Alignment & Monitoring from SPS to HL-LHC

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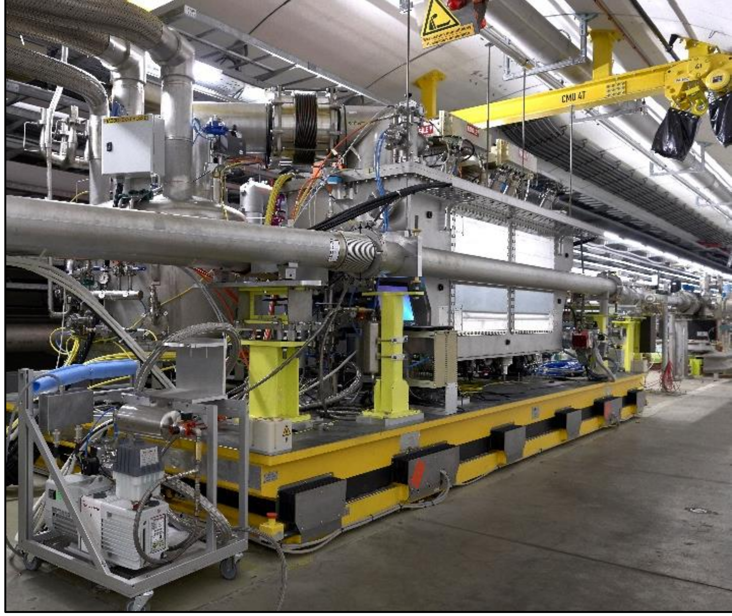
International Review of the Crab Cavity system design and production plan for the HL-LHC , 19 - 21 June 2019

Outline

SPS DQW prototype position monitoring

- Alignment requirements
- FSI System reminder
- Configuration of the crab cavities FSI monitoring system
- Test results (ambient, cool-down, cold)
- SPS test - Conclusion



Crab cavity FSI system optimization

- Inner triplet FSI system
- HL-LHC new approach – Multi-target FSI
  - FSI heads
  - Glass ball reflectors
  - Cryo-condensation configuration test
- Summary

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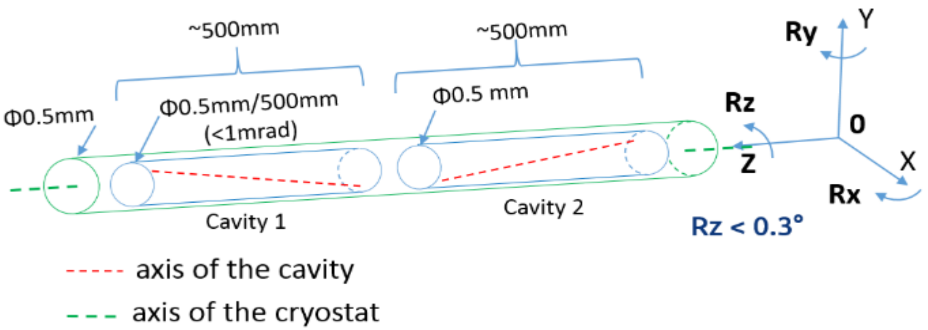
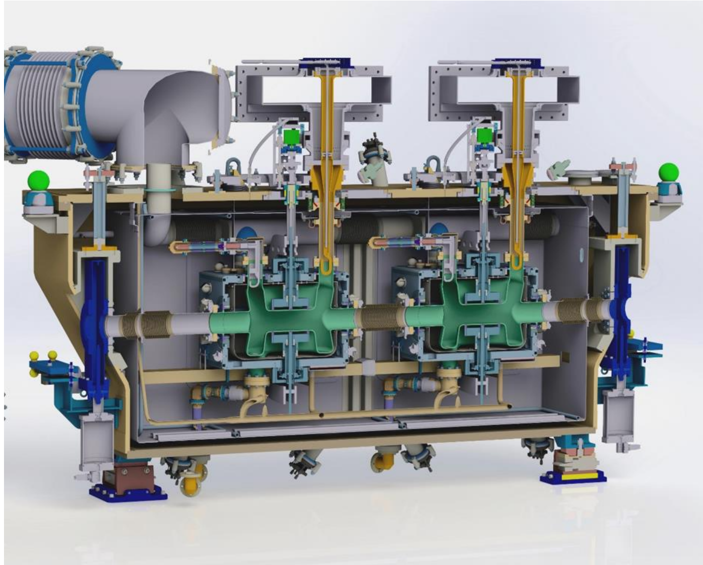
Alignment requirements and solutions chosen

- **Alignment requirements :**
  +/-0.25 mm at 3σ
- **Environmental conditions:**
  Radiation : 10 MGy (beam pipe),
  1 MGy (cryostat surface)
  Vacuum : 10-6 mbar
  Temperature : 2 K





SPS prototype position adjustment and monitoring

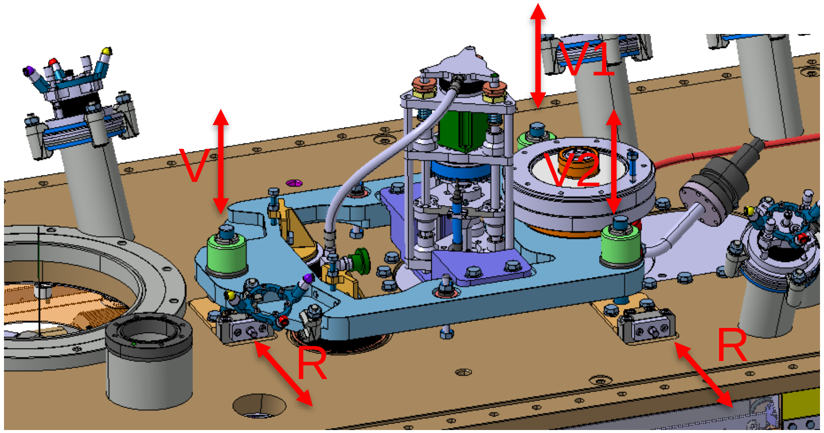
- 5DOF manual adjustment system integrated on the top plate of the cryomodule
- Two monitoring systems:
  - Frequency Scanning Interferometry (FSI) based – future HL-LHC solution
  - „Brandeis" Camera Angle Monitoring (BCAM) – only for SPS test for crosscheck purposes

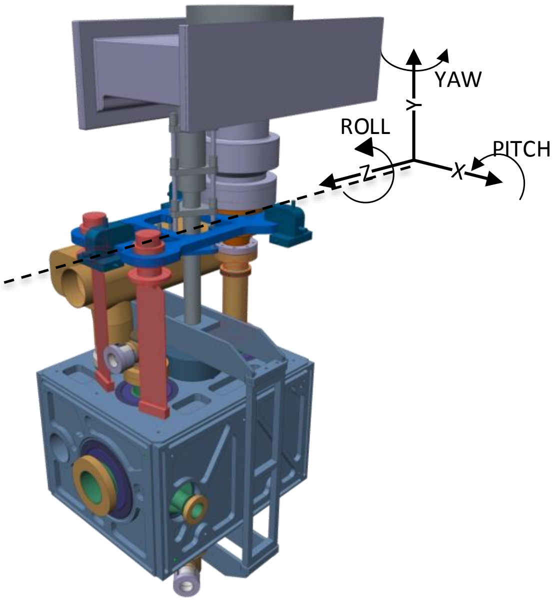
Cryomodule position monitoring w.r.t. tunnel reference (other LSS components) thanks to WPS system and inclinometers integrated on the cryostat

