature (i.e. Vacuum pressure = vapor pressure). This is conservative.

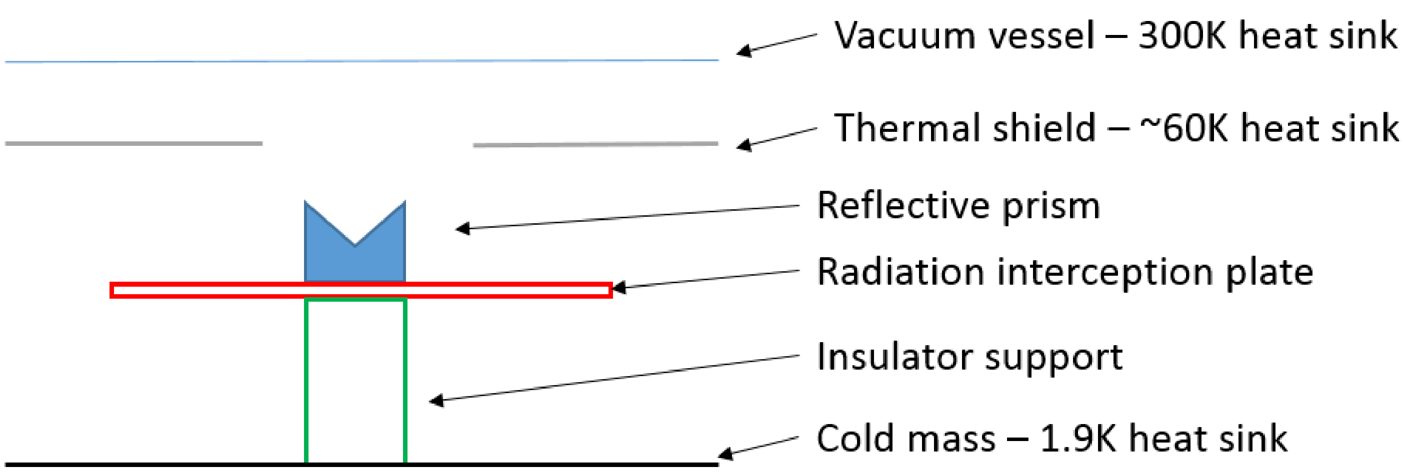
# Cryo-condensation - how to cope

How can we achieve a “heating” of the probes up to ~200K :

❑ Temporary heating – by heating the probe from the outside of the view port (with adequate wavelength) one could in principle temporarily “evaporate” the layer of condensed crystals.

→ technical complexity – not the preferred solution for now.

❑Permanent heating – by making sure that the probe stays at >=200K, no cryo-condensation should ever take place in principle. This could be achieved using the power radiated from the vacuum vessel (which is 300K “hot”).

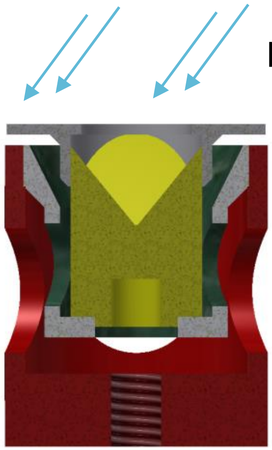


# Dipole test – initial validation of insulated prism concept (Phase 2)

- Exchange of upper prism to prototype ones:
  - Thermally insulated prism with radiation interception surface
  - Prism shielded from the top (to check if particles are freezing due to gravity falling)

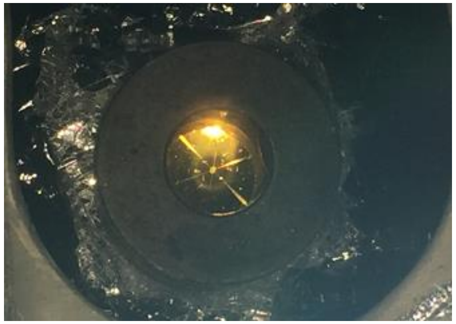
INSULATED REFLECTOR

Radiation

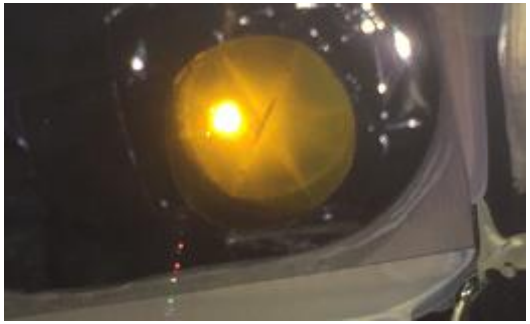


- Cooldown 4 (80K): 27/11/2017-8/12/2017
  - Screen cold, the cold mass heated and cooled down afterwards
  - After several days reference prism and top shielded prism signal lost while measuring using ETALON FSI
  - No problem with insulated prism intensity during whole time of test (ETALON FSI measurement)

INSULATED REFLECTOR

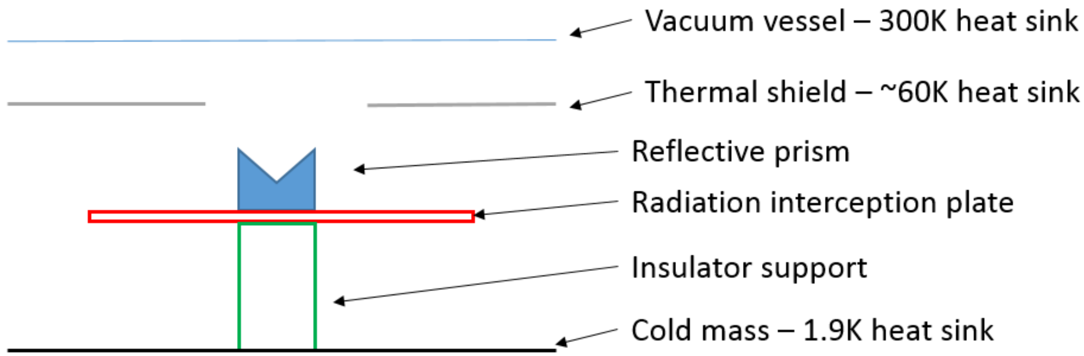


REFERENCE REFLECTOR



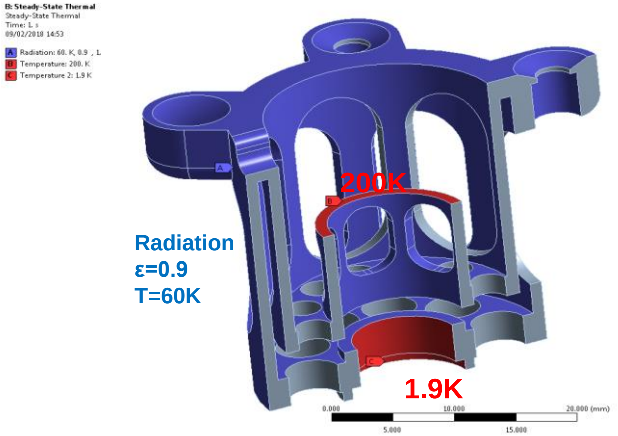
# Dipole case in-leak on the cold mass

On the dipole test, cryo-condensation issues lead us to use an isolated target support to keep an adequate temperature. A radiative plate is added to intercept radiative in-leak from the V. Vessel to heat up the reflector.




