Internal monitoring of the HL-LHC components

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Outline

Introduction

- HL-LHC project
- Internal monitoring

Internal monitoring of Crab Cavities

- Configuration
- Results

Internal monitoring of IT quadrupoles

- Configuration
- Results

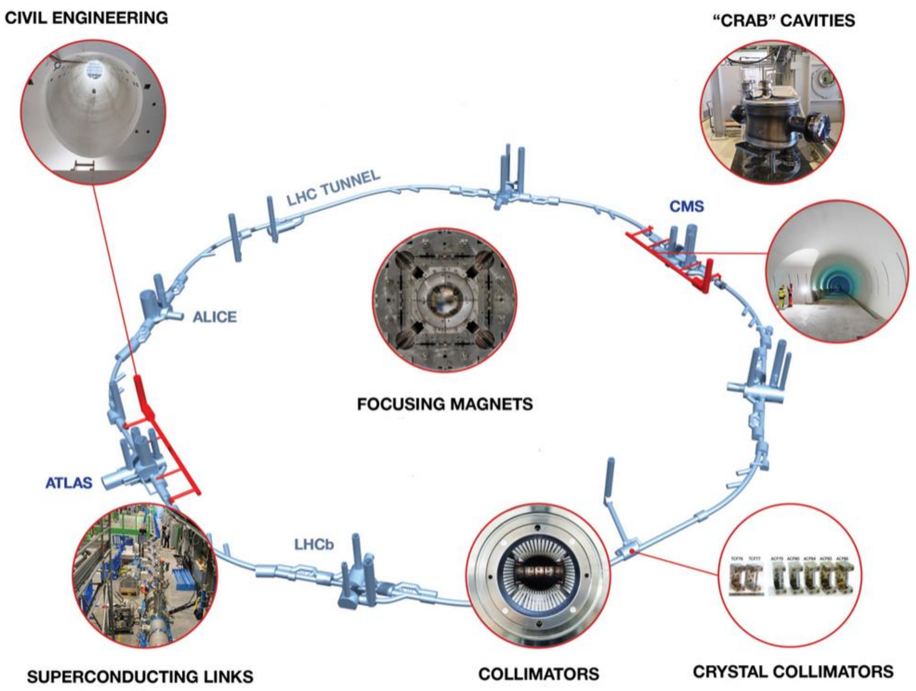
Summary

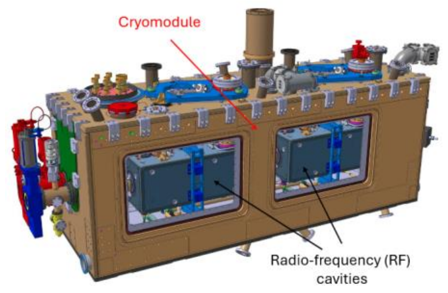
Introduction to HL-LHC project

- HL-LHC means **High-Luminosity LHC**
- Aim to increase the integrated luminosity and potential for discoveries after 2030.
- Relies on several **key technological innovations**, including:
  - **New focusing magnets:** superconducting quadrupole magnets, Nb3Sn-based.

    24 new IT quadrupoles in production.
  - **«Crab cavities»** to give the particle bunches a transverse momentum before they meet.

    16 crab cavities in production.
- For both types of components: request to monitor continuously the position of the component inside its cryostat → **internal monitoring**.



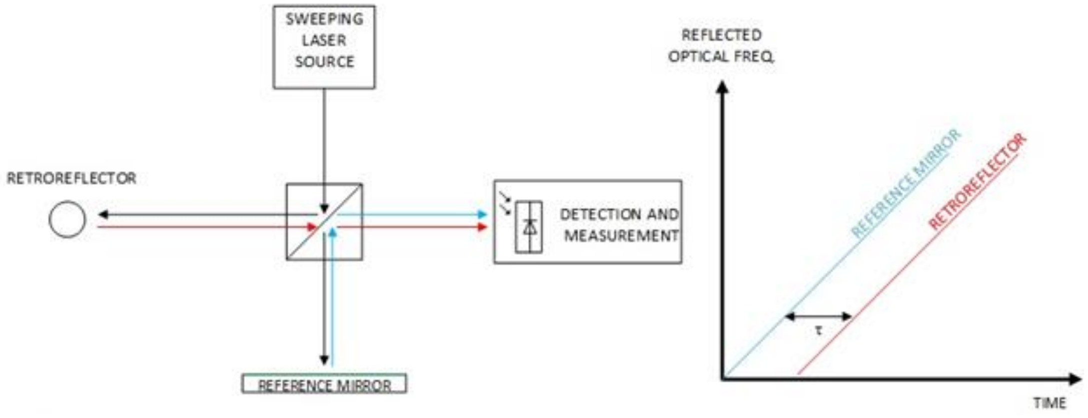


Introduction to internal monitoring

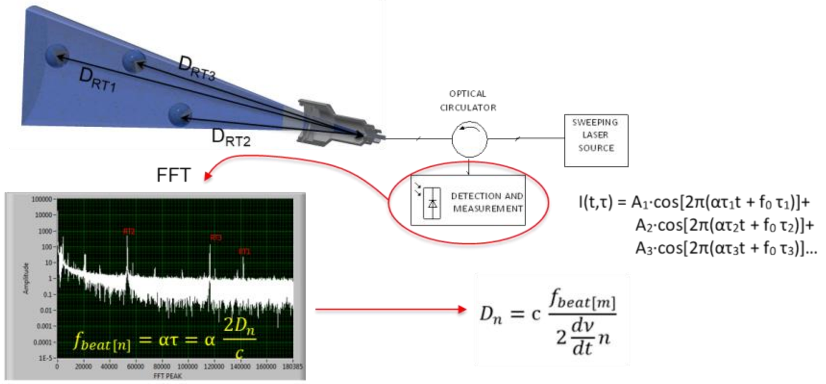
Requirements:

- Absolute measurements needed: determination of the component (magnet, crab cavity) in the reference frame of the cryostat, within ± 0.1 mm (1σ)
- Important displacement of the target during the cooling of the component up to 10 cm.