Cavity position adjustment

System requirements

- Position adjustment in 5DOF: X, Y translations, roll, yaw, pitch
- Easy intuitive, smooth and ergonomic operation



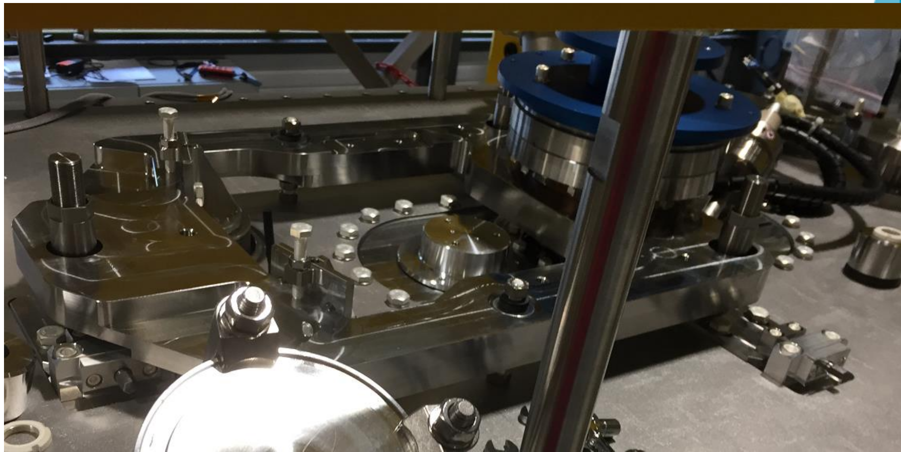


Solution deployed in SPS prototype

- Top supporting plate 3-point kinematic mount, with 2 radial and 3 vertical adjusters
- Dressed cavity suspended on the FPC and blades (operating as flexural joints to anticipate contraction)
- Easy access to adjustment knobs

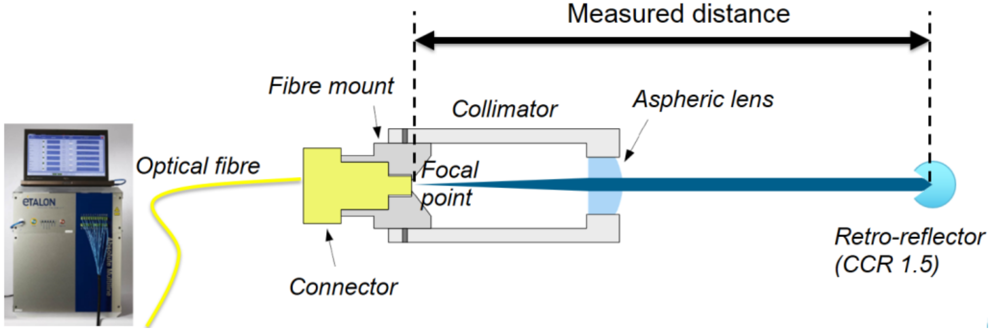
Adjustment experience – SPS prototype

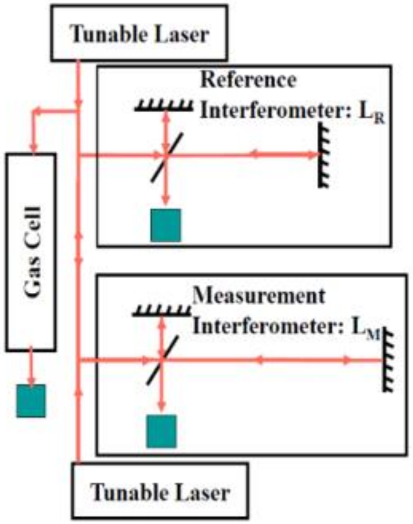
- Ergonomics OK, considering limited access
- Assembly of vertical rods and radial sliding plates should be more rigid



Frequency Scanning Interferometry – ETALON MULTILINE system

Absolute interferometric distance measurement





- Uncertainty (95%) = 0.5 µm/m
- Measurement distance: 0.2 – 20 m

- System sensitive to return signal intensity level:
  - Reflector lateral position have big impact on measurement performance
- Beam diameter defines transversal movement range of the target (for typical collimators limited to max ±3.5mm)
- Optical feedthroughs needs to include a tip-tilt adjustment functionality

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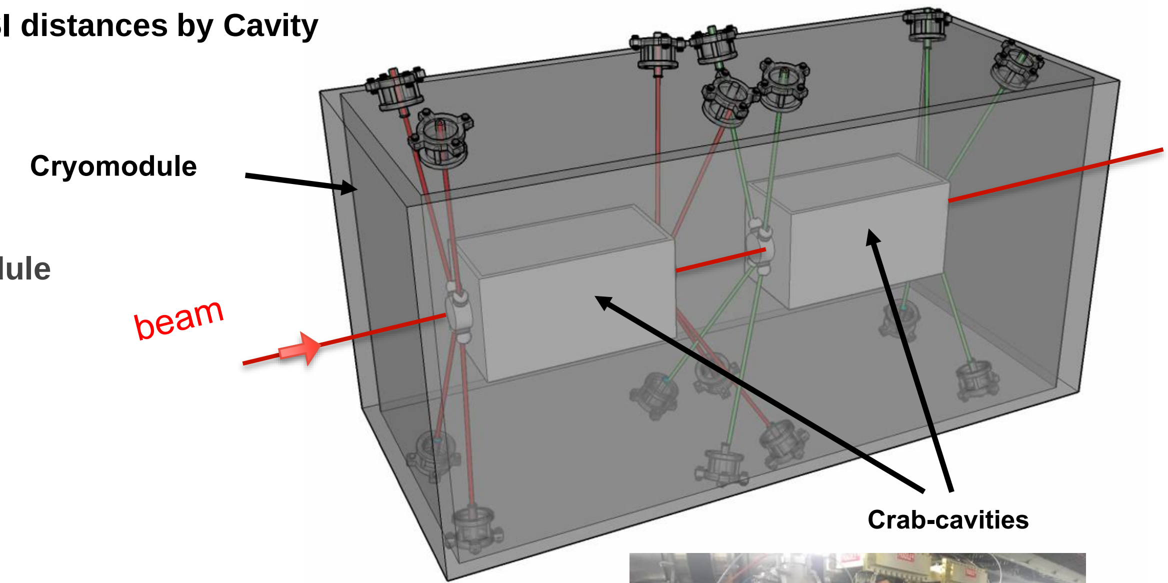
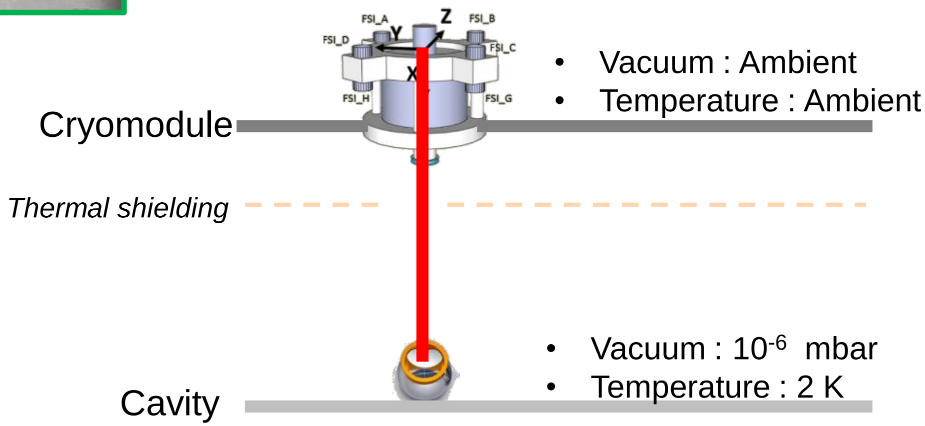
Crab cavity FSI monitoring system