# Dipole case in-leak on the cold mass

**2 & 3) Flux conducted by the insulating support & flux self-radiated by the "hot" insulating support (FE simulations)**




| Probe temperature (K) | Power conducted to CM (W) | Power self radiated (W) | Power in-leak to CM (W) |
|---|---|---|---|
| 150 | 0.02 | 0.01 | 0.022 |
| 200 | 0.026 | 0.03 | 0.032 |
| 250 | 0.044 | 0.062 | 0.056 |

Power to CM = power conducted + 1/5*power radiated

**Cold mass thermal in-leaks summary**

| | Power (mW) |
|---|---|
| Residual opening | 60 |
| Heat conducted by support | 56 |
| **Total heat to CM** | **116** |

The FSI system is fitted with 12 holes per magnet – 48 holes per triplet
→ 48*0.116=5.57W (note: this is valid as long as all TS holes are Φ40mm)

By taking the approx. operating costs issued by TE/CRG
1W@1.8K ~ 5kCHF for 10 years operation

→ Thermal in-leaks additional operating cost is 28kCHF for 10 years operation per triplet string

F. Micolon

**FSI thermal load budget discussed with S. Claudet 20.03.2018 and assessed as acceptable**

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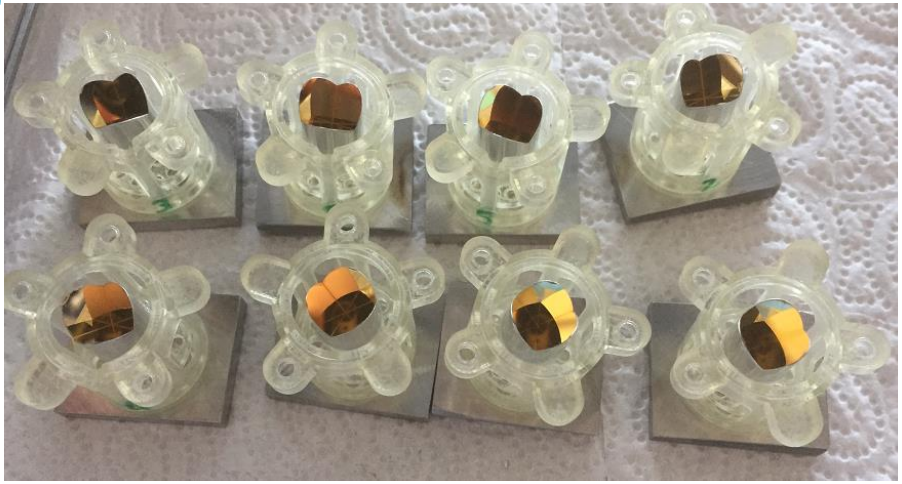
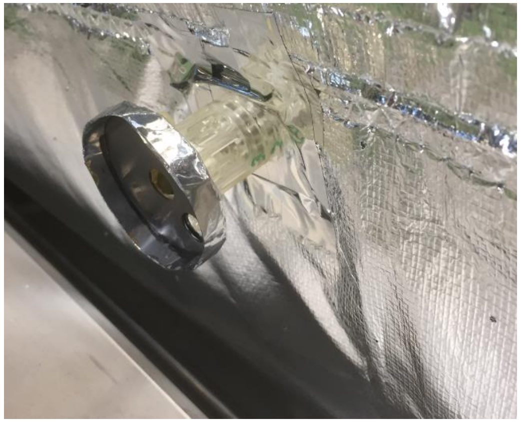
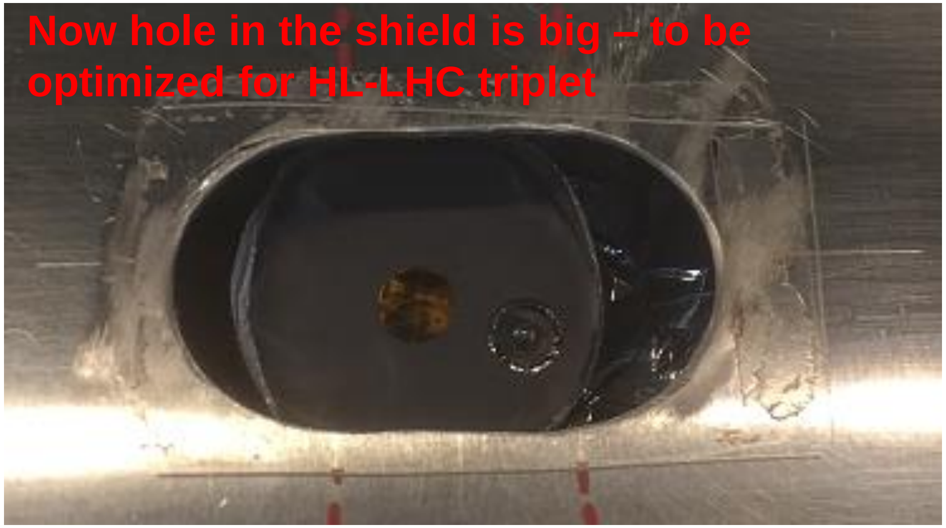
# 200K insulated prism prototype design and integration (Phase 3)

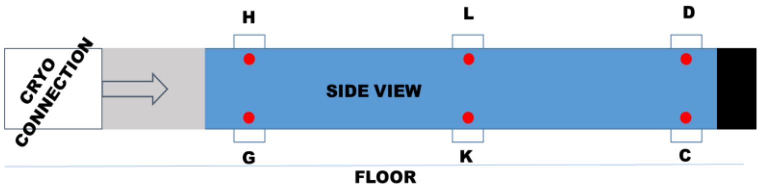


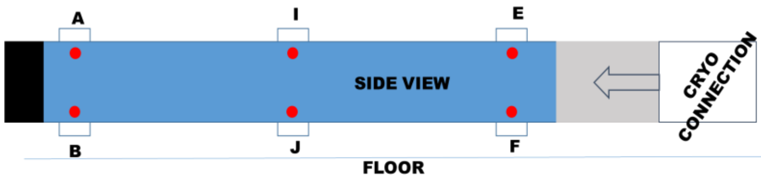


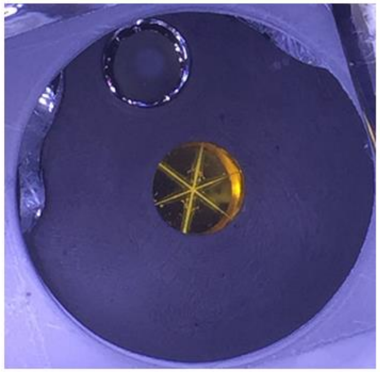



8 insulated targets were then attached to the magnet for testing in February 2018.