- Under vacuum
- Under high radiation level: TID ~ 1 MGy
- At cold: 1.9 K



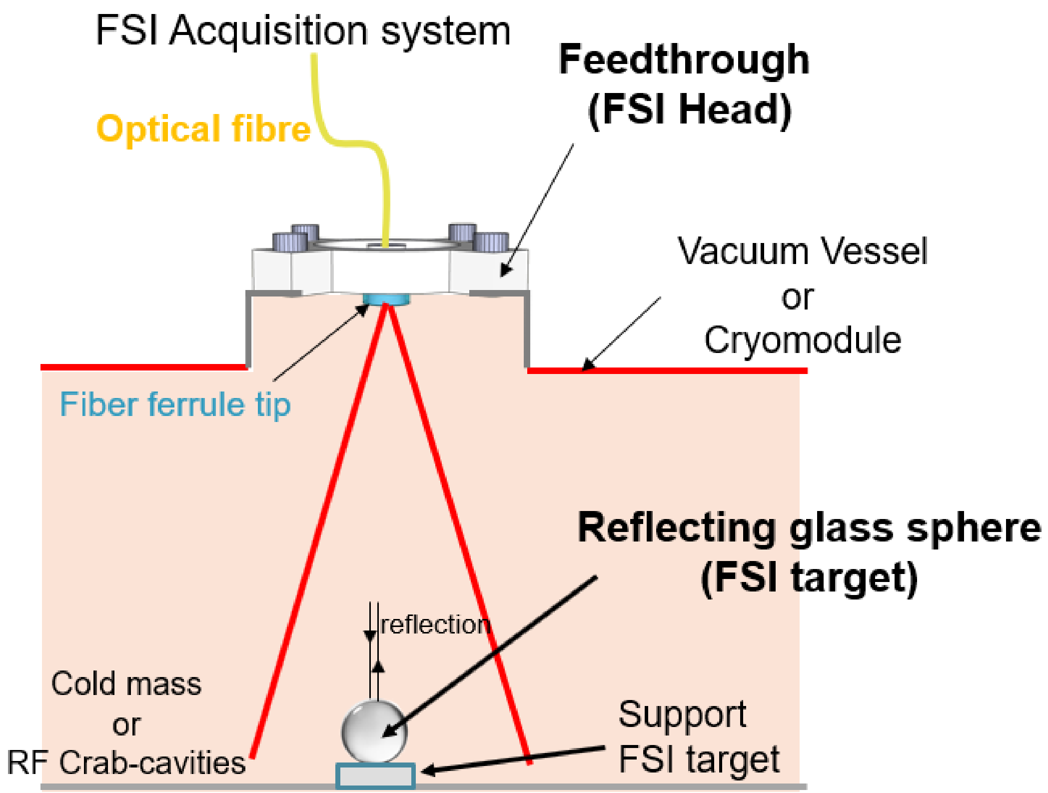
Solution = multi-target Frequency Scanning Interferometry (FSI)



α – is a sweep rate of the laser ($\alpha = \frac{dv}{dt}$ - 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

- We measure the absolute distance between the optical fiber tip and targets
- The interference signal mixes the interference beat frequencies from the ferrule tip and the reflective target
- If the laser sweep is constant, the beat frequencies become proportional to the reflective target distances and can be retrieved using FFT.

Introduction to internal monitoring



Reflecting glass spheres (FSI targets)

Feedthroughs

- **544 targets, feedthroughs and acquisition channels,**
- **Cone vision of ± 6° for quadrupoles and ±2° for crab cavities,**
- **In-house FSI acquisition system.**

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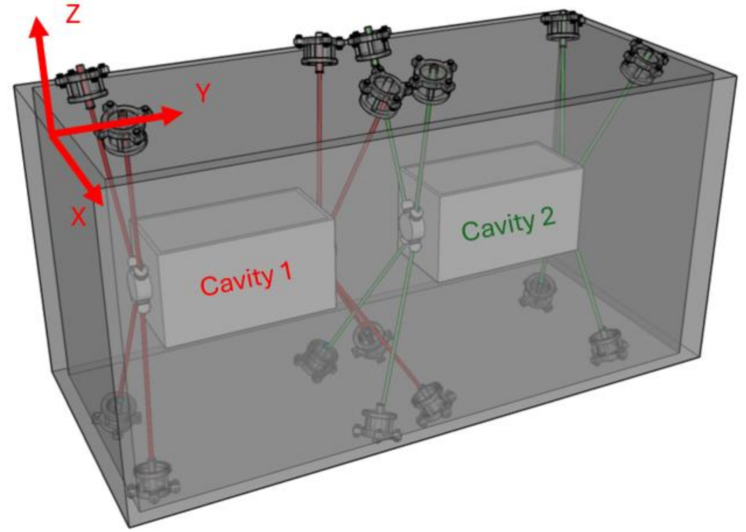
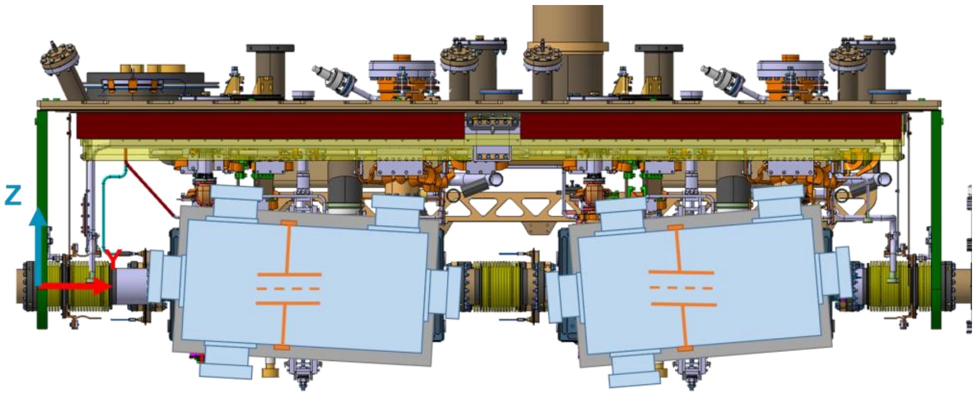
Internal monitoring for crab cavities