Configuration

- **Collimator → Feedthrough → Cryomodule**
- **Retroreflector → Crab-cavities**

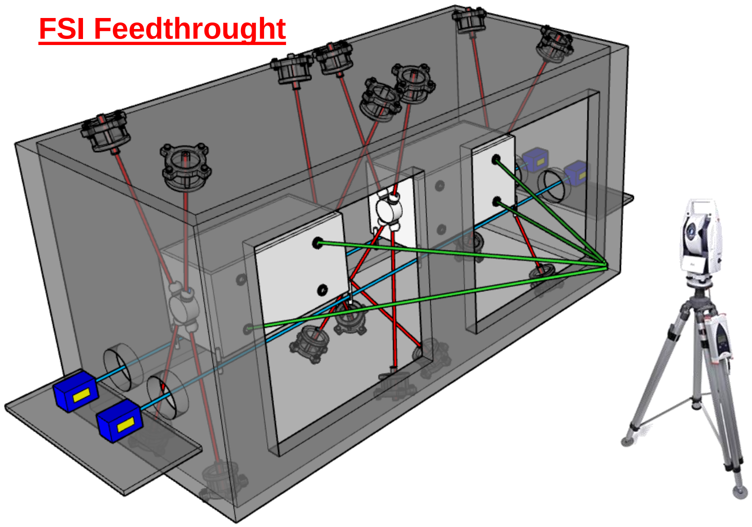
8 FSI distances by Cavity





Intercomparison between FSI / BCAM / Laser Tracker (Before to closing of the cryomodule)

FSI Feedthrought



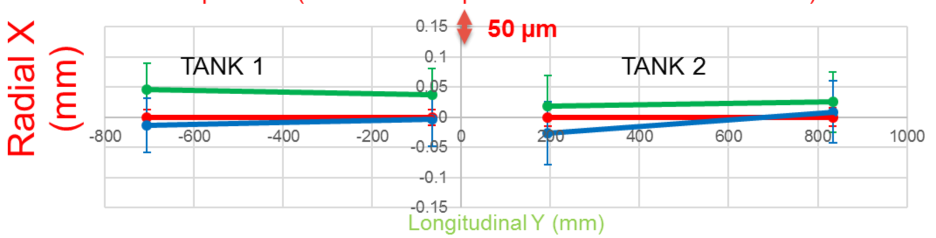
Laser Tracker

FSI (absolute distances)

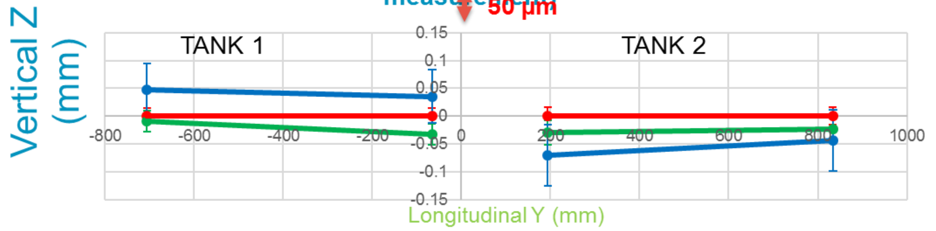
BCAM (Angle measurements)

Laser Tracker (Angles and distances measurements)

Radial position (relatif with respected to AT401 measurement)

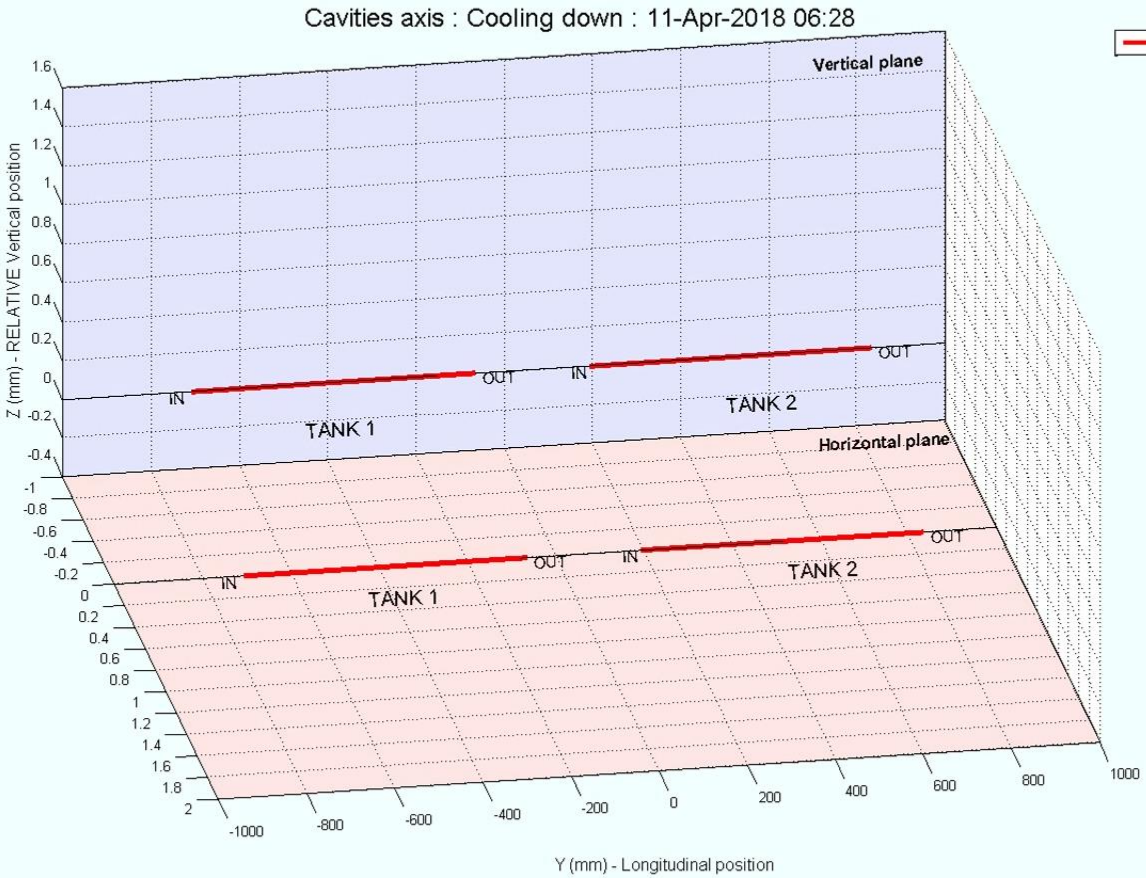


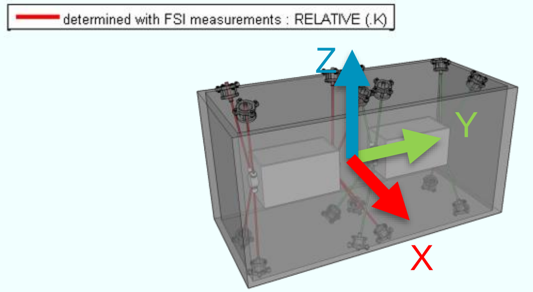
Vertical position (relatif with respected to AT401 measurement)