# 200K insulated prism test results after 3 weeks of cool-down (Phase 3)

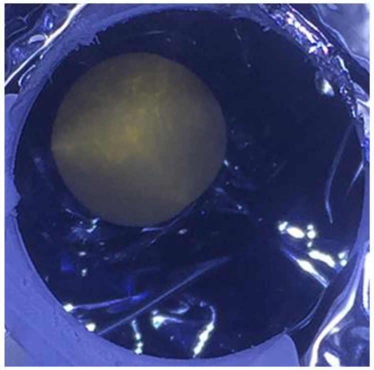


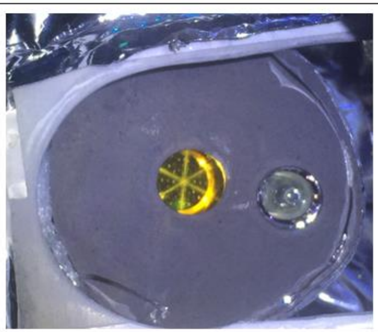
Target L – thermally insulated (0.5"CCR + Φ4mm S-LAH79 ball).

Condensation on S-LAH79, no condensation on CCR.



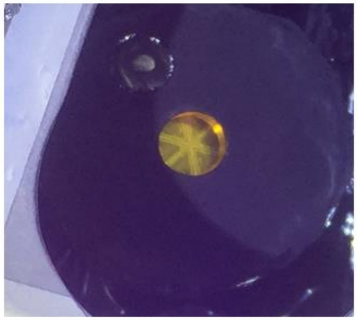
Target K – no thermal insulation (1" CCR + Φ4mm S-LAH79 ball).

Thick cryo-condensed 'ice' layer visible on the reflector and ball surface.



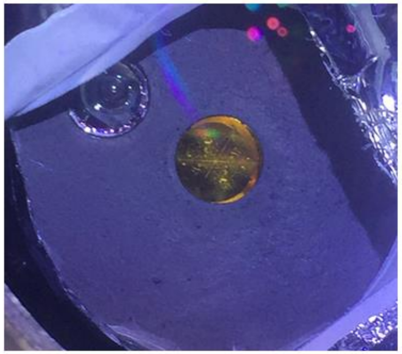
Target H – thermally insulated (0.5"CCR + Φ4mm S-LAH79 ball).

No condensation visible



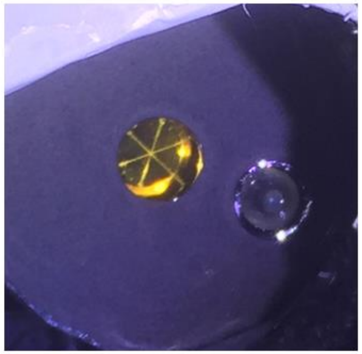
Target G – thermally insulated (0.5"CCR + Φ4mm S-LAH79 ball).

Light condensation on CCR, no condensation on S-LAH79 ball



Target D – thermally insulated (0.5"CCR + Φ4mm S-LAH79 ball).

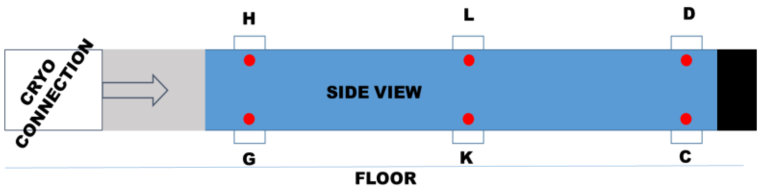
No condensation visible

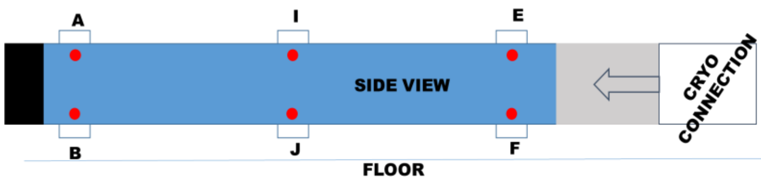


Target C – thermally insulated (0.5"CCR + Φ4mm S-LAH79 ball).

Light condensation on S-LAH79, no condensation on CCR.

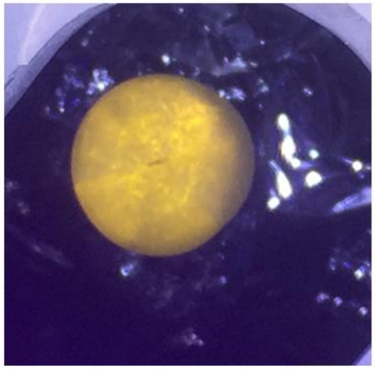
# 200K insulated prism test results after 3 weeks of cool-down



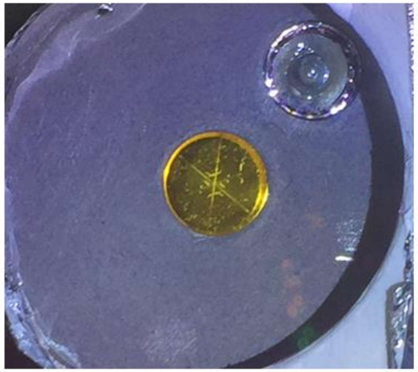

Target E – thermally insulated (0.5″CCR + Φ4mm S-LAH79 ball).

No condensation visible



Target F – no thermal insulation (1″ CCR + Φ4mm S-LAH79 ball).

Thick cryo-condensed 'ice' layer visible on the reflector and ball surface

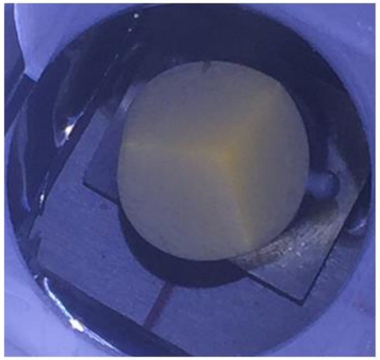


Target A – thermally insulated (0.5″CCR + Φ4mm S-LAH79 ball).

No condensation visible

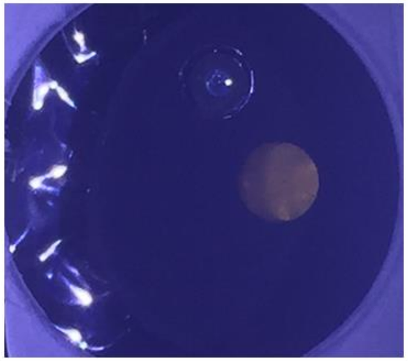
Target B – no thermal insulation (1″ CCR).

Thick cryo-condensed 'ice' layer visible on the reflector surface



Target I – no thermal insulation (1″ CCR + Φ4mm S-LAH79 ball).