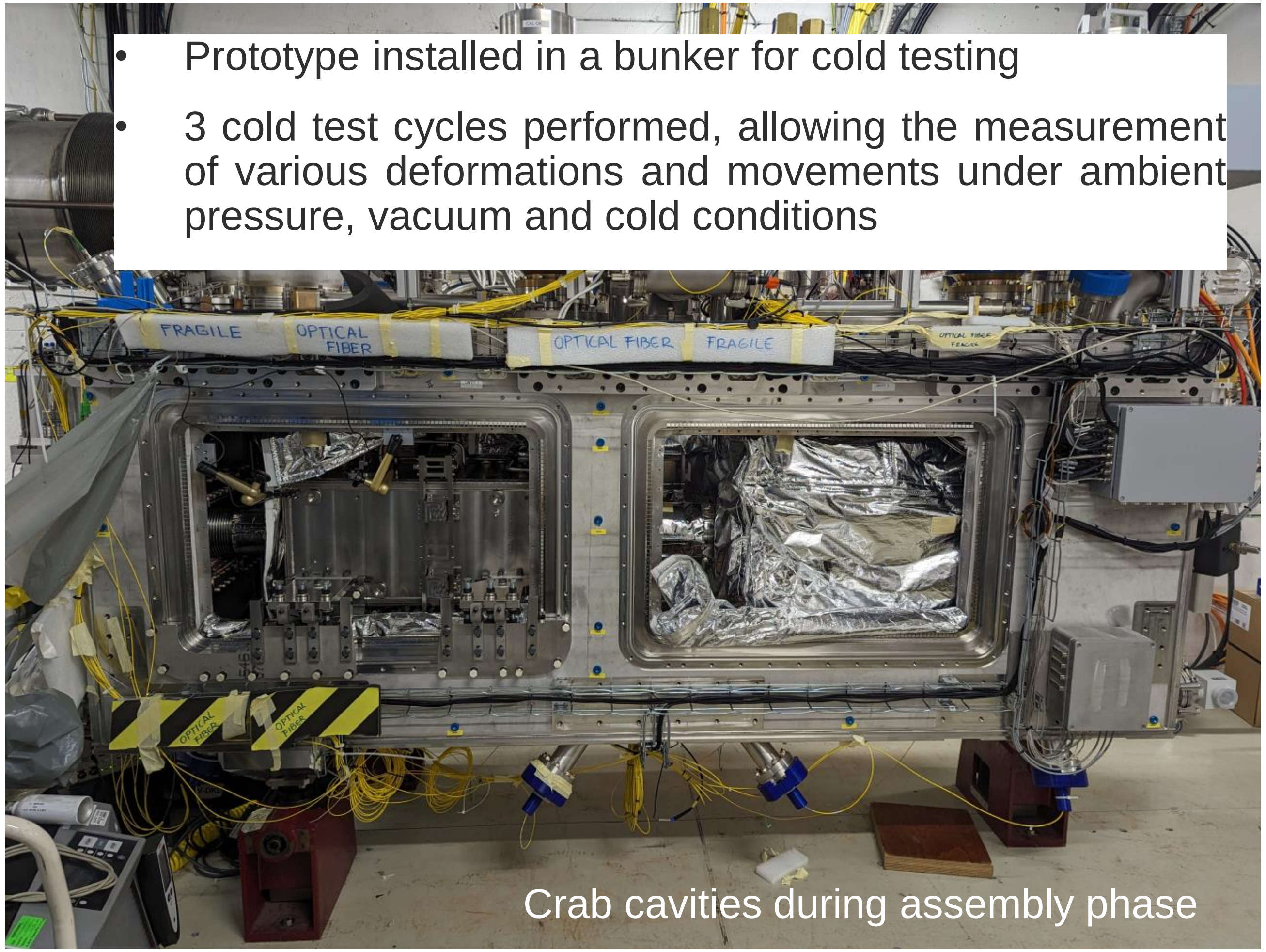
Configuration of FSI measurement system



Cavities are suspended on the top plate

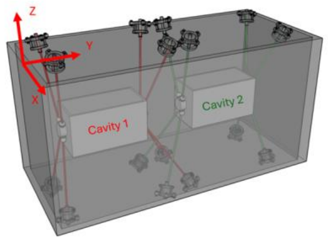


- Prototype installed in a bunker for cold testing
- 3 cold test cycles performed, allowing the measurement of various deformations and movements under ambient pressure, vacuum and cold conditions



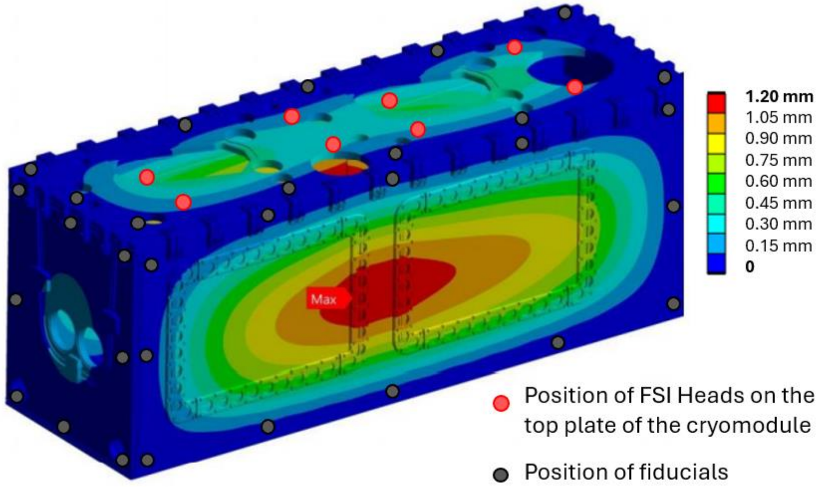
Crab cavities during assembly phase

Internal monitoring for crab cavities: results



Displacements and deformations: impact of different parameters – vacuum

Deformation of the cryomodule due to vacuum pumping



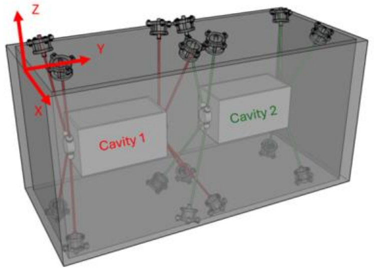
Cavities movements due to vacuum pumping

	Movement	Accuracy
Radial : Tx (mm)	**0.40**	<0.10
Longitudinal : Ty (mm)	-0.02	0.10
Vertical : Tz (mm)	**-0.42**	<0.10
Pitch : Rx (mrad)	**0.15**	0.04
Roll : Ry (mrad)	-0.63	0.40
Yaw : Rz (mrad)	-0.01	0.10

Impact of vacuum:

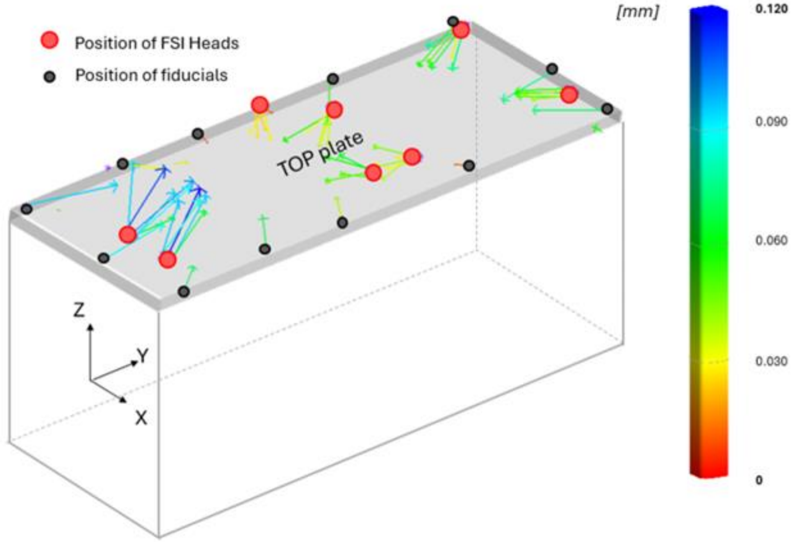
- Important deformation of the cryomodule during pumping: simulated deformation was confirmed by measurements.
- Fiducials and FSI heads return to their original positions with an accuracy of better than 50 µm.
- During the 3 pumping cycles, the same movement of the 2 cavities inside the cryomodule was observed, with a repeatability better than 0.05 mm both in the radial and vertical directions.

