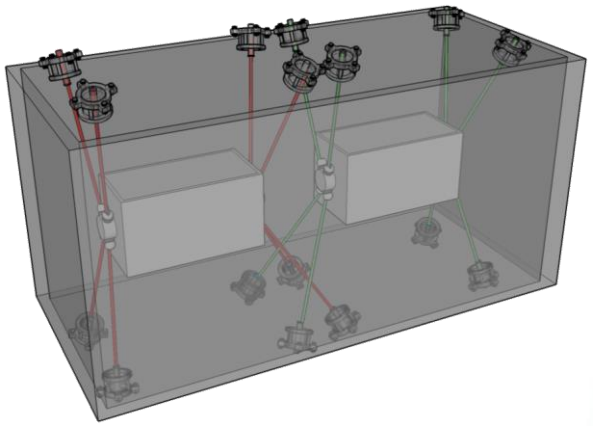

Alignment analysis of the RFD prototype during cold test at CERN

Vivien RUDE

2024-10-09

On behalf :

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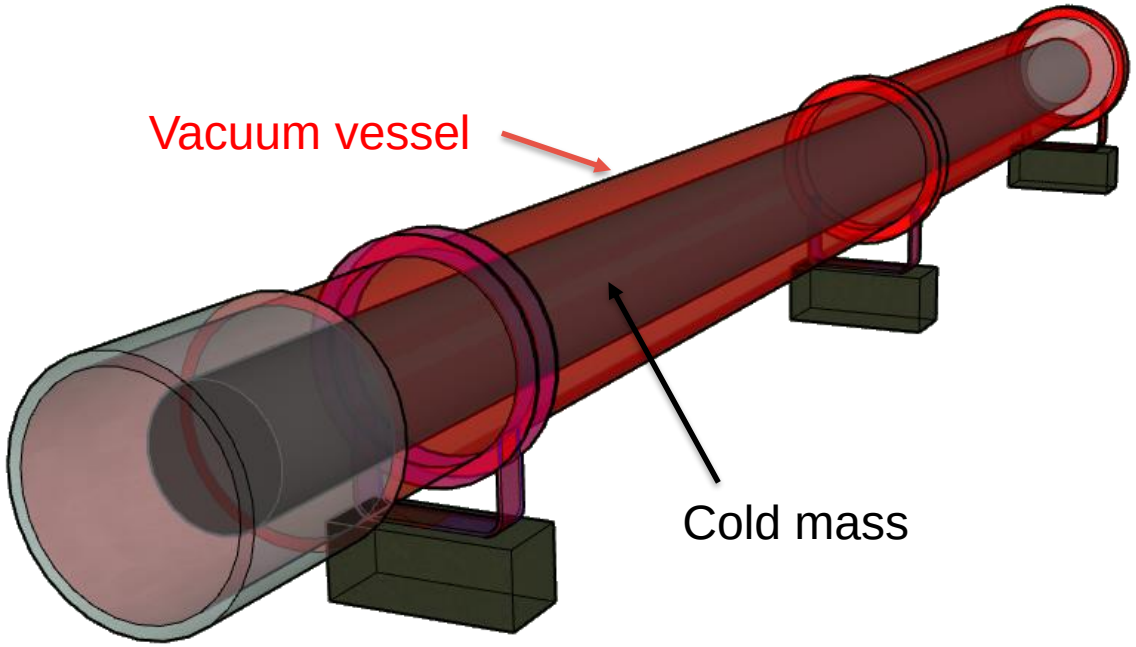
14th HL-LHC Collaboration Meeting, Genoa (Italy), 7-10 October 2024

Outline

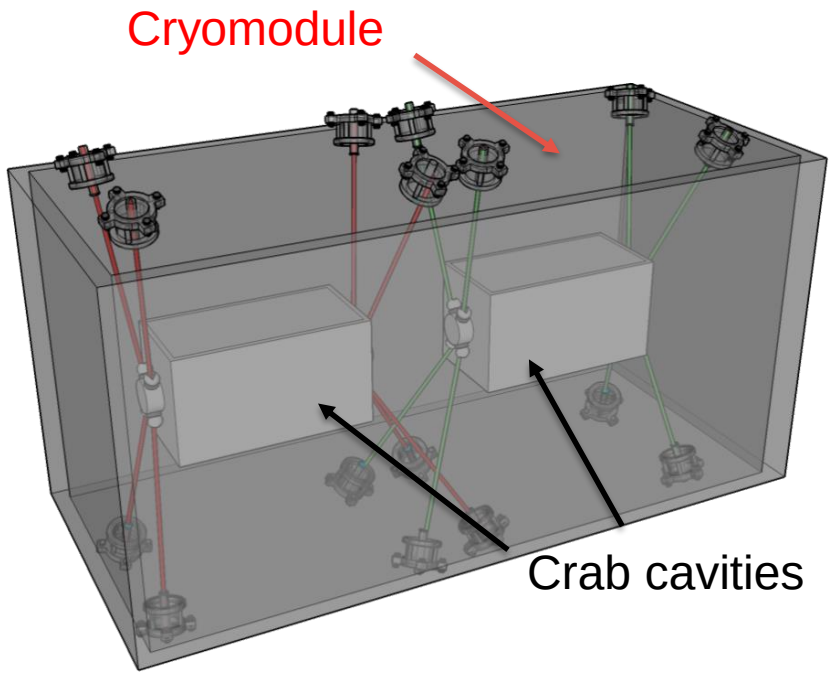
- Alignment objectives (3 objectives)
- Internal monitoring configuration and challenges
- Alignment RFD Prototype results
- Conclusion and perspectives
- Spare : FSI following during Cavity 2 repair

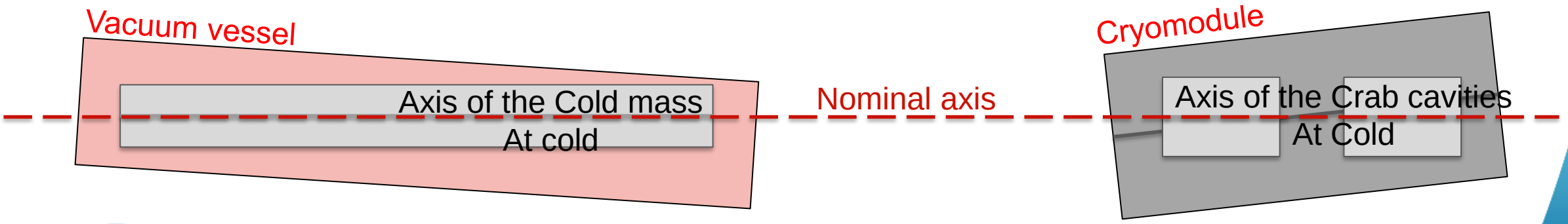
Internal monitoring for “special” components