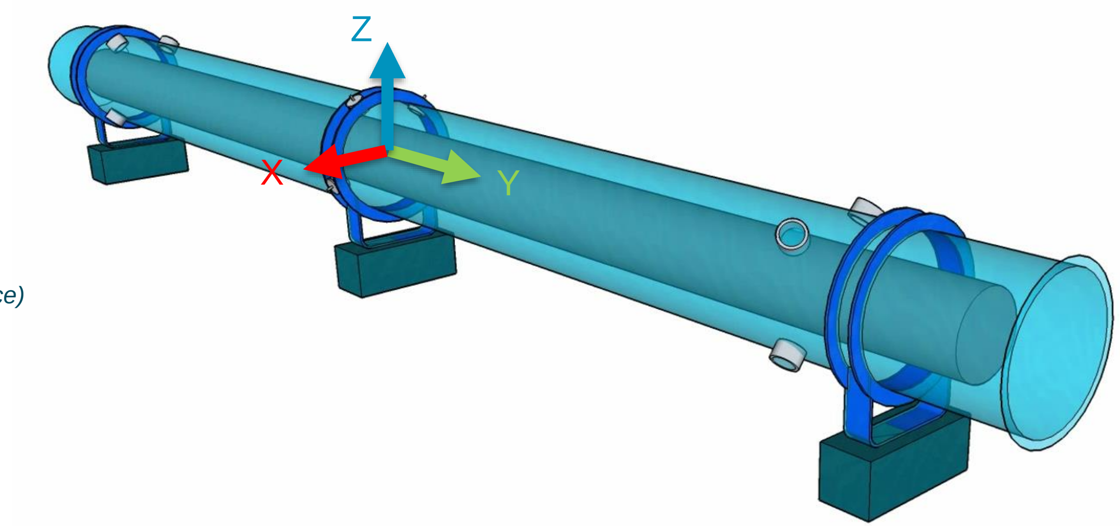
Thick cryo-condensed 'ice' layer visible on the reflector and ball surface



Target J – thermally insulated (0.5″CCR + Φ4mm S-LAH79 ball).

Light condensation on CCR, no condensation on S-LAH79 ball.

# Phase 3 – measurements results




**Results of cooling down (phase 3)**

- *0 / 4 : CCR or optical retroreflectors*
- *7(8)/ 8 : isolating targets visible (one out of fitting tolerance)*

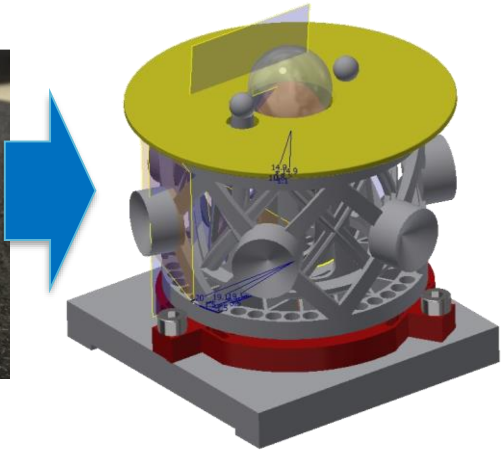
→ Max residual : 7 µm

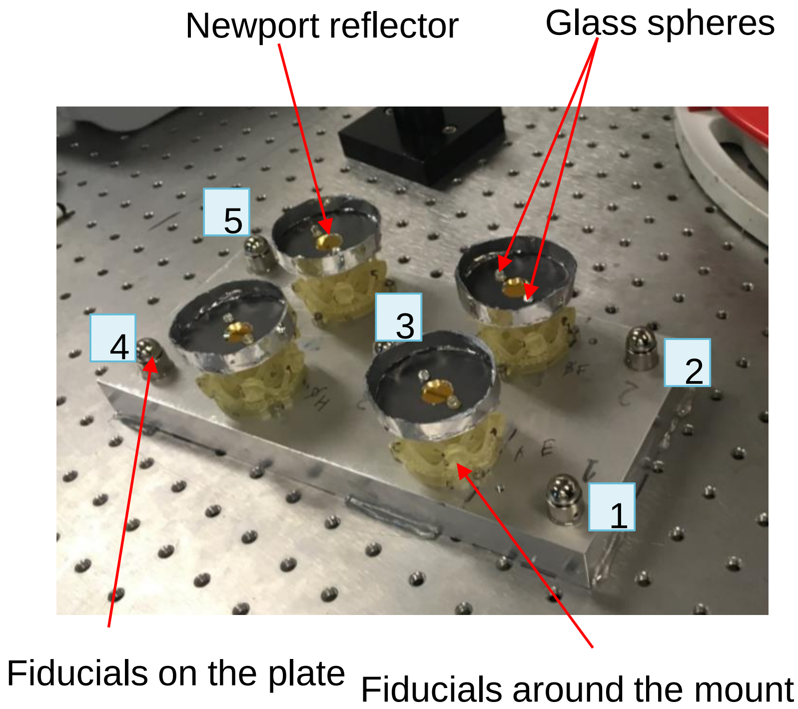
| | 293 K → 4 K | |
|---|---|---|
| Tx : radial (mm) | -0.001 mm | +/- 0.066 mm |
| Ty : longitudinal (mm) | *0.825 mm* | |
| Tz : vertical (mm) | **-1.078 mm** | +/- 0.023 mm |
| Rx : pitch (rad) | 0.000003 rad | +/- 0.000004 rad |
| Ry : yaw (rad) | -0.001050 rad | +/- 0.001282 rad |
| Rz : roll (rad) | -0.000022 rad | +/- 0.000003 rad |
| F : scale factor | **-0.002889** | +/- 0.000015 |

} **Coherent with the simulation**

# Insulated prism – rigid prototype design and integration (Phase 4)

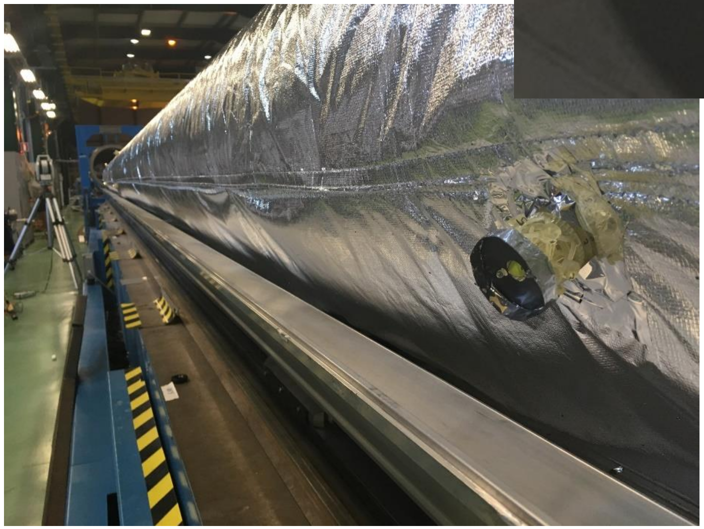
- **Phase 4 to fully validate metrological strategy of IT cold mass FSI measurements**
  - Use of new rigid insulated target support
  - Check of cost optimized reflectors (n=2 glass balls)
  - Check of new technology of multi-target FSI





# Insulated prism – rigid prototype design and integration (Phase 4)

- Phase 4 current status
  - Fiducialisation of the dipole cold mass, cryostat performer mid of September
  - Cool-down started Begin of October
  - For now the dipole is at 4K (no cryo-condensation)