Internal monitoring for crab cavities: results



Displacements and deformations: impact of different parameters – cool-down

Deformation of the top plate due to the cool down



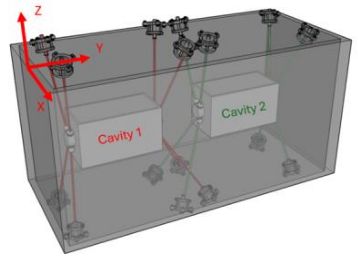
Cavities movements due to the cool down

	Movement	Accuracy
Radial : Tx (mm)	**0.19**	<0.10
Longitudinal : Ty (mm)	-0.10	0.10
Vertical : Tz (mm)	**1.18**	<0.10
Pitch : Rx (mrad)	**-0.17**	0.04
Roll : Ry (mrad)	0.29	0.40
Yaw : Rz (mrad)	**0.38**	0.10
Scale factor (mm/m)	**-2.60**	0.25

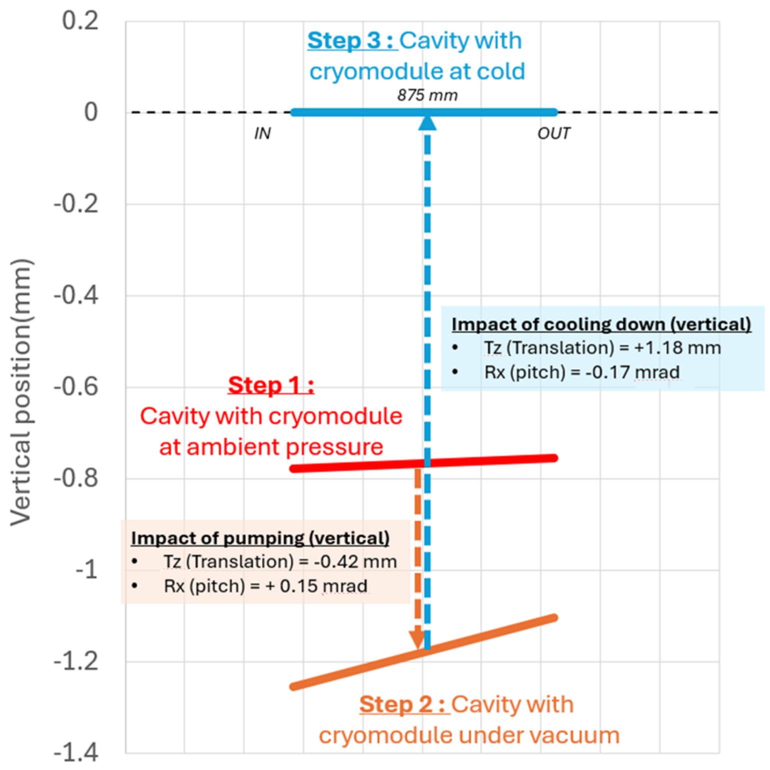
Impact of cool-down:

- Deformation of the top plate due to the cool down: maximum 0.1 mm, measured by laser tracker
- Fiducials and FSI heads return to their original positions with an accuracy of better than 50 µm.
- Behavior of the 2 cavities consistent with the model within 0.1 mm.

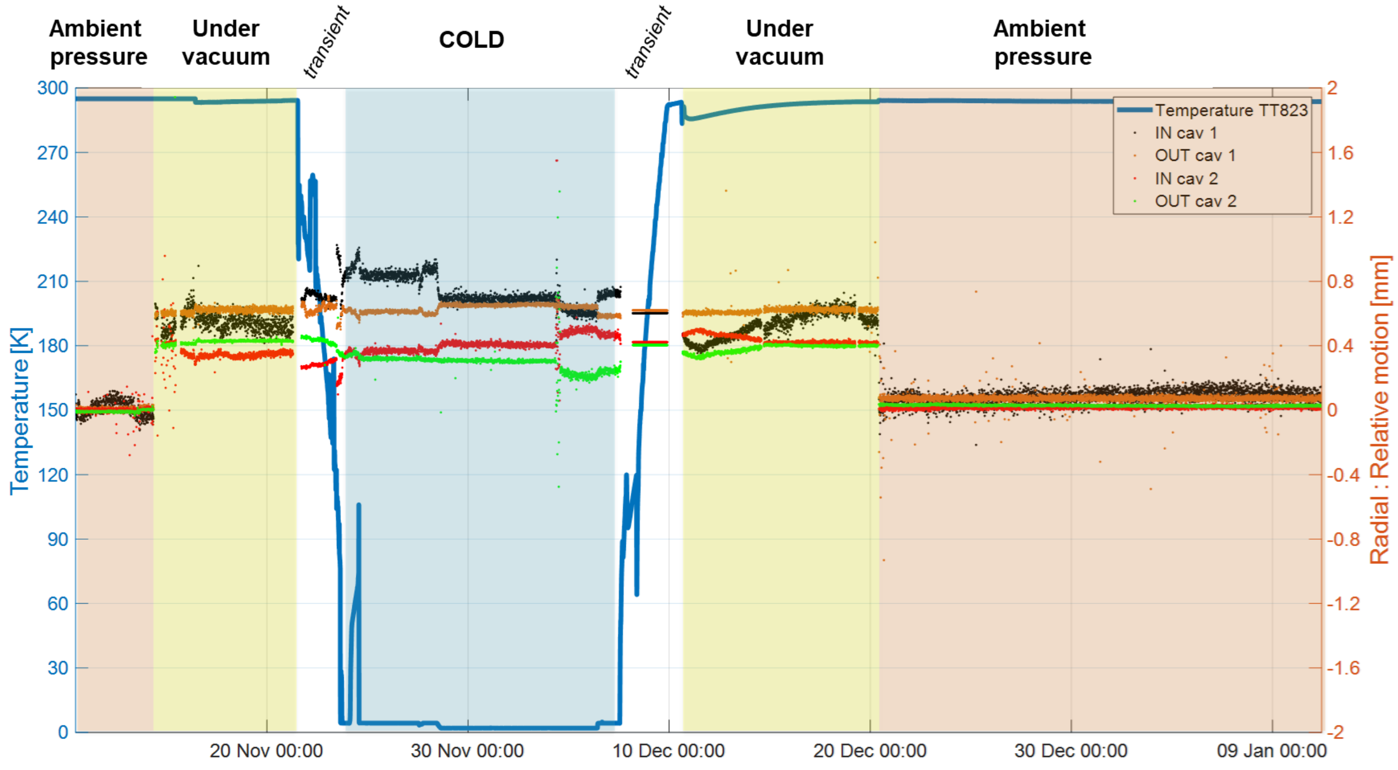
Internal monitoring for crab cavities: results