Q1, Q2a, Q2b, Q3



Crab-Cavities

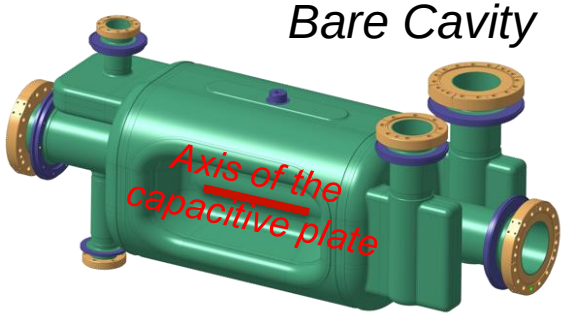




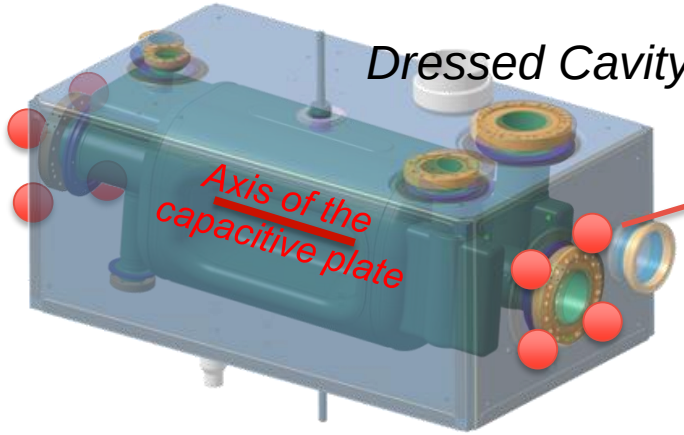
Alignment Objective n°1 : Fiducialisation

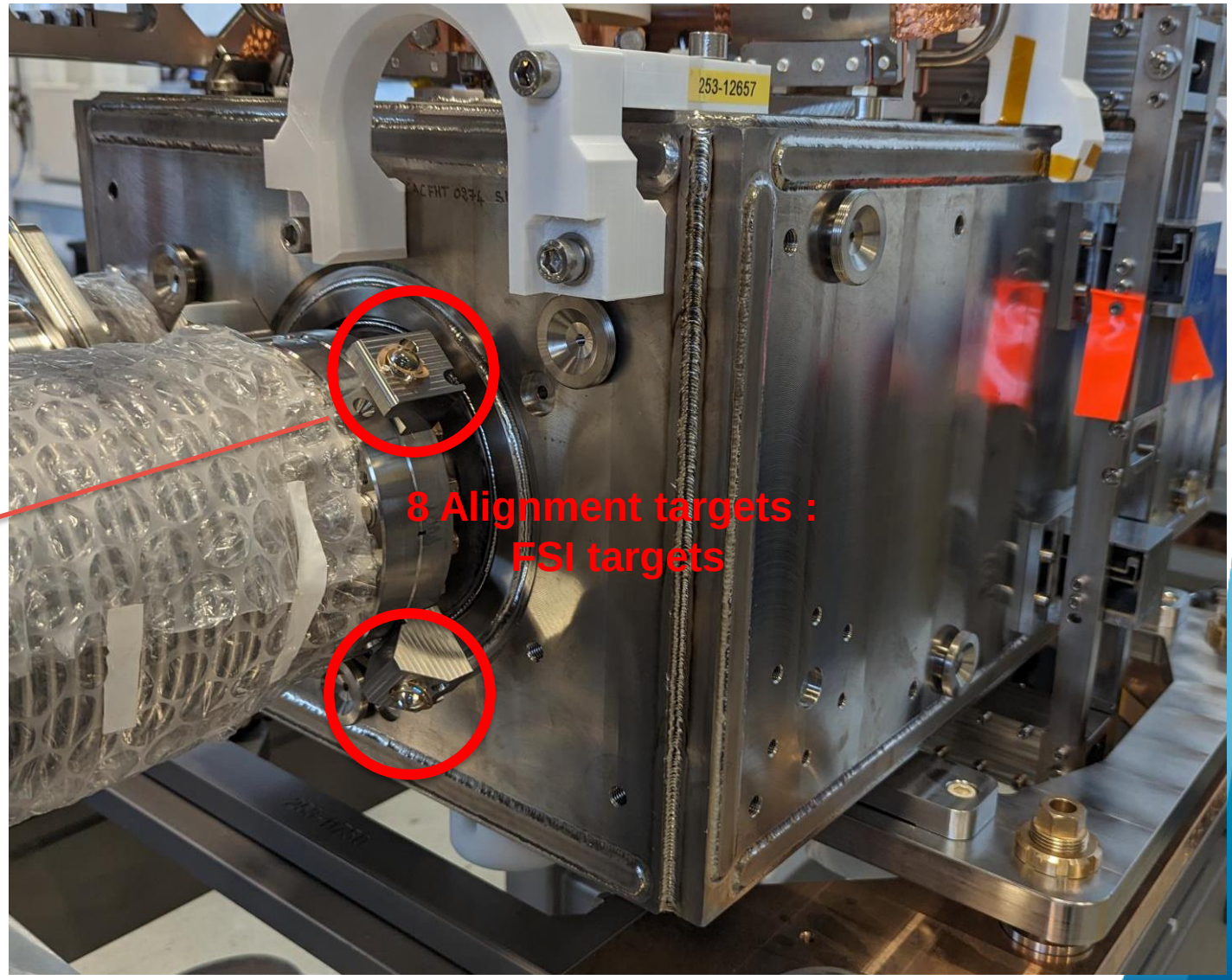
Cavity radio frequency axis → Approximated to mechanical axis of the capacitive plate