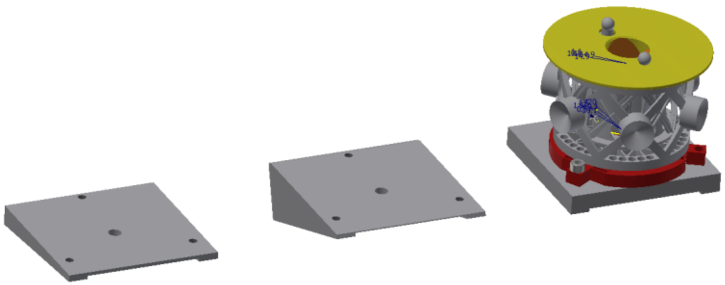


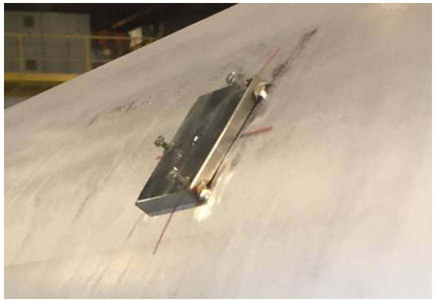
# Latest results – Phase 4 cool down

| | October 2018<br>PHASE 4<br>293 K → 4 K | |
|---|---|---|
| Tx : radial (mm) | 0.016 mm | +/- 0.138 mm |
| Ty : longitudinal (mm) | 0.266 mm | +/- 0.126 mm |
| Tz : vertical (mm) | **-0.975 mm** | +/-0.045 mm |
| Rx : pitch (rad) | 0.000012 rad | +/- 0.000009 rad |
| Ry : roll (rad) | 0.000781 rad | +/- 0.002861 rad |
| Rz : yaw (rad) | 0.000020 rad | +/- 0.000005 rad |
| F : scale factor | **-3109 ppm** | +/- 17ppm |
| Sag (radial) | -0.069 mm | +/- 0.024 mm |
| Sag (vertical | 0.034 mm | +/- 0.042 mm |

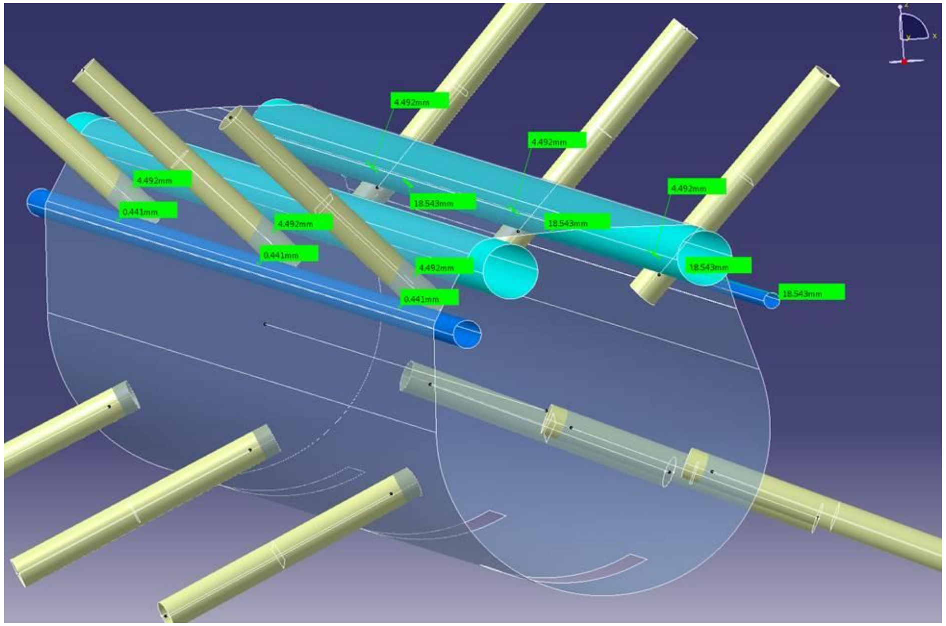
Successful test at 4 K of the new support of targets!
Cryo-condensation issue solved!