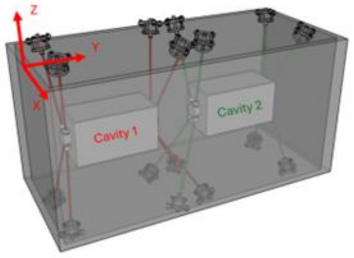
The pre-alignment of the cavities at warm and ambient pressure must take into account the cryomodule deformation and the cavities movements: 3 steps strategy



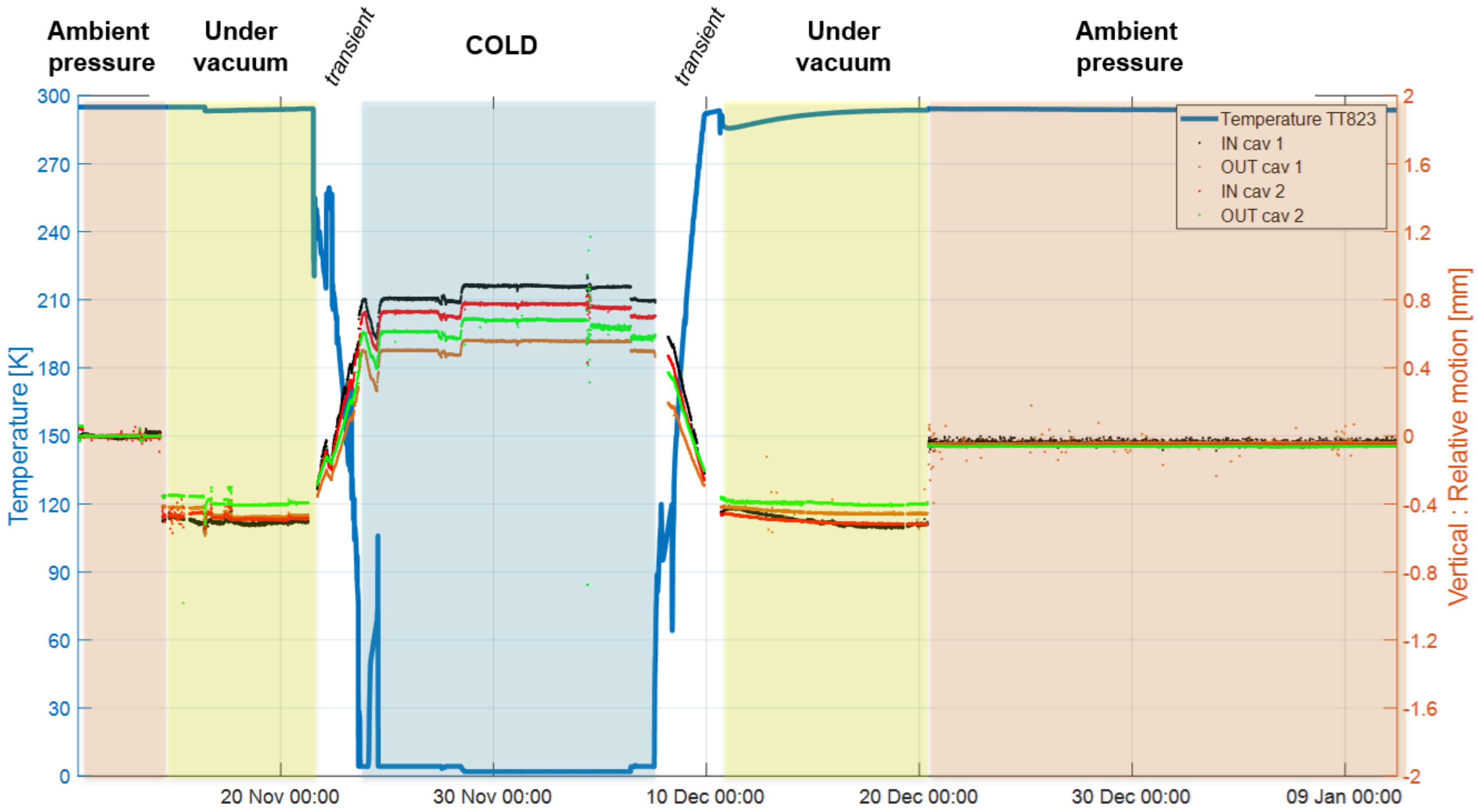
In radial: relative motion of the cavities inside the cryomodule