Bare Cavity



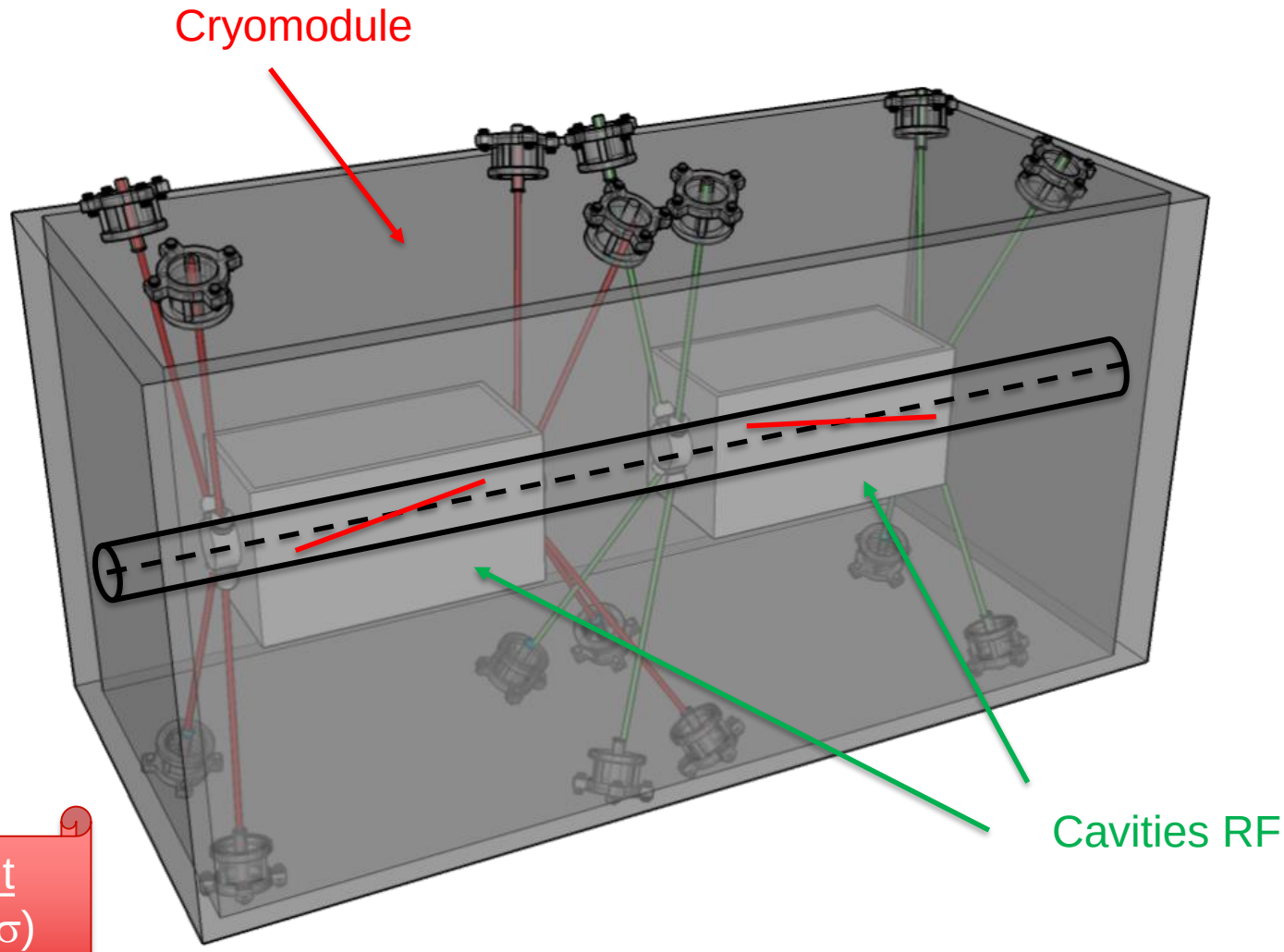
Dressed Cavity





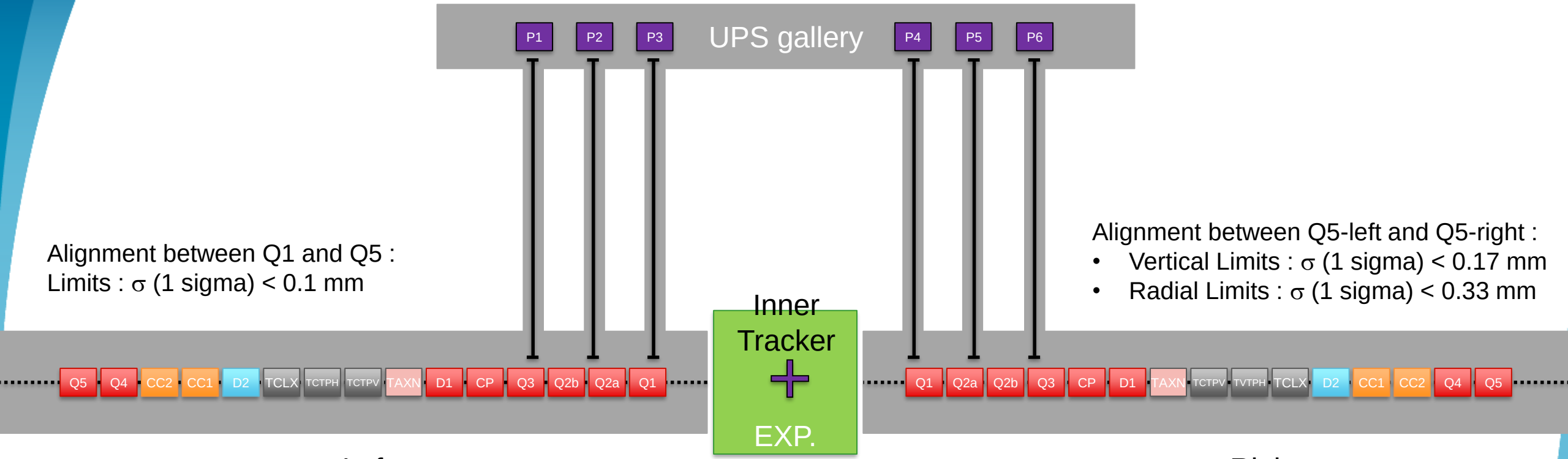
Alignment requirement
Position : 50 µm (1σ)
Roll : 100 µrad (1σ)

Alignment Objective n°2 : Internal monitoring



Alignment requirement
Position : < 100 µm (1σ)
Roll : < 400 µrad (1σ)

Alignment Objective n°3 : External monitoring

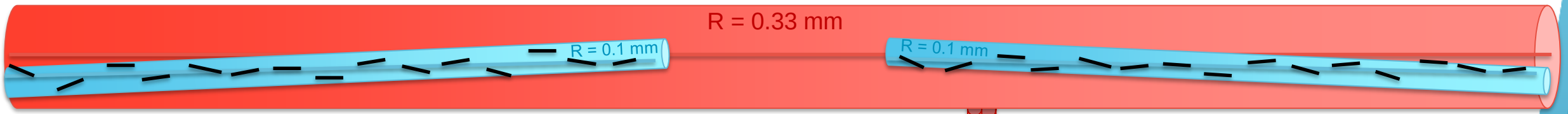


Alignment between Q1 and Q5 :
Limits : σ (1 sigma) < 0.1 mm

Alignment between Q5-left and Q5-right :
- Vertical Limits : σ (1 sigma) < 0.17 mm
- Radial Limits : σ (1 sigma) < 0.33 mm