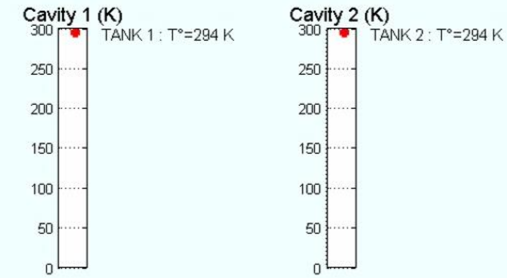


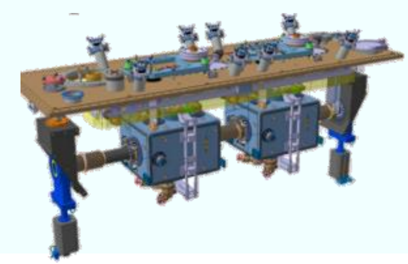
Cool down in SPS : From 293 K to 4 K

Accuracy : < 50 µm (1σ)

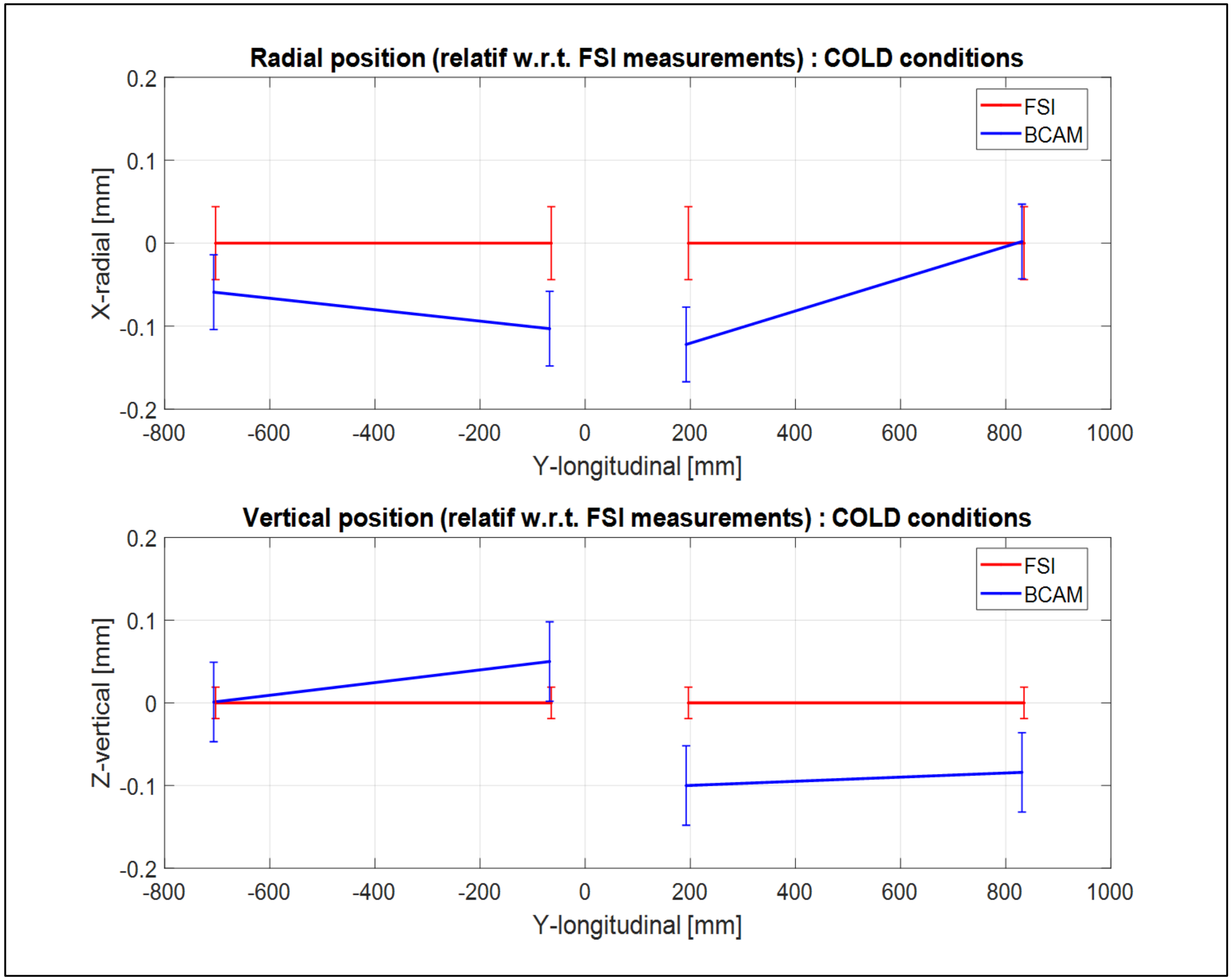




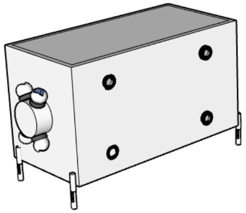




Intercomparision FSI vs. BCAM @ cold



FSI Target



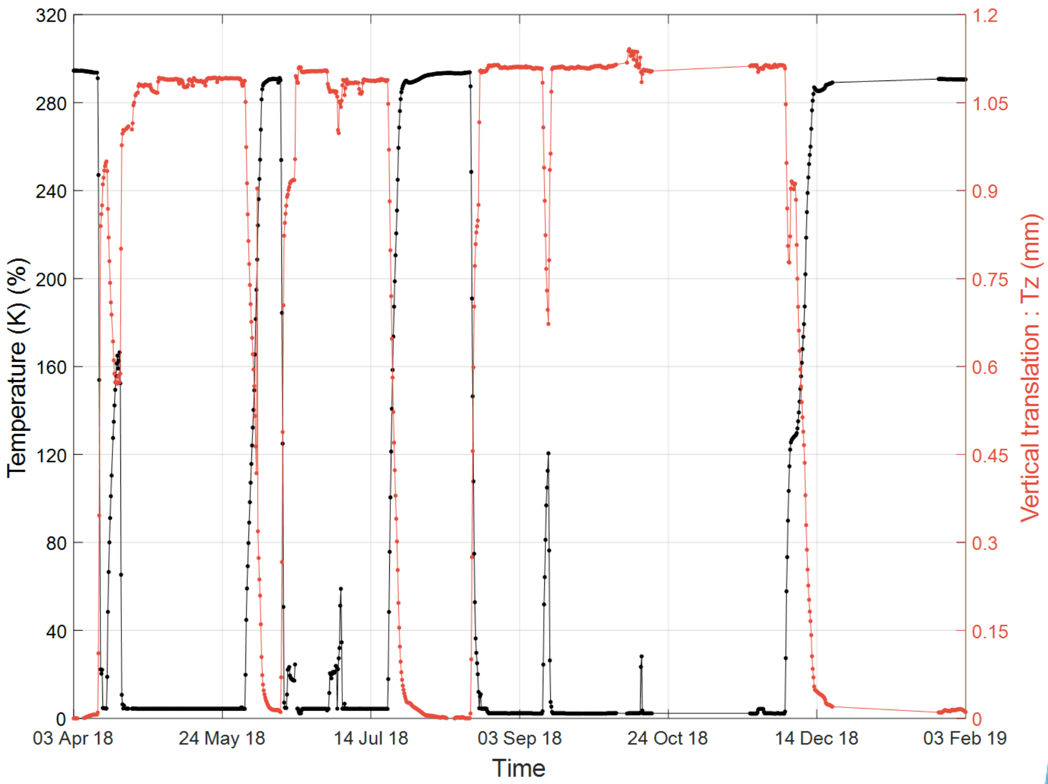
BCAM Target

Long term SPS measurements

Conclusion

Since April 2018, the monitoring of the Crab-cavities worked correctly.