Internal monitoring for crab cavities: results



In vertical: relative motion of the cavities inside the cryomodule



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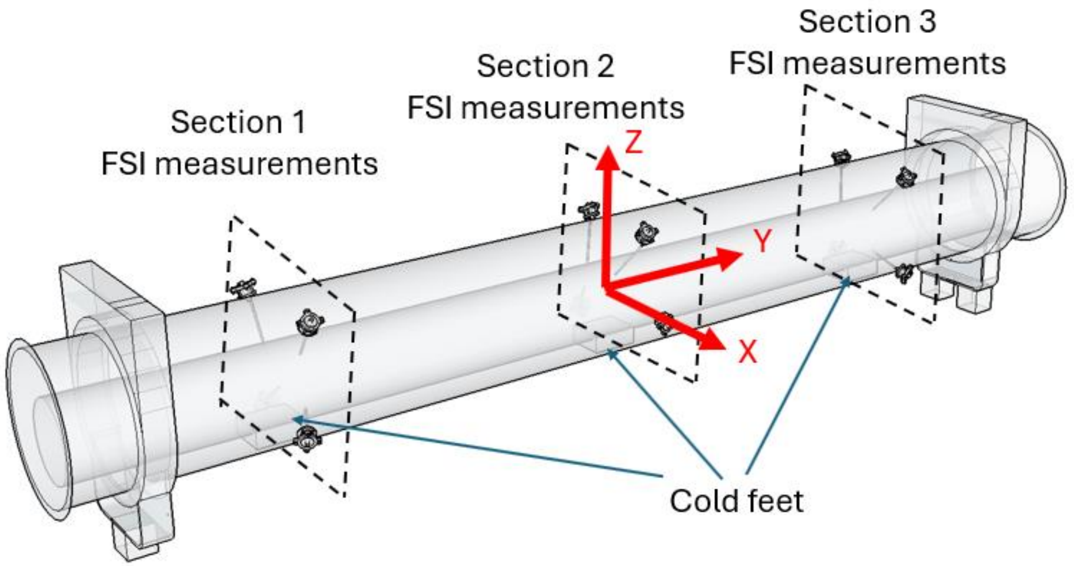
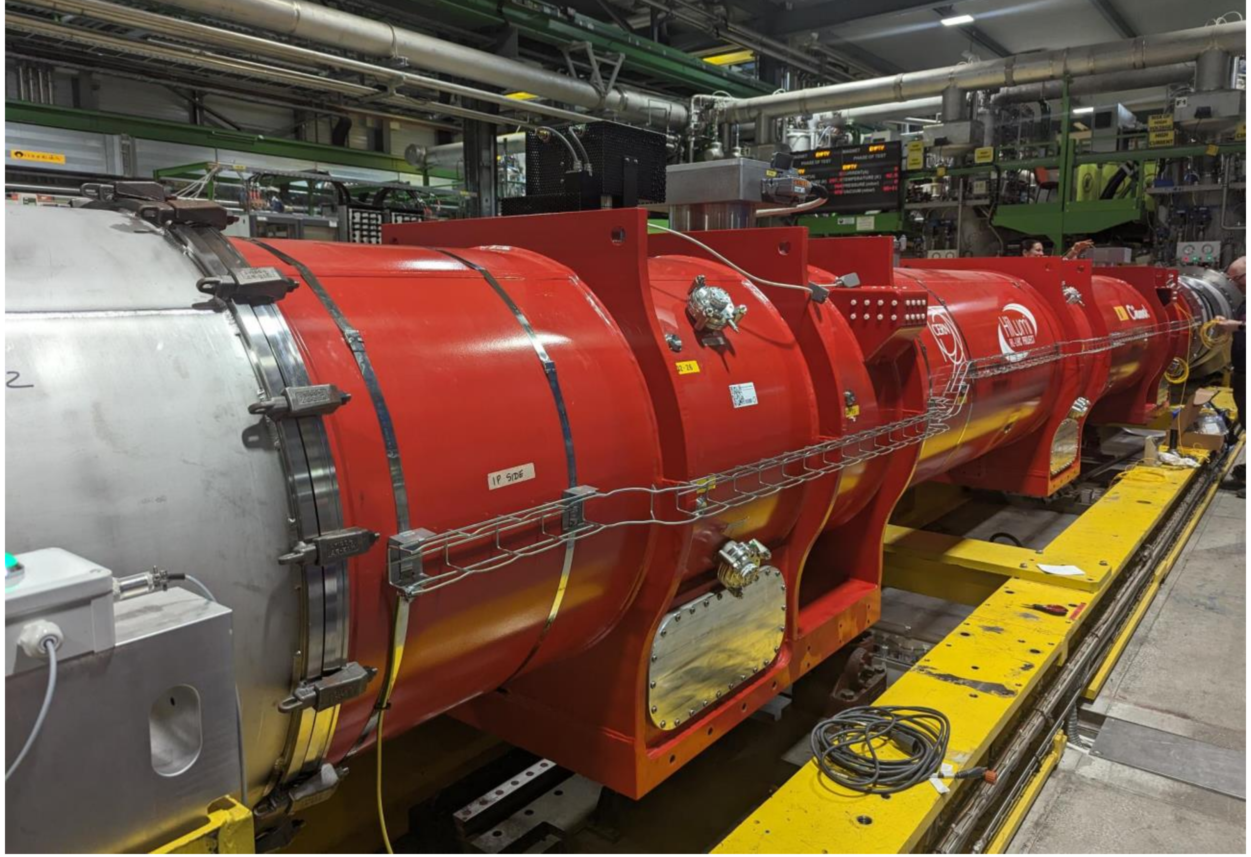
Internal monitoring for IT quadrupoles

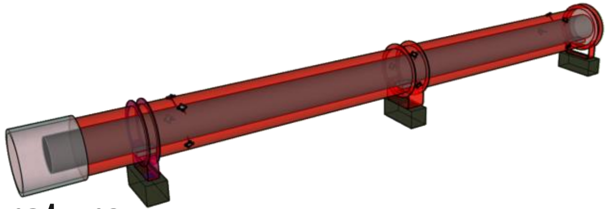
Configuration of FSI sections for quadrupoles



IT quadrupole equipped with FSI system

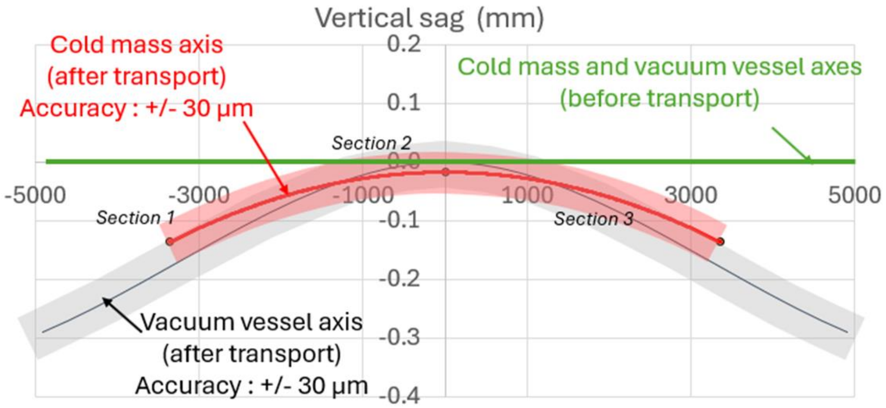


Internal monitoring for IT quadrupoles



Displacements and deformations: impact of different parameters – transport and temperature