Left

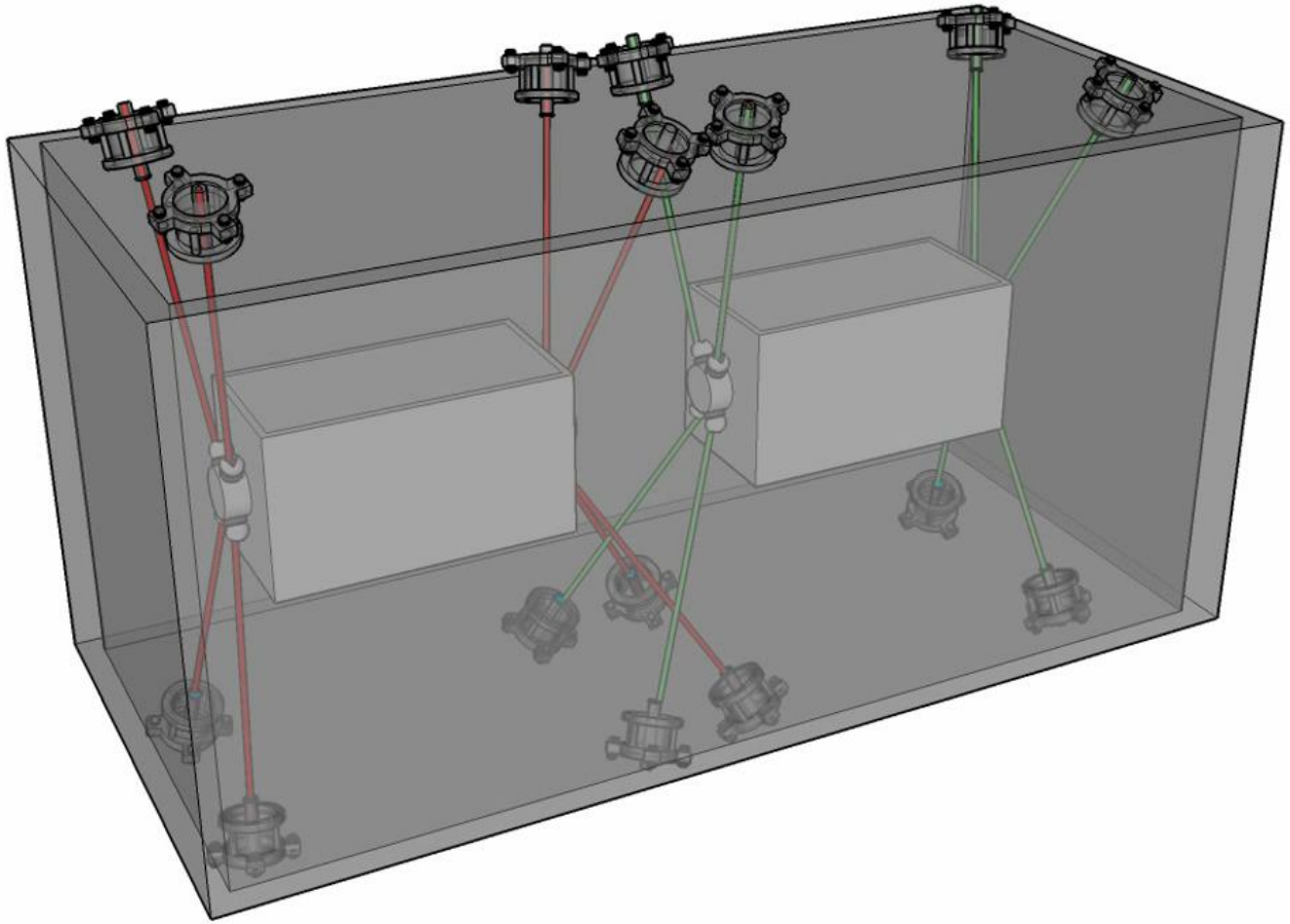
Right



Alignment requirement
- Align all the components per IP side : < 100 µm (1σ)
- Align all the components (Left and Right) : Vertical < 170 µm (1σ)
- Align all the components (Left and Right) : Radial < 330 µm (1σ)
- Roll : < 150 µrad (1σ)

Internal monitoring

Alignment requirement
Position : < 100 µm (1σ)
Roll : < 400 µrad (1σ)



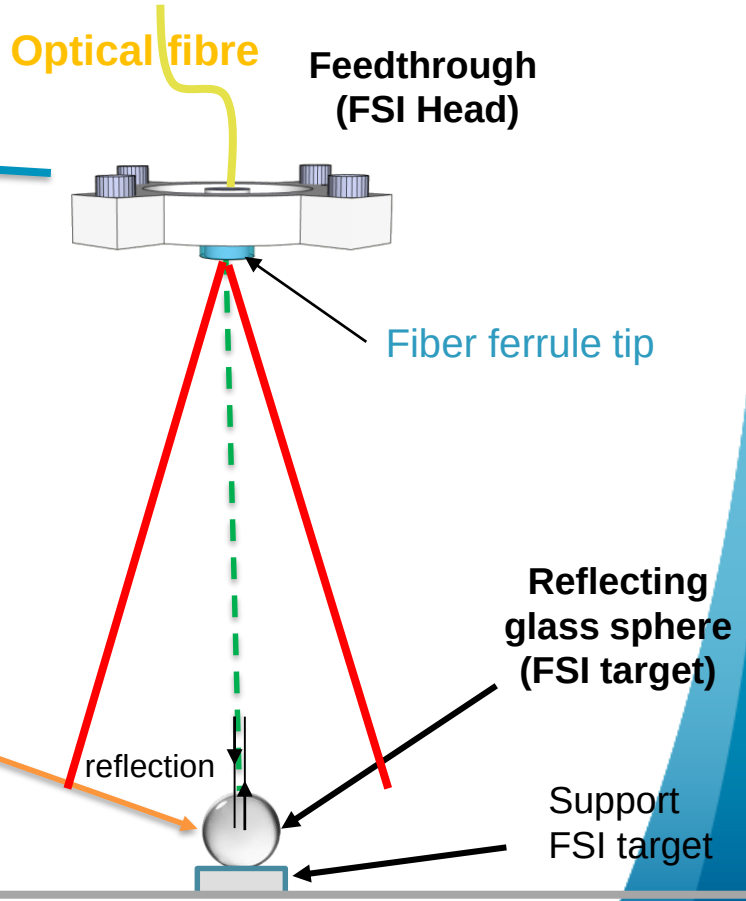
Internal monitoring : Configuration

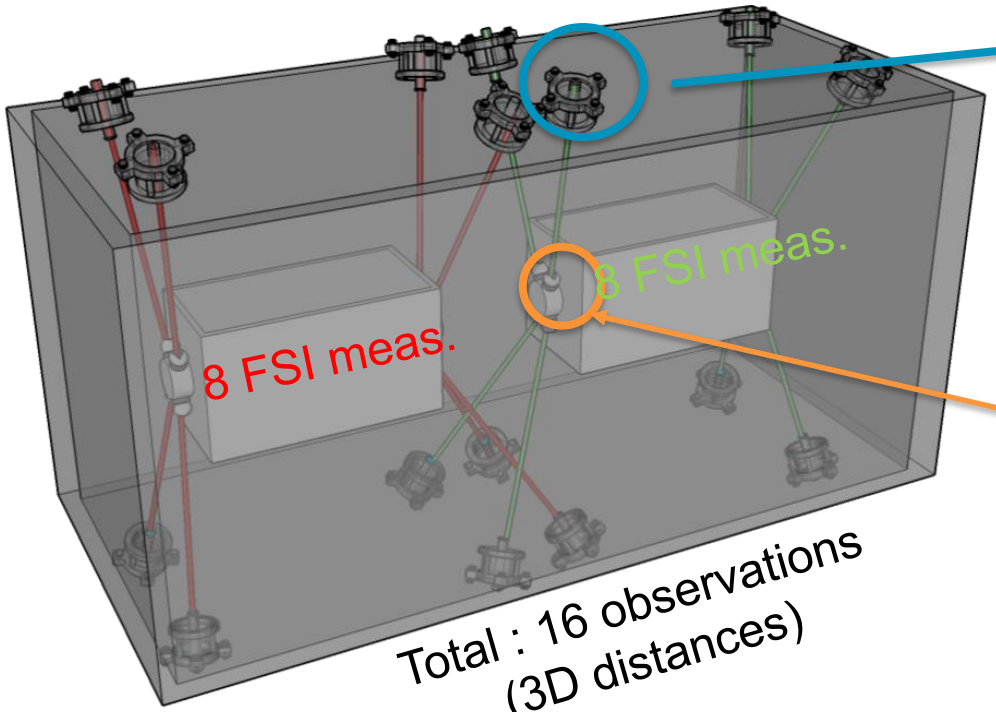
Largest standard uncertainties	Uncertainty (1σ)
Position of the FSI Sensor in the framework of the cryomodule	40 µm
Position of the FSI target in the framework of the crab-cavity	<15 µm