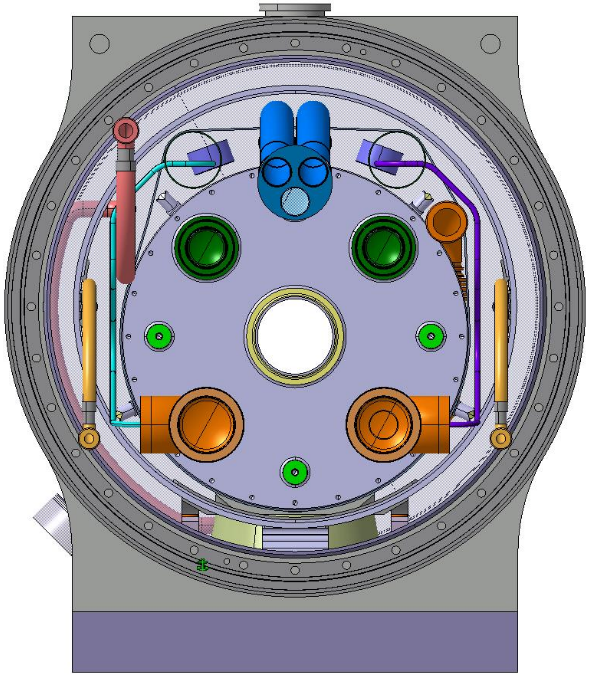
# HL-LHC triplet FSI integration





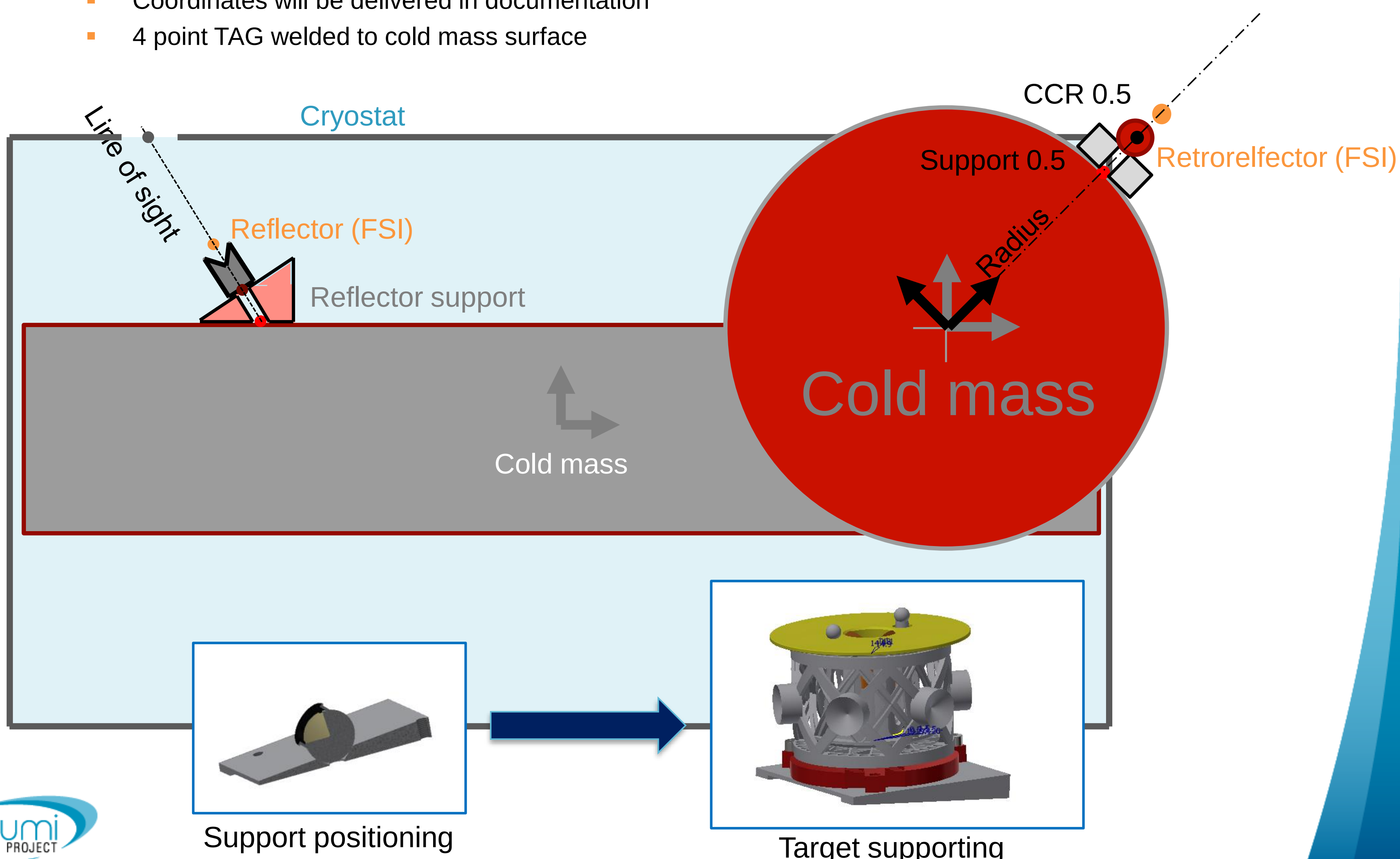
- Final design of HL-LHC IT FSI target after finalisation of Phase 4 test (begin 2019 and onwards)
- Cold mass interface is a 316L machined plate, to be welded on cold-mass surface
- Integration within cryostat ongoing (space reserved, cryostat flanges done, MLI/thermal shield to be finalized)



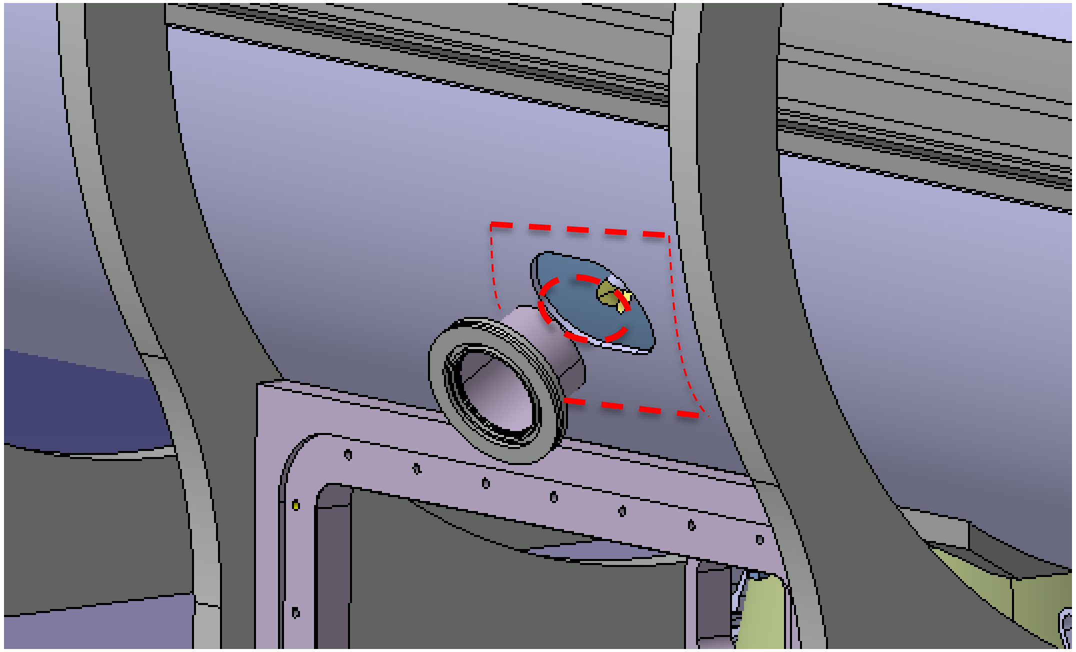
# HL-LHC triplet FSI assembly

- Target support welding
  - Targets support positioning with help of integrated fiducial for 0.5” CCR (or CCR adapter)
  - Coordinates will be delivered in documentation
  - 4 point TAG welded to cold mass surface



# HL-LHC triplet FSI assembly

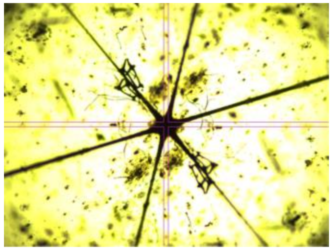
- Thermal shield hole positioning approach – under design and integration
  - Bigger hole in the thermal shield to allow line of sight considering lower machining tolerances of thermal shield
  - Fine adjustable plate point welded (or riveted) during cryostating
  - Plate positioning with help of delivered reference tooling of with use of fiducials integrated on plate (under discussion)



# Pre-test achieved on FSI

- Validation of targets through irradiation & vacuum and cold tests

10 MGy



**Liquid nitrogen test:**

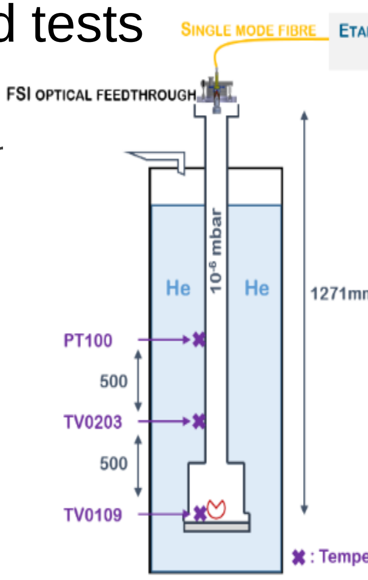
- No damage of targets
- No loss of performance

**Radiation tests of BMRs :**

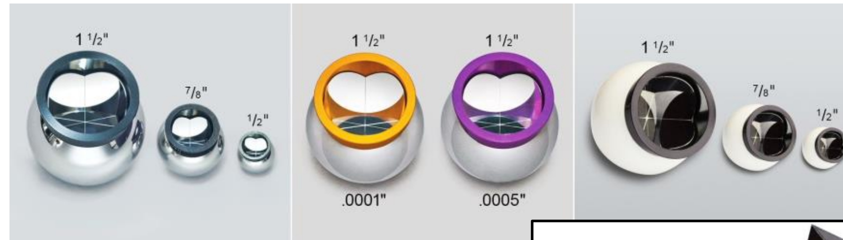
- Ceramic BMRs and collimators validated with TID of 10MGy
- BMR mirror centricity lost ~20µm