Parameter	Precision (1σ)
Tx (radial)	+/- 25 µm
Ty (longitudinal)	+/- 45 µm
Tz (vertical)	+/- 10 µm
Rx (pitch)	+/- 30 µrad
Ry (roll)	+/- 150 µrad
Rz (yaw)	+/- 70 µrad
Scale	+/- 60 ppm

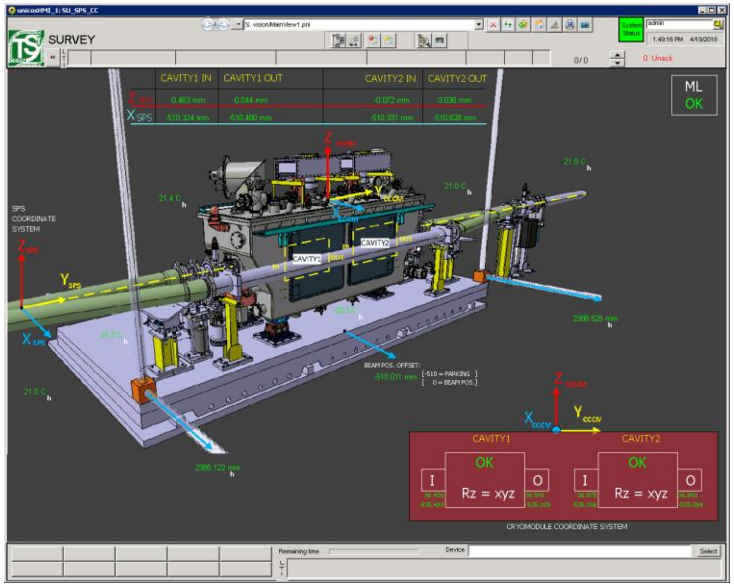


During the cooling-down :

- **a reduction of the feedback signals has been observed→ Cryo-condensation ?**
- **loss of 1/16 optical paths → Cryo-condensation / Obstacle ?**

Conclusions - SPS test

- ETALON FSI system used with specially designed optics
- System allows to follow the cooled crab cavity position/orientation
- Accuracy of absolute position of Crab-cavities inside cryomodule : +/- 50 µm



- Several cool-down cycles performed
- Repeatability of several heat-up and cool down sequences : Below 10 µm
- Relative precision : Few microns
- Continuous measurement by over 6 months
- Sensitive to optical components missalignment
- Cryo-condensation?

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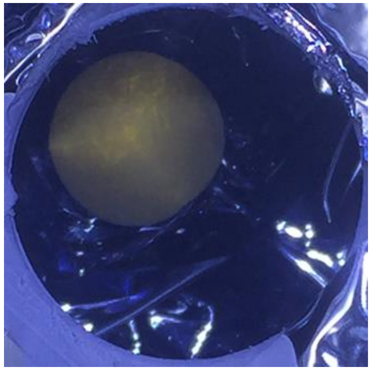
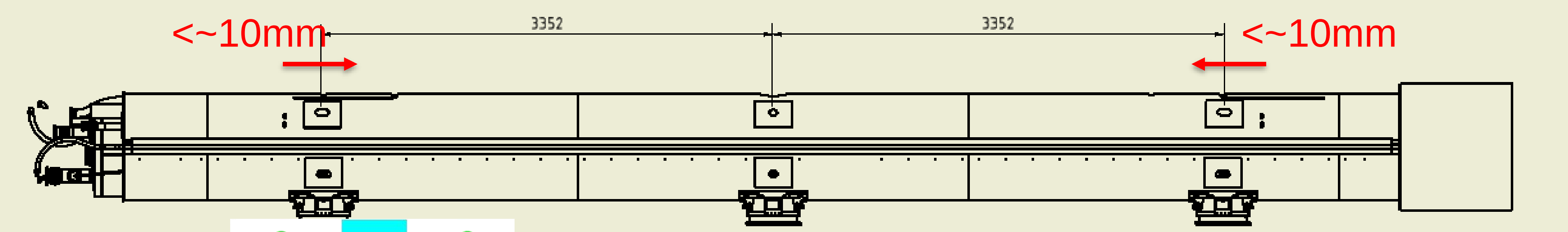
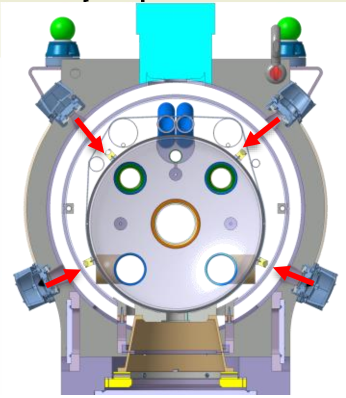
HL-LHC Inner Triplet FSI system

- Continuous measurement of position 12 reflectors installed on the cold mass from the vacuum vessel level
- Main constraints
  - Available space (integration)
  - Target thermal loss have to be minimized (cost of cryogenics)
  - Cryo-condensation effect on the reflectors
  - Extremity reflectors move ~10mm with cold mass contraction
  - Equipment handling, installation and alignment
  - Cost of overall installation







- Same FSI system for IT and crab cavities internal position monitoring
- Cryo-condensation issues to be checked for crab cavities too (crabs cryomodule much cleaner than IT one)