- **FSI : Frequency Scanning interferometry**
  - → Absolute distance measuring interferometric technique

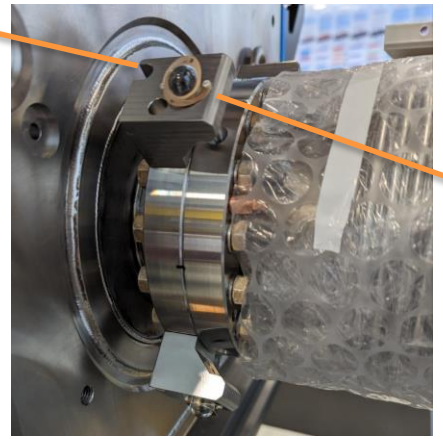
FSI Head (sensor)
on the Cryomodule

FSI Acquisition system





FSI target
on the flange of Helium TANK of the cavities



Internal monitoring : Challenges and prerequisites

Ambient pressure Measurement + Adjustment

The position of the FSI sensors w.r.t. cryomodule must be measured with an accuracy of less than 40 microns.

All adjustments should be carried out at ambient pressure.

ANTICIPATION : The position of the cavities should be at their nominal position at warm with an accuracy of less than 40 microns.

Under vacuum Anticipation

Anticipation of the Deformation of the outer envelope with an accuracy of less than 40 microns
(deformation up to 1.2 mm)

Anticipation of the Movement of the cavities :
(Complex movement up to 0.4 mm
6 DOF)

Cooling down Anticipation

Anticipation of the Deformation of the outer envelope with an accuracy of less than 40 microns
(deformation up to 0.1 mm)

Anticipation of the Movement of the cavities :
(Complex movement up to 1.2 mm
7 DOF)

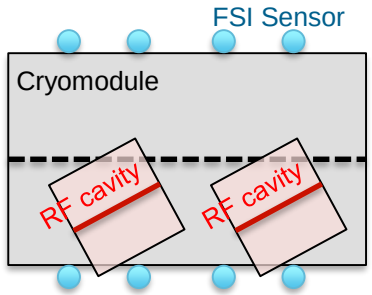
The position of two cavities should be determined **at cold** at less than 0.1 mm (1sigma)

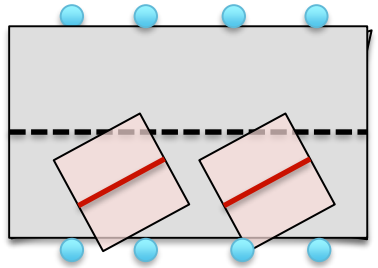
The position of two cavities **at cold** should be aligned **at less than 0.1 mm** (1sigma)

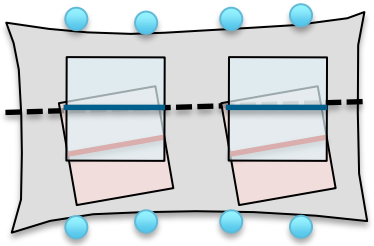
Two inner components

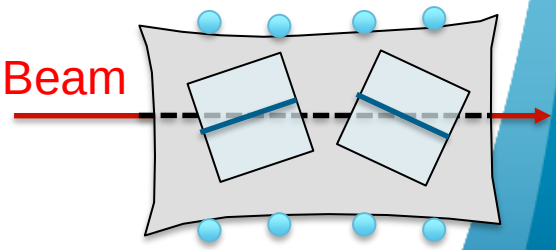
Non compensable misalignment on the external envelope

No possibility to adjust







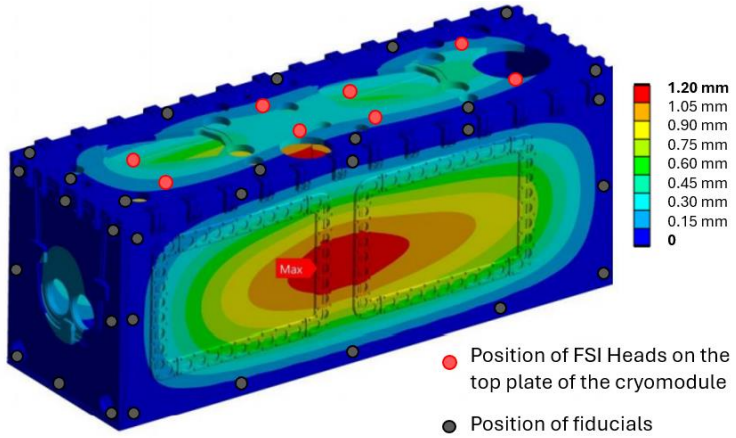


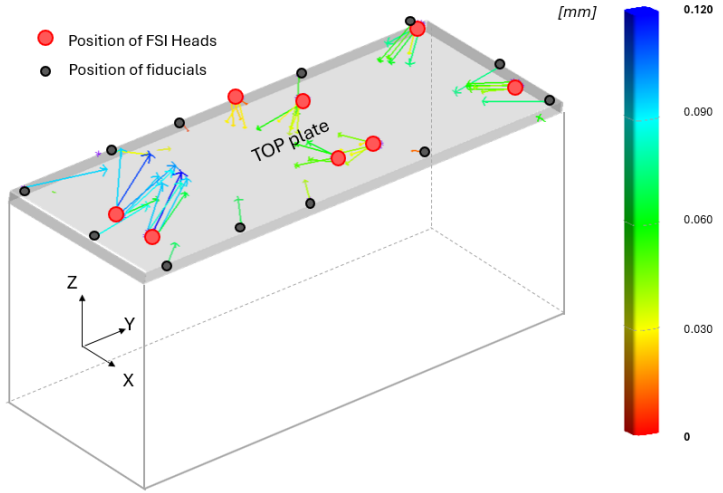
Alignment analysis of the RFD prototype during cold test at CERN

Deformations of the cryomodule (due to pumping and cooling down)

No deformation was observed on the edge of the top plate during pumping.