Vacuum vessel deformation after transport

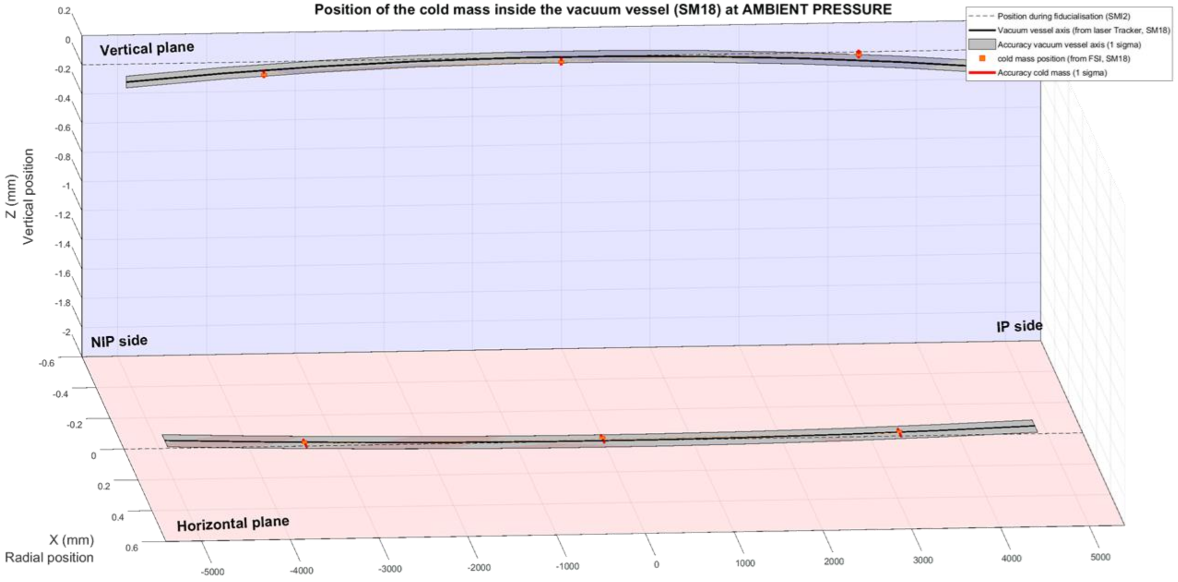


Impact of transport and temperature:

- The shape of the vacuum vessel is influenced by transport and temperature changes. This can be modelized by a 2nd order polynomial.
- The vertical sag of the cold mass is consistent with the vertical sag of the vacuum vessel.

Test conducted using a single vacuum vessel, installed with 4 different configurations, at various temperature:

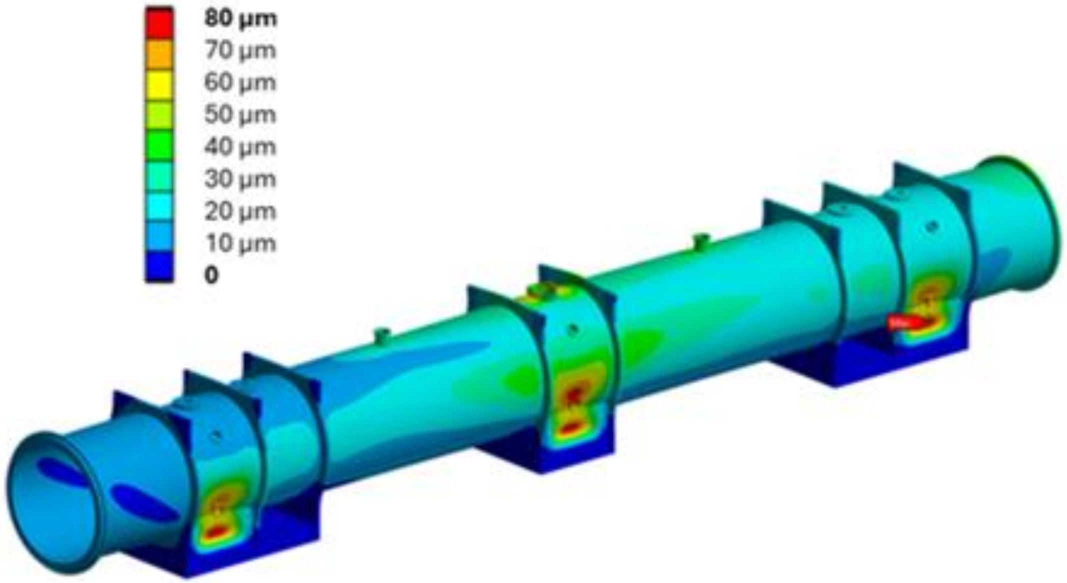
- Its shape was measured using a laser tracker and modelled as a second-order polynomial: the deformation was found to include a random movement of up to 200 µm and a temperature correlated deformation of 35 µm/°C.
- Behavior consistent on 6 other cryostats.