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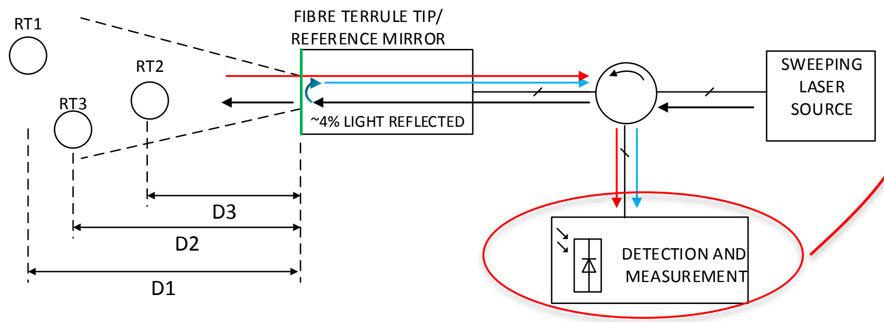
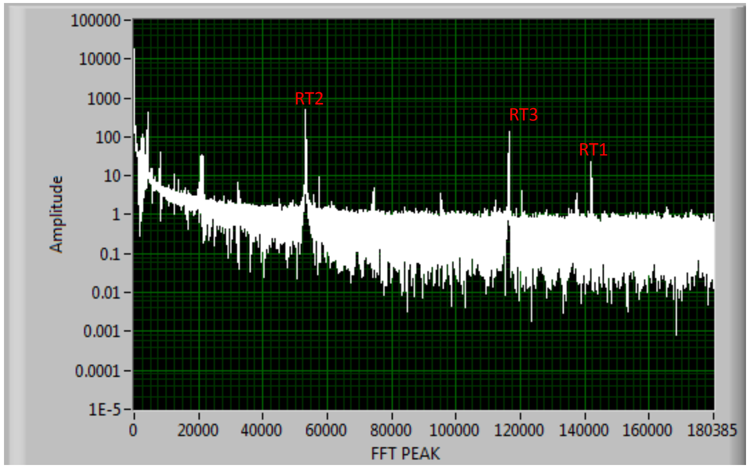
HL-LHC approach: Multi-target FSI

- New approach to FSI signal analysis – Fourier based distance calculation from detected beat frequencies



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



Considering α **= constant**, the interference "beat" signal frequency for each target distance will be:

$$f_{beat} = \alpha\tau = \alpha\,\frac{2D}{c}$$

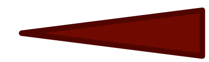
To calculate distance D_m to each target

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

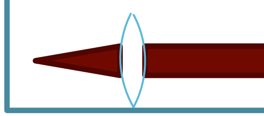
HL-LHC approach: Multi-target FSI

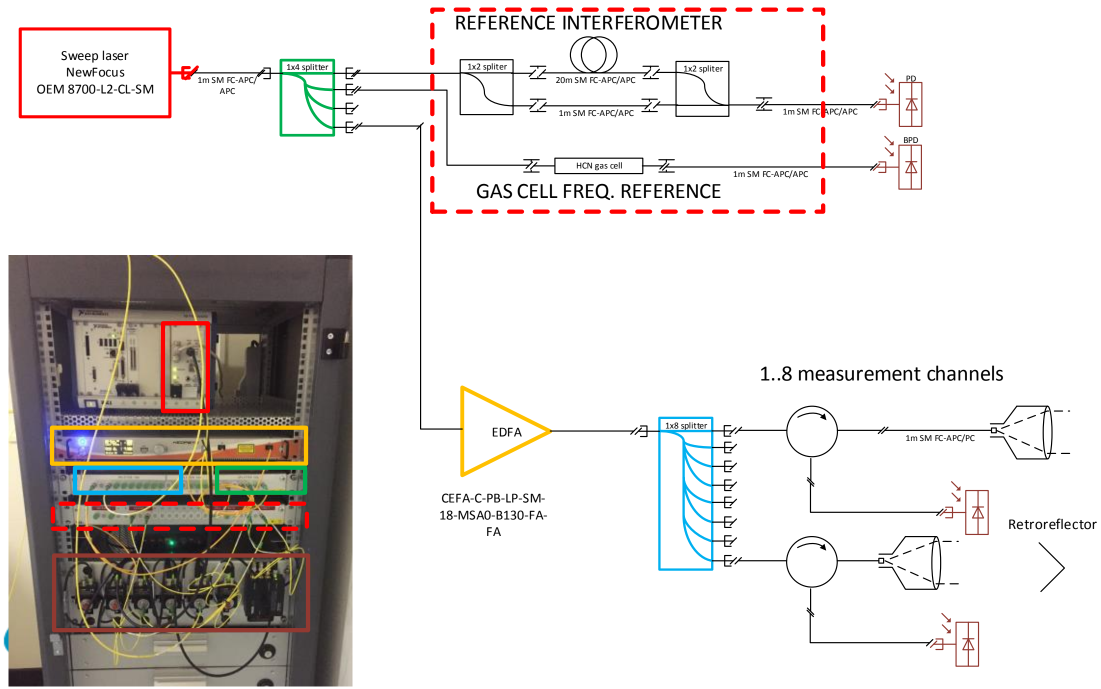
- **Very robust measurement method – almost insensitive to the light intensity (high and very small power reflections visible over the noise background**
  - Possibility to use cheap glass balls as a reflectors
- Measurement uncertainty <5um
- Possibility to measure multiple targets within single laser scan
- Simple optics
- **Possibility to use collimated and divergent beams**
- Simple and scalable Optics - prototype interferometer tested at CERN since 2017, production interferometer (multi-channel) unit ready in June 2019