During cooldown, the top plate observed a thermal contraction due to thermal convection between the thermal screen and the top plate --> not expected but repeatable--> Can be anticipated





Ambient pressure	Max deformation : 1.20 mm ⟷	Under vacuum	Max deformation : 0.12 mm ⟷	Cold

Shape Repeatability
For 3 cycles :

- Maximum dispersion : 67 µm
- Average dispersion : 18 µm

Shape of the cryomodule at ambient pressure
Repeatable at +/- 0.040 mm (RMS)

Shape Repeatability
For 3 cycles :

- Maximum dispersion : 57 µm
- Average dispersion : 16 µm

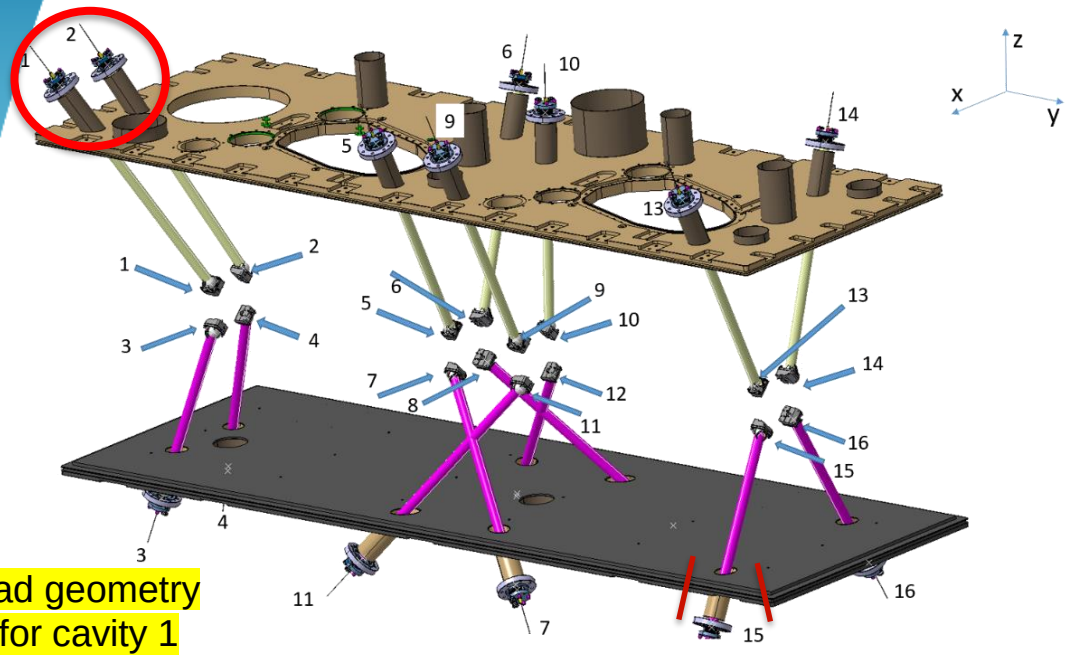
Shape of the cryomodule under vacuum
Repeatable at +/- 0.040 mm (RMS)

Shape Repeatability
For 3 cycles :

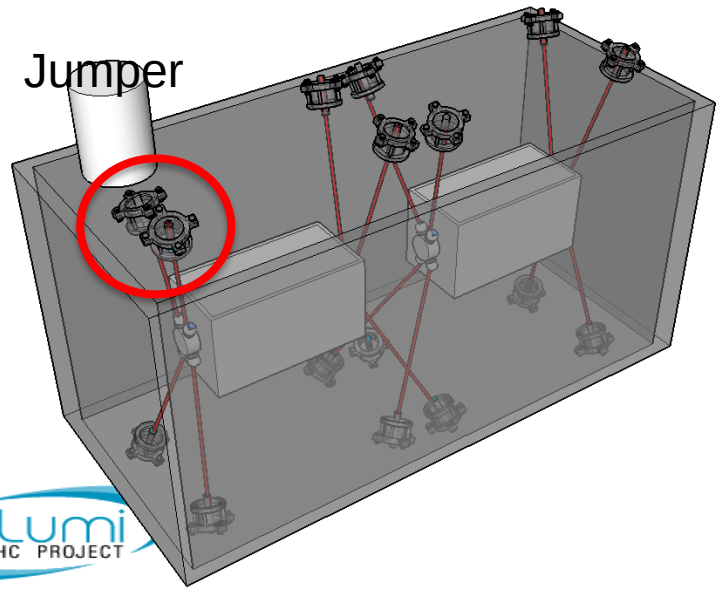
- Maximum dispersion : 68 µm
- Average dispersion : 17 µm

Shape of the cryomodule at cold
Repeatable at +/- 0.040 mm (RMS)

Uncertainty of position of cavities inside the cryomodule



Bad geometry for cavity 1



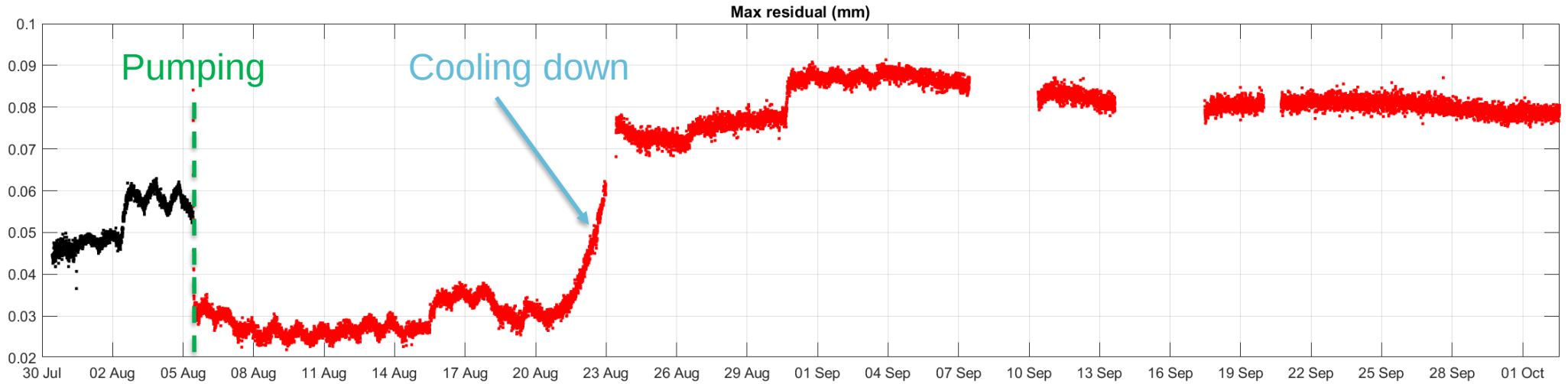
Alignment requirement
Position : < 100 µm (1σ)
Roll : < 400 µrad (1σ)