Internal monitoring for IT quadrupoles: results

Displacements and deformations: impact of different parameters - vacuum

Deformations of the vacuum vessel due to vacuum pumping

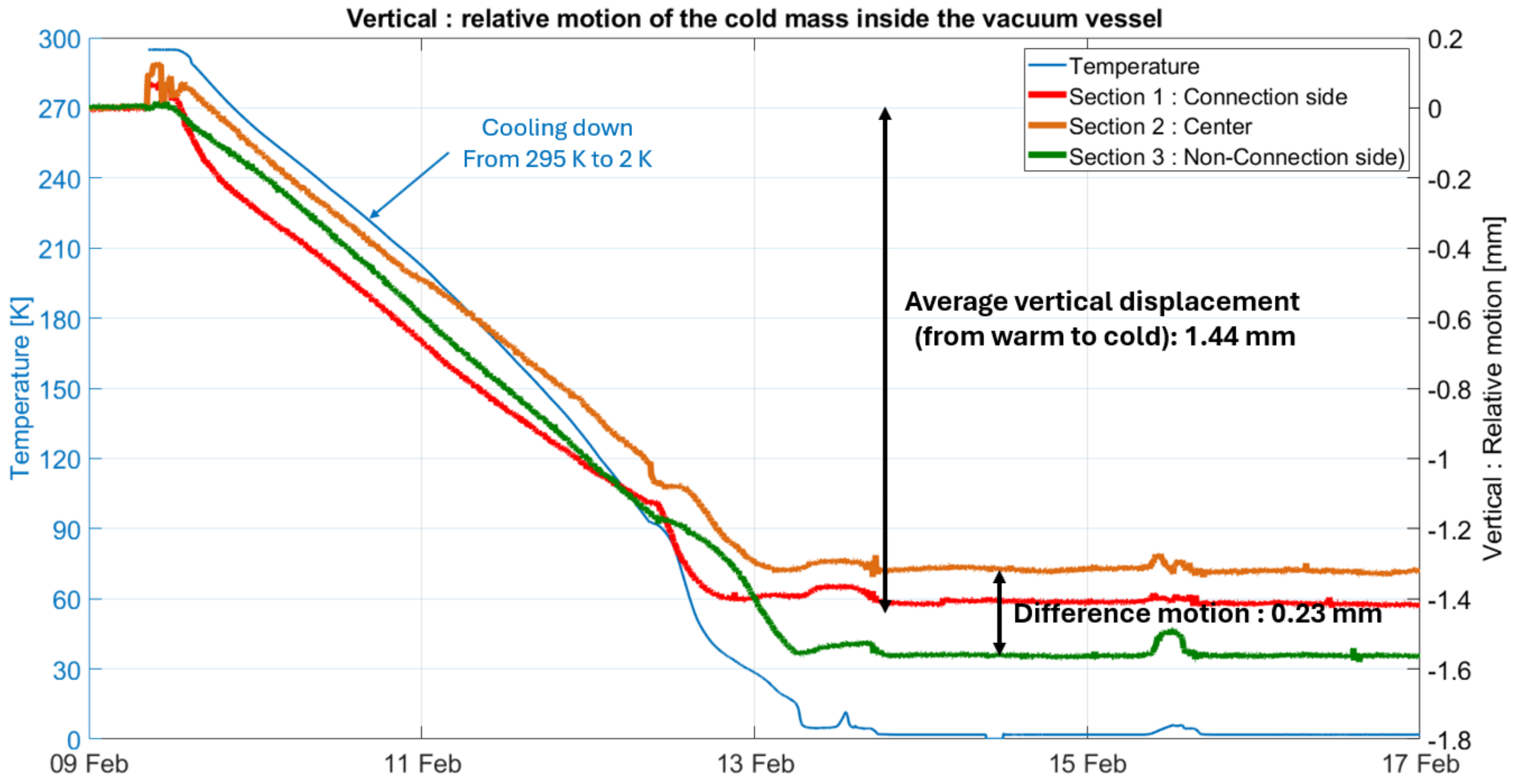


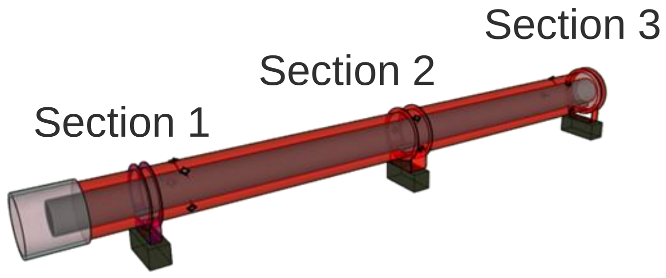
Impact of vacuum:

- The vacuum vessel’s shape is distorted during pumping (up to 80 µm)
- This impact can be modelled and is repeatable
- Maximum difference between model and real observation is below 50µm.
- No clear deformation of the cold mass observed (smaller than our uncertainty of measurement of 30 µm)
- The movement of the cold mass inside the vacuum vessel in radial and in vertical is smaller than 0.1 mm.

Internal monitoring for IT quadrupoles: results

Displacements and deformations: impact of different parameters – cooling-down



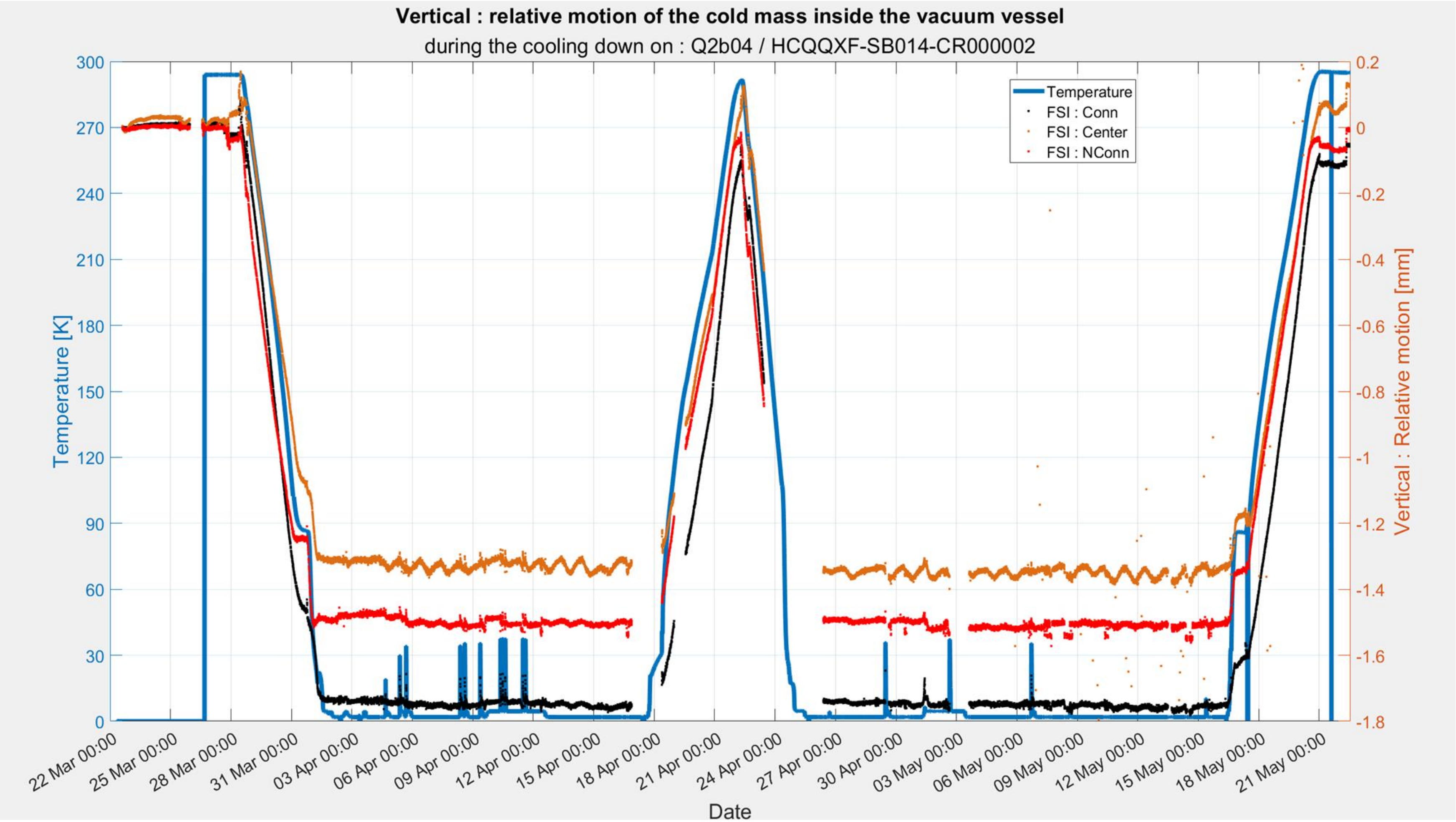


Impact of cooling-down:

- Relative motion of 0.23 mm observed between the vertical motion of the 3 feet during cooling.
- Can be explained by the variations in the materials composition of feet

Uncertainty of measurement < 0.1 mm (1σ)

Internal monitoring for IT quadrupoles: results



Summary

Internal monitoring based on FSI technology is implemented on both IT quadrupoles and crab cavities for the HL-LHC project.

Measurements on the first pre-series and series have shown **important deformations but repeatable**, with a **good correlation** with the **simulated deformation models**.

The internal monitoring provides the possibility to monitor the position of the cavities and magnets inside their cryomodule or vacuum vessel during different phases (after transport, during vacuum pumping, during cool-down, etc.) within an accuracy below 0.1 mm in both radial and vertical directions, which will be key for the alignment strategy of the LHC.

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