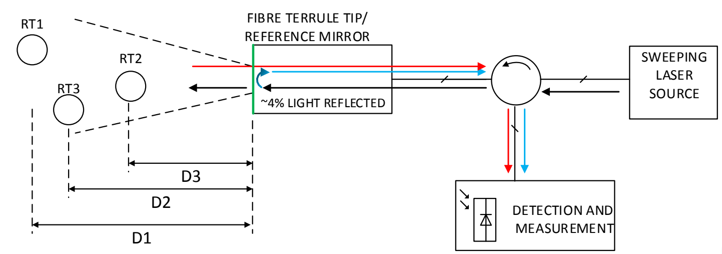
Divergent beam

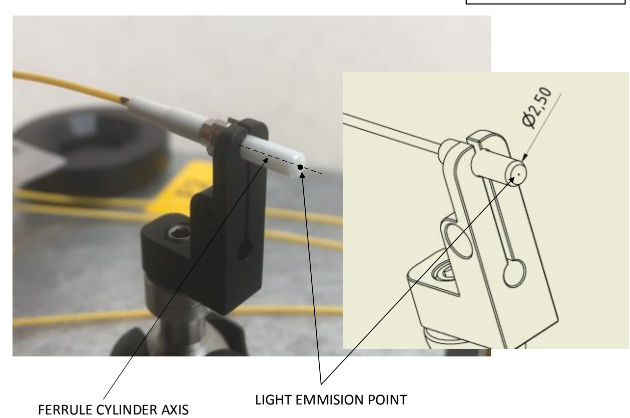


Collimated cylindrical beam





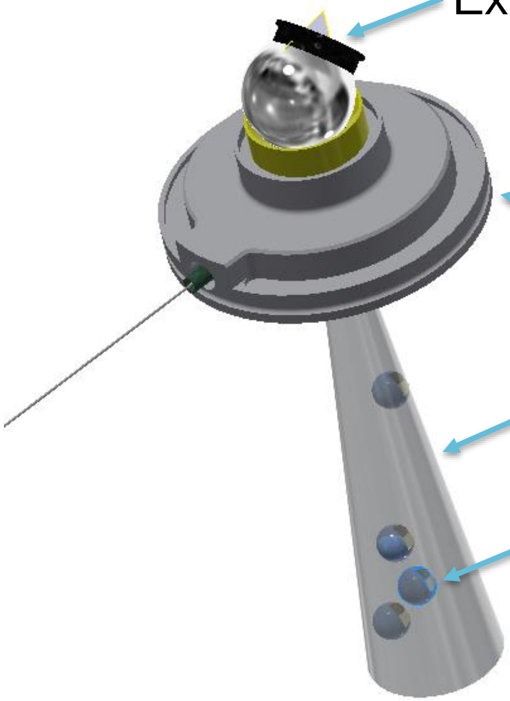




FSI heads optimization

Divergent beam FSI heads for HL-LHC

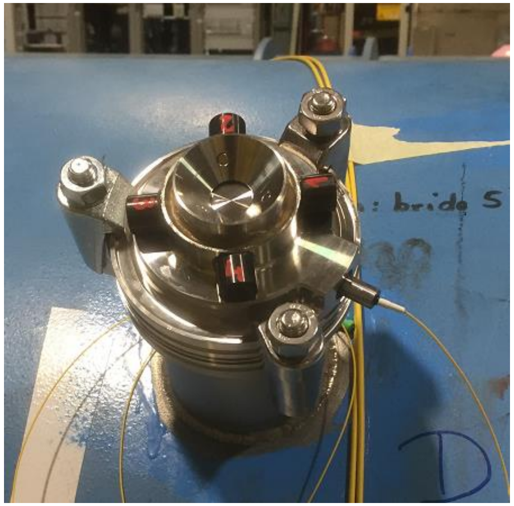
- Compact and simple construction
- Wide PATROL field (i.e. IT head patrol zone diameter ~60mm) – to observe reflectors in variable positions (cold mass contraction)
- Low cost (3000CHF vs. ~1000CHF for SPS Crab cavity FSI head)

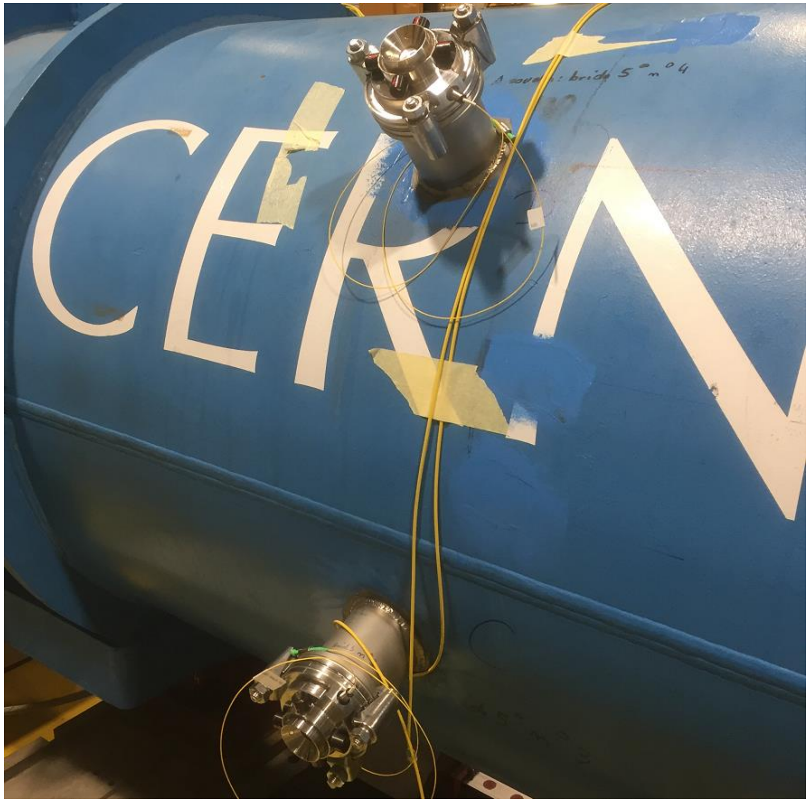


FSI heads optimization

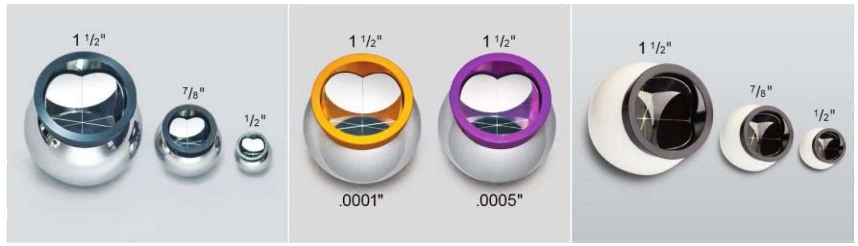
Cost optimized, multi-target, divergent beam FSI head for HL-LHC

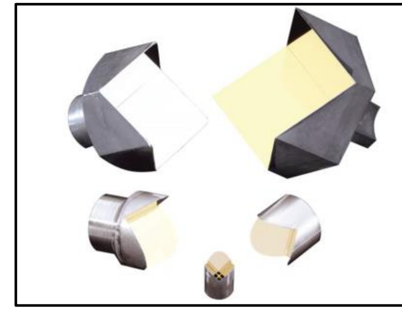
- No problem with target alignment on the dipole flanges
- Negligible loss of intensity even with target movements with cold mass contraction
- 10 heads tested at DIPOLE test campaign in SM18