- Validation of measurement chain through cold tests

  - No visible deformation of the feethrough
  - Decrease of intensity but no impact on the measurem
  - Comparison with AT401 measurements within 20 µm




# Reflectors validation and optimisation


- Cheap, hollow retroreflector already used in dipole test
- Refractive index ≈2 glass ball as a alternative to hollow retroreflectors or replicated reflectors (~40€ vs. ~2k€ vs. 300 €)
- Balls glasses behaviour under investigation (impact on sweeping interferometry, laser tracker measurements, …)
- Radiation tests of hollow and glass reflectors started in August 2018

# Summary

- The special design of targets (temperature optimized) allows for use ETALON FSI without cryo-condensation effect, with thermal load at reasonable level
- Dipole measurement results confirm
- Further works on optimization of the insulated targets and their integration within HL-LHC triplet cryostat ongoing
  - Final HL-LHC target design after Phase 4 dipole test

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***Thank you!***

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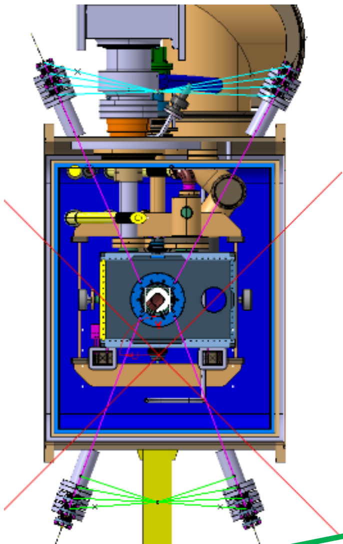
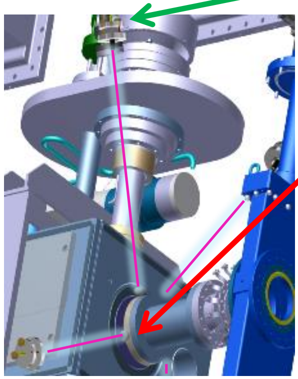
# *Spare slides*

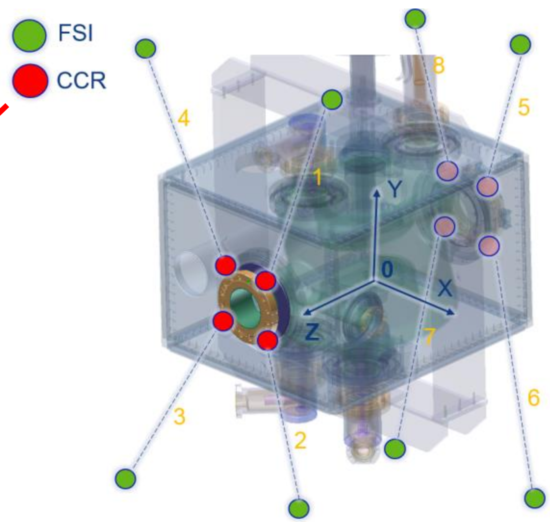
# Crab cavity FSI monitoring system

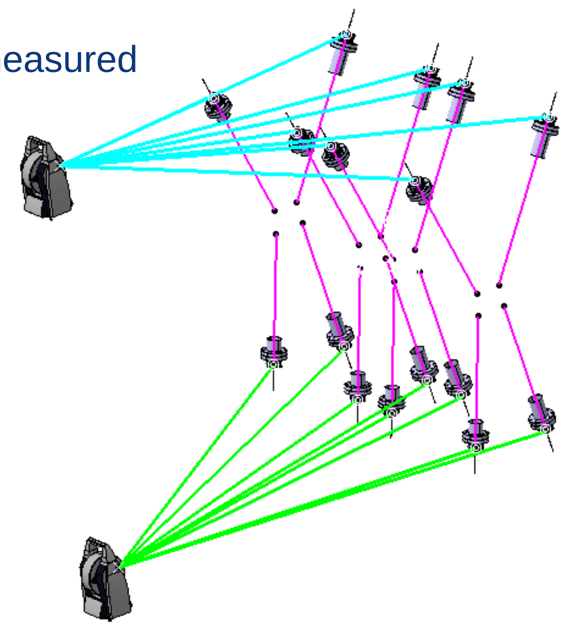
## FSI solution – system configuration

- 6 targets per cavity is required to calculate cavity position and orientation (least mean square method).
  Cavity fiducialisation data and measured distances between all FSI heads and centres of CCR targets are used
- Current design assumes 4 targets per flange
  (8 Corner Cube Retroreflectors [CCR] per cavity) to provide measurements redundancy
- Dressed cavity have to be fiducialized (known cavity geometry w.r.t. refernece targets)
- Positions of the FSI heads have to be measured







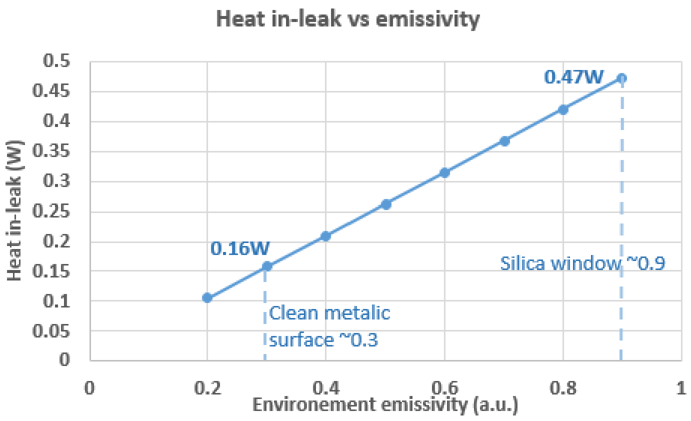
# 200K insulated prism design, heat in-leak from the thermal shield openings optimization

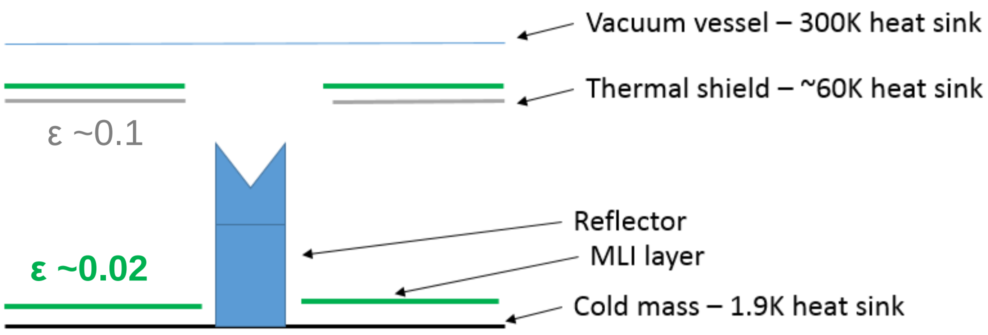
Hyp. For the dipole – the hole are Φ40mm on the center

The maximum heat radiated from the environment :

$$P_{in} = \sigma.\varepsilon_E.S_{opening}.(T^4_{ambient} - T^4_{rad\_surface})$$

Assuming $\varepsilon_E$=0.9, the power inlet is ~0.5W per Φ40mm hole (~400W/m²)




The ratio of emissivity between the thermal shield inner surface and the MLI covering the CM is ~5.

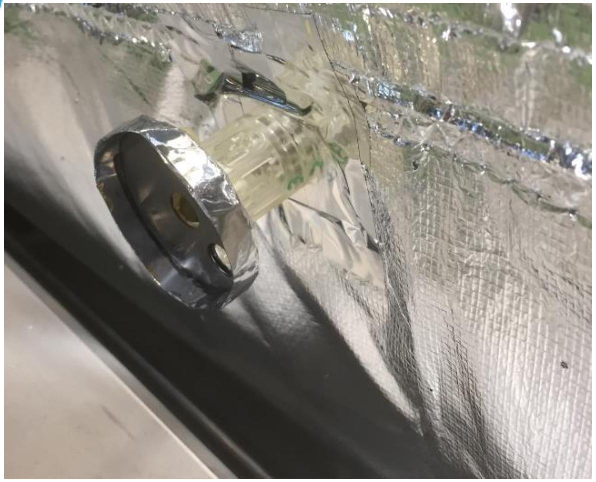
Thus we assume that the flux leaked in the hole will be absorbed at :
80% by the thermal shield inner surface
20% by the cold mass

→ ~0.1W per Φ 40 hole on the cold mass (~80W/m²)



F. Micolon

# Dipole case in-leak on the cold mass



The MLI *collerette* attempts to :

→ focus as much radiation as possible on the heat interception plate.
→ close the direct view between the cold mass and the vacuum vessel to limit the in leak

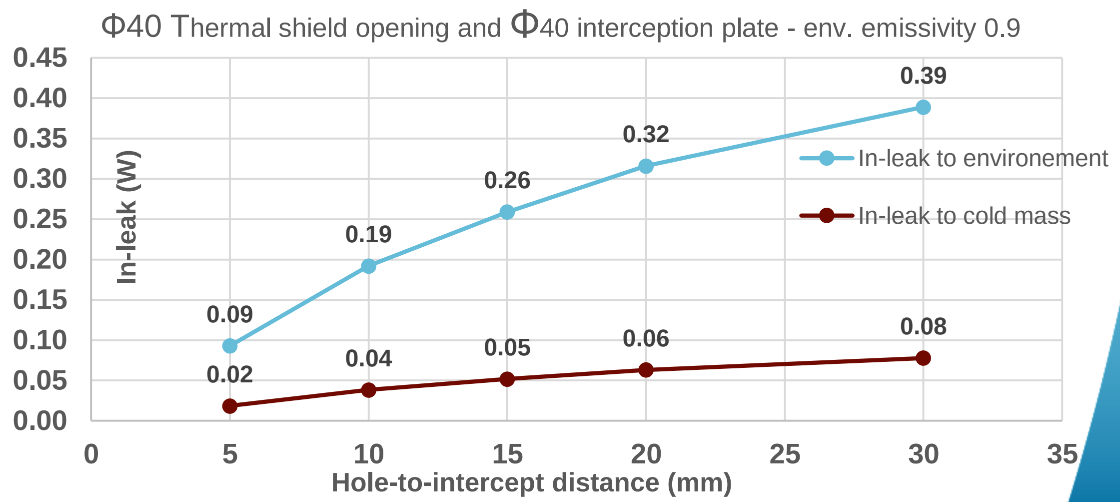
The remaining cold mass in-leaks are :

1) Residual opening between TS and heat intercept
2) Flux conducted by the insulating support
3) Flux self-radiated by the "hot" insulating support

**Residual opening between TS and heat intercept (**With a Φ40 TS opening and Φ 40 interception plate**):**

→ The closer the colerette is from the thermal shield the better
…but we should make sure to avoid permanent contact between the colerette and the inner thermal shield however.

**Thermal in-leak vs. hole-to-intercept distance**



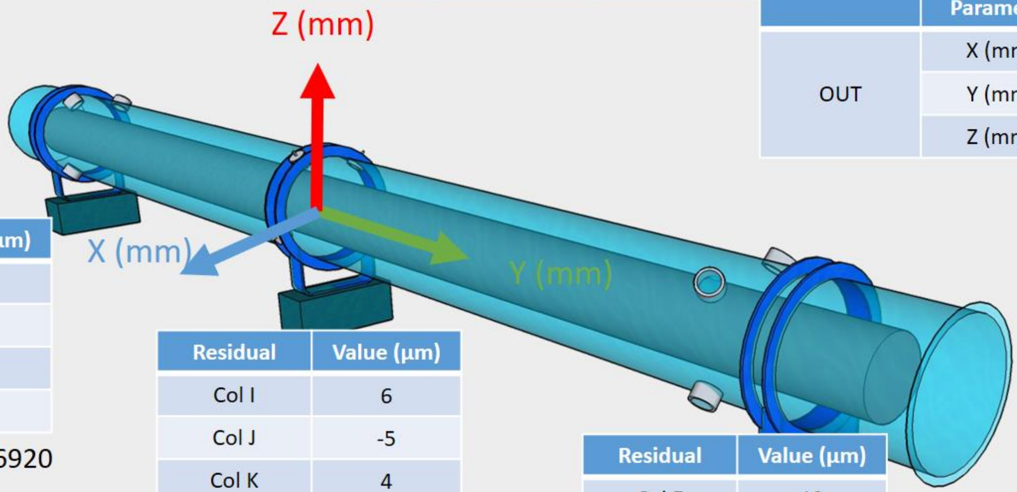

F. Micolon

# Latest results – Phase 4 cool down

| | Parameter | Value |
|---|---|---|
| IN | X (mm) | 0.569 |
| | Y (mm) | -6200.536 |
| | Z (mm) | 71.602 |

| | Parameter | Value |
|---|---|---|
| CENTER | X (mm) | 2.286 |
| | Y (mm) | 0.306 |
| | Z (mm) | 73.991 |

| | Parameter | Value |
|---|---|---|
| OUT | X (mm) | 4.053 |
| | Y (mm) | 4984.820 |
| | Z (mm) | 76.003 |




| Residual | Value (µm) |
|---|---|
| Col A | 39 |
| Col B | -19 |
| Col C | 36 |
| Col D | -31 |

Scale factor : 0.996920

| Residual | Value (µm) |
|---|---|
| Col I | 6 |
| Col J | -5 |
| Col K | 4 |
| Col L | -4 |

Scale factor : 0.997129

| Residual | Value (µm) |
|---|---|
| Col E | 12 |
| Col F | -5 |
| Col G | 11 |
| Col H | -9 |

Scale factor : 0.996903