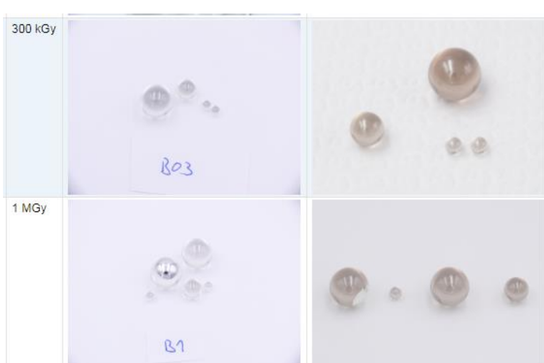


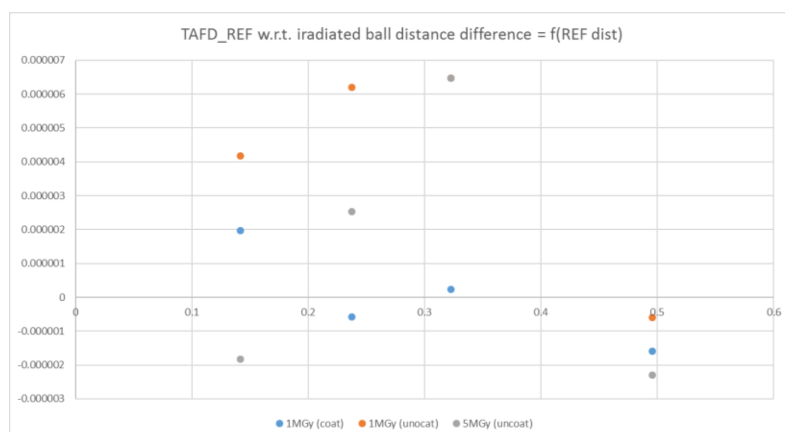
Low cost glass ball reflector



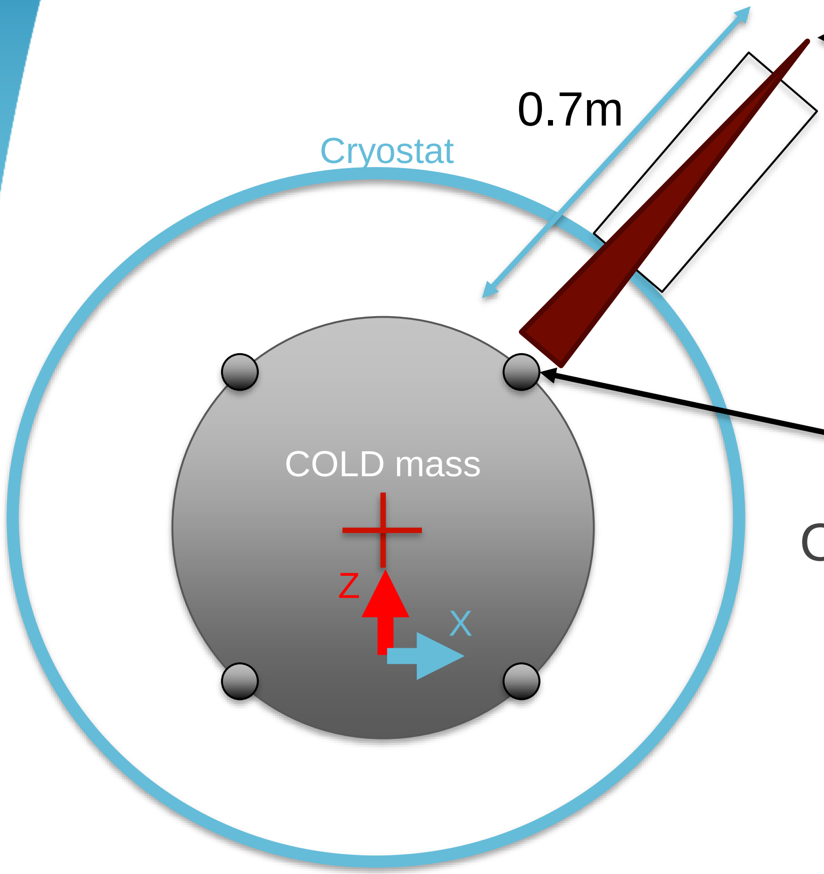


- Coated glass ball reflector and cheap hollow retroreflector used in dipole test – no specific issues observed
- Coated glass ball reflector measurable by laser tracker
- Refractive index ≈2 glass ball as a alternative to hollow retroreflectors or replicated reflectors (**~50€** vs. ~2k€ vs. 300 €)
- Radiation hard (up to now 5MGy tested)

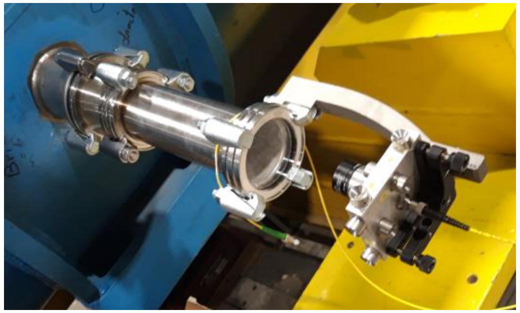




CRAB – Dipole test – March, July 2019



Low opening angle divergent beam optics



Glass ball reflector

Objective:

- Check MTFSI in CRAB configuration, considering ultimate (cryo-condensation) conditions
- Check prototype of CRAB divergent beam optics

- March 2019 – test @ 80K – no issues observed
- July 2019 – test @ 4K soon

Summary

- SPS DQW prototype tests showed very good performance of FSI system for crabs position monitoring
- Multi-target FSI, simple optical heads and glass reflectors chosen for HL-LHC crab-cavity application
  - Allows for small space integration
  - No issues with optics handling and alignment
  - Tolerance to big lateral target(s) movements
  - Low cost (instrumentation cost can be lower ~one to two orders of magnitude w.r.t. initial crab solution)
  - Still adaptation of new optics to be done for final HL-LHC CC FSI heads and reflector supports

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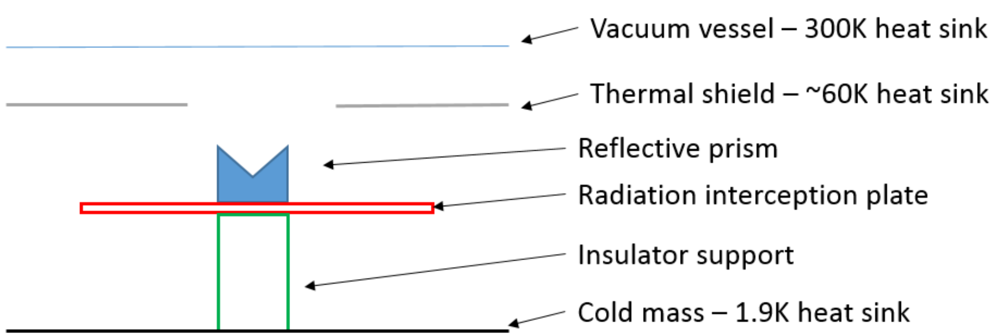
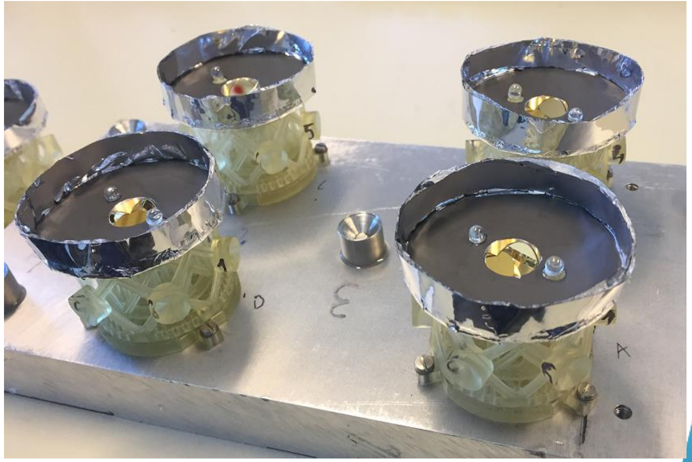
Thank you for your attention

Status of development and tests: IT (Dipole test)

- The special design of targets (temperature optimized) allows for use ETALON FSI and MT FSI without cryo-condensation effect, with thermal load at reasonable level
- New (rigid and less fragile) target supports tested on the DIPOLE with Newport hollow retroreflector and coated glass ball reflector tested
- Crab-cavity heads / External collimator through window / Dedicated MTFSI heads tested on the DIPOLE
- Radiation tests of aluminium reflectors and cheap glass reflectors - DONE





- Impossible to use insulated reflectors for CRAB application
- possible that cryo-condensation was observed

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Material cost

Internal monitoring (cryostat hardware per single FSI line):

    - FSI target: ~80 CHF (vs. ~2000 EUR of SPS used BMR)
    - FSI support: ~300 CHF
    - FSI feedthrough: ~1000 CHF (vs. ~3000 CHF of SPS used TIP-TILT head)
  - Cost per channel (not including acquisition system & cables): 1.4 kCHF
  - **Total cost (8 cryostats + spares): 220 kCHF**

Cost of acquisition system: based on the number of channels used (preliminary estimate)

    - Channels foreseen per IP: 64 channels for crabs monitoring (~1 kCHF/ch)
    - Acquisition system estimated: 64 kCHF for WP4
  - **Total cost: 130 kCHF**

- Above costs not includes optical fibres + patch panels

Additional costs

- 215 kCHF: PJAS during 38.5 months throughout the production and installation phase of crab cryomodules until the end of the project

- 50 kCHF for the prototype of RFD cryomodule, whichwill be tested in the SM18 in 2021 and in the SPS from 2022