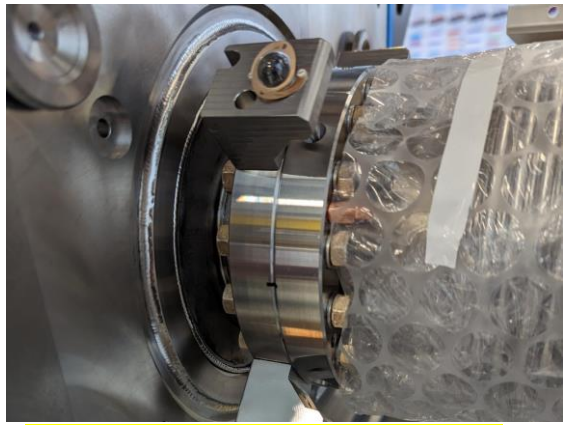
A priori sigma : 0.04 mm	Parameter	Accuracy expected (simulation)
Cav1	**Tx (mm) radial**	**0.16**
	Ty (mm) longitudinal	*0.08*
	Tz (mm) vertical	**0.08**
	Rx (mrad) pitch	*0.08*
	Ry (mrad) roll	*0.41*
	Rz (mrad) yaw	*0.41*
Cav2	**Tx (mm) radial**	**0.04**
	Ty (mm) longitudinal	*0.10*
	Tz (mm) vertical	**0.02**
	Rx (mrad) pitch	*0.04*
	Ry (mrad) roll	*0.36*
	Rz (mrad) yaw	*0.10*
SCALE (mm/m)		0.11

Uncertainty of position of cavities inside the cryomodule

Objective : RMS residual < 0.04 mm

Maximum Residual [mm]





Alignment requirement
Position : < 100 µm (1σ)
Roll : < 400 µrad (1σ)

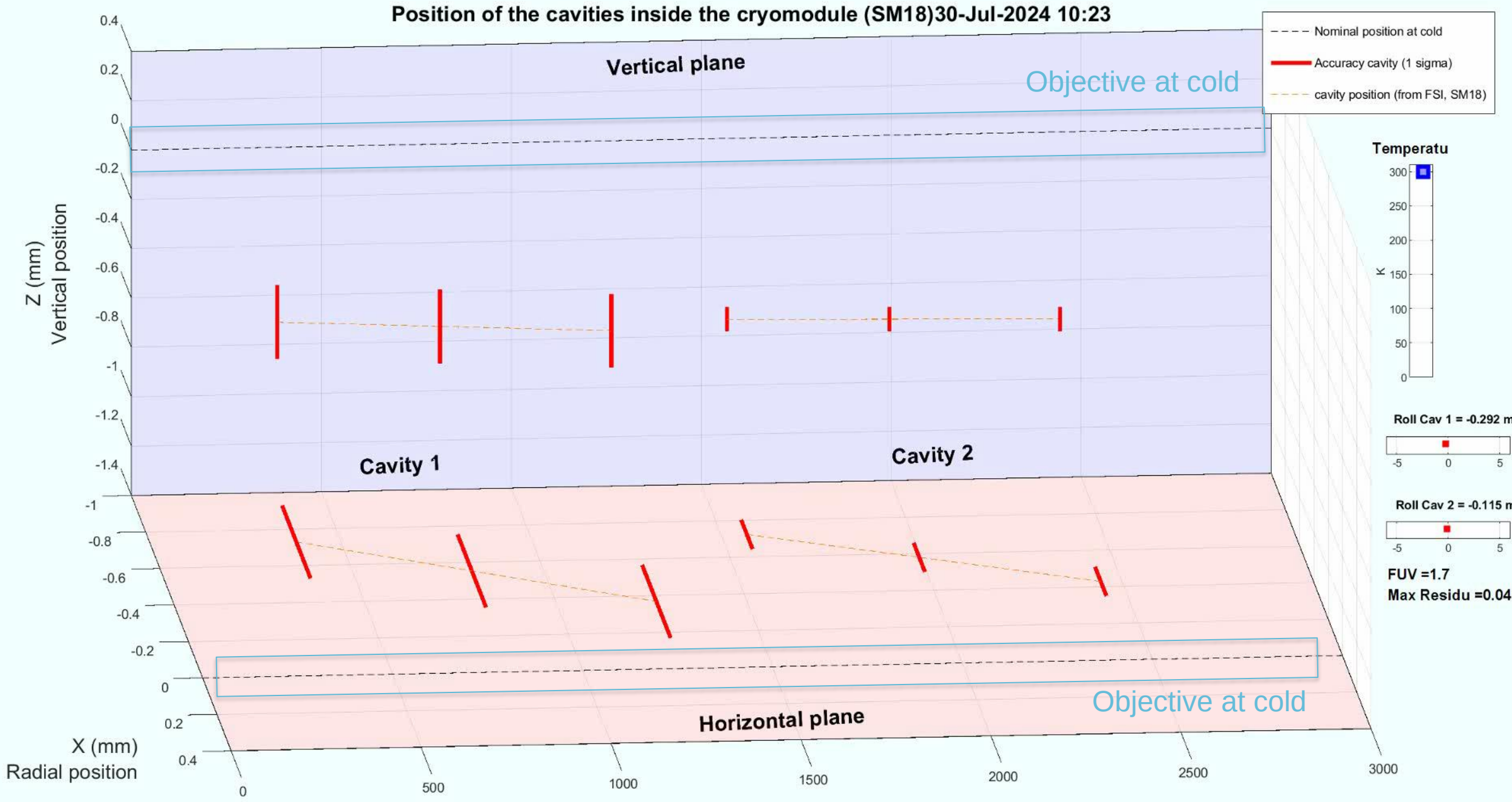
Issue with FSI Target Holder:

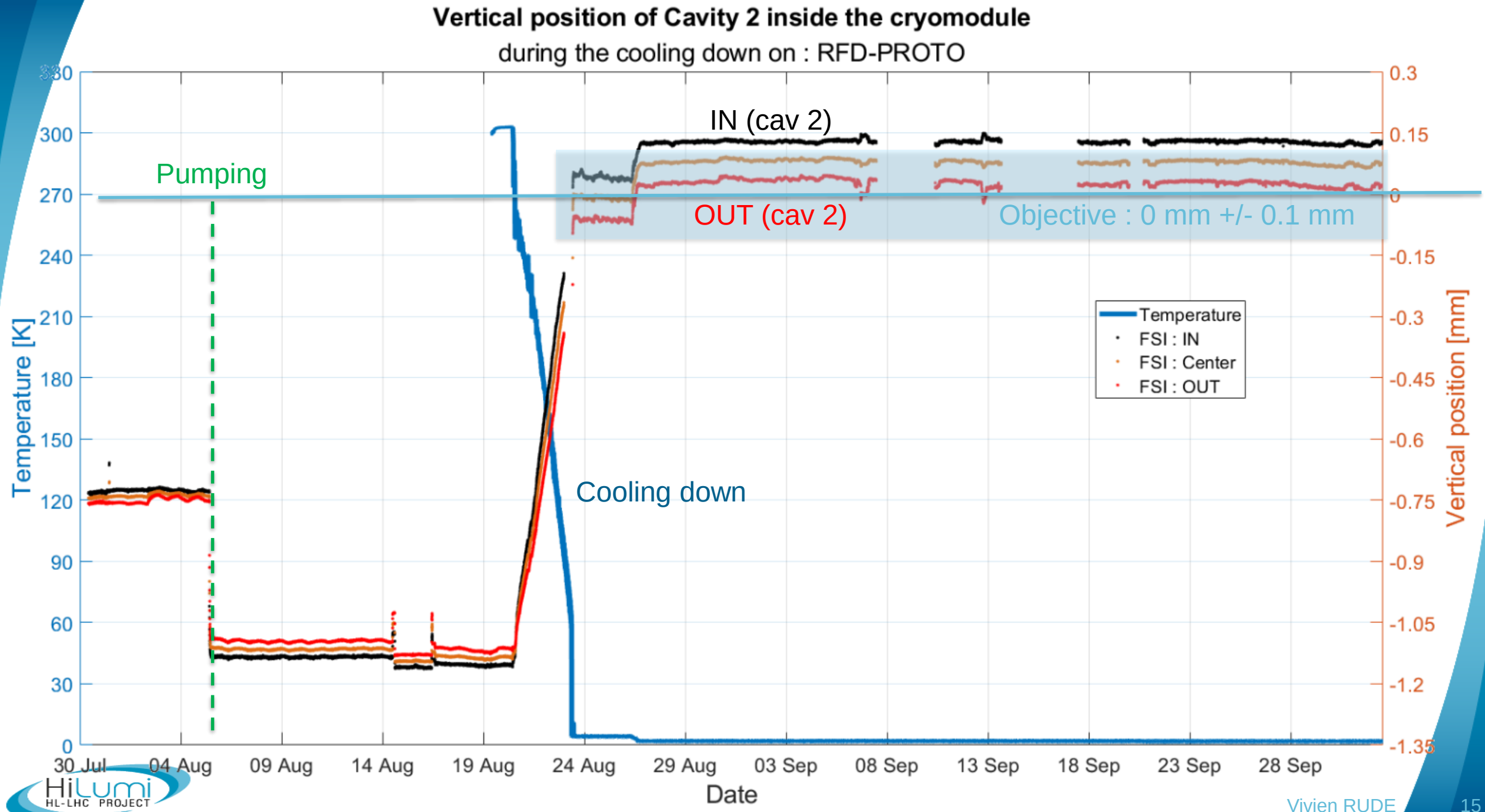
- FSI targets are not making proper contact with the holder.
- Different thermal contraction of glass and metal causes spring permanent deformation

→ Upgrade to spring frictionless fixation

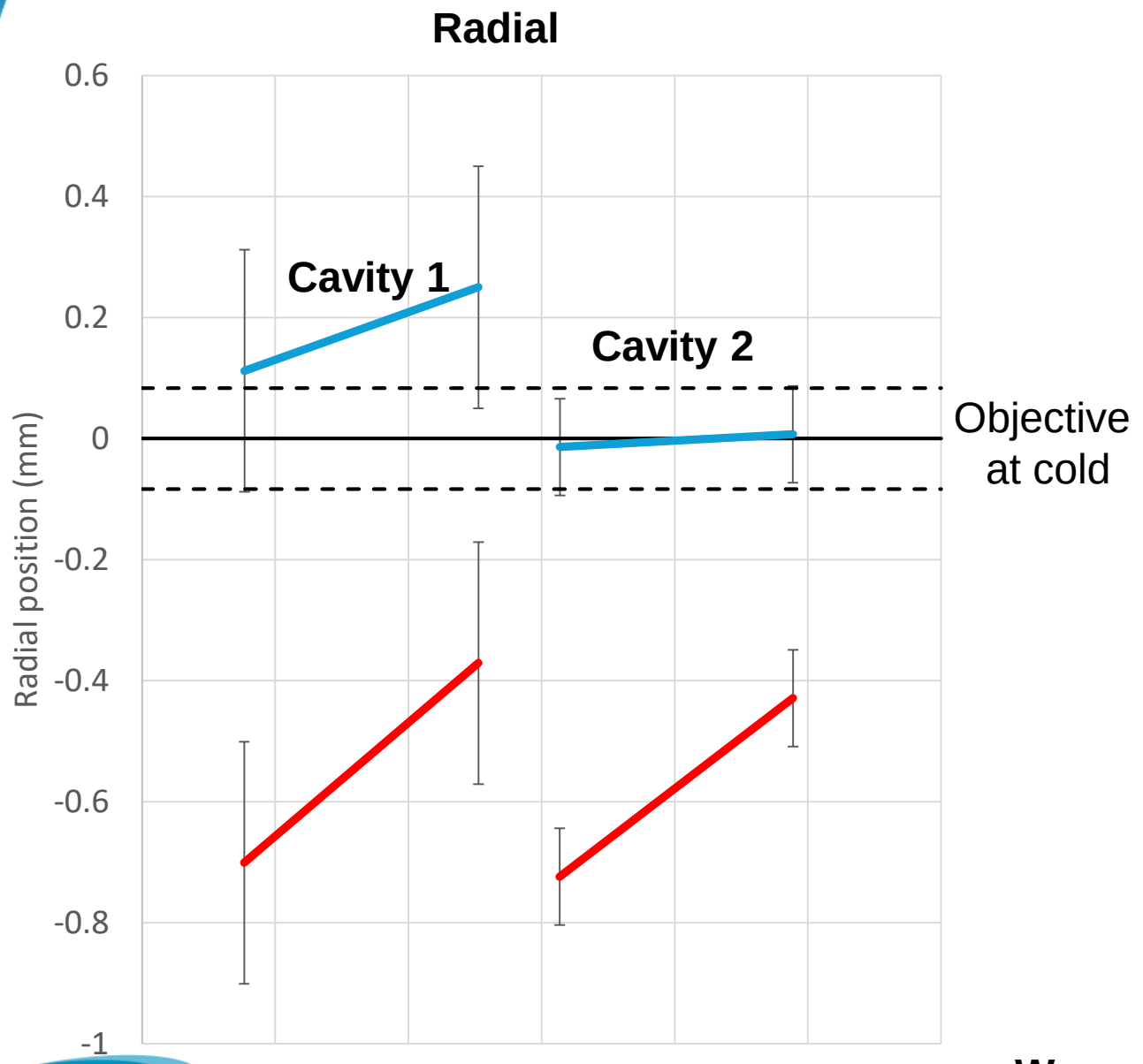
	Parameter	Current accuracy (reality)
Cav1	**Tx (mm) radial**	**0.20**
	Ty (mm) longitudinal	***0.20***
	Tz (mm) vertical	**0.15**
	Rx (mrad) pitch	*0.15*
	Ry (mrad) roll	*0.70*
	Rz (mrad) yaw	*0.50*
Cav2	**Tx (mm) radial**	**0.08**
	Ty (mm) longitudinal	***0.10***
	Tz (mm) vertical	**0.05**
	Rx (mrad) pitch	*0.05*
	Ry (mrad) roll	*0.40*
	Rz (mrad) yaw	*0.10*
SCALE (mm/m)		0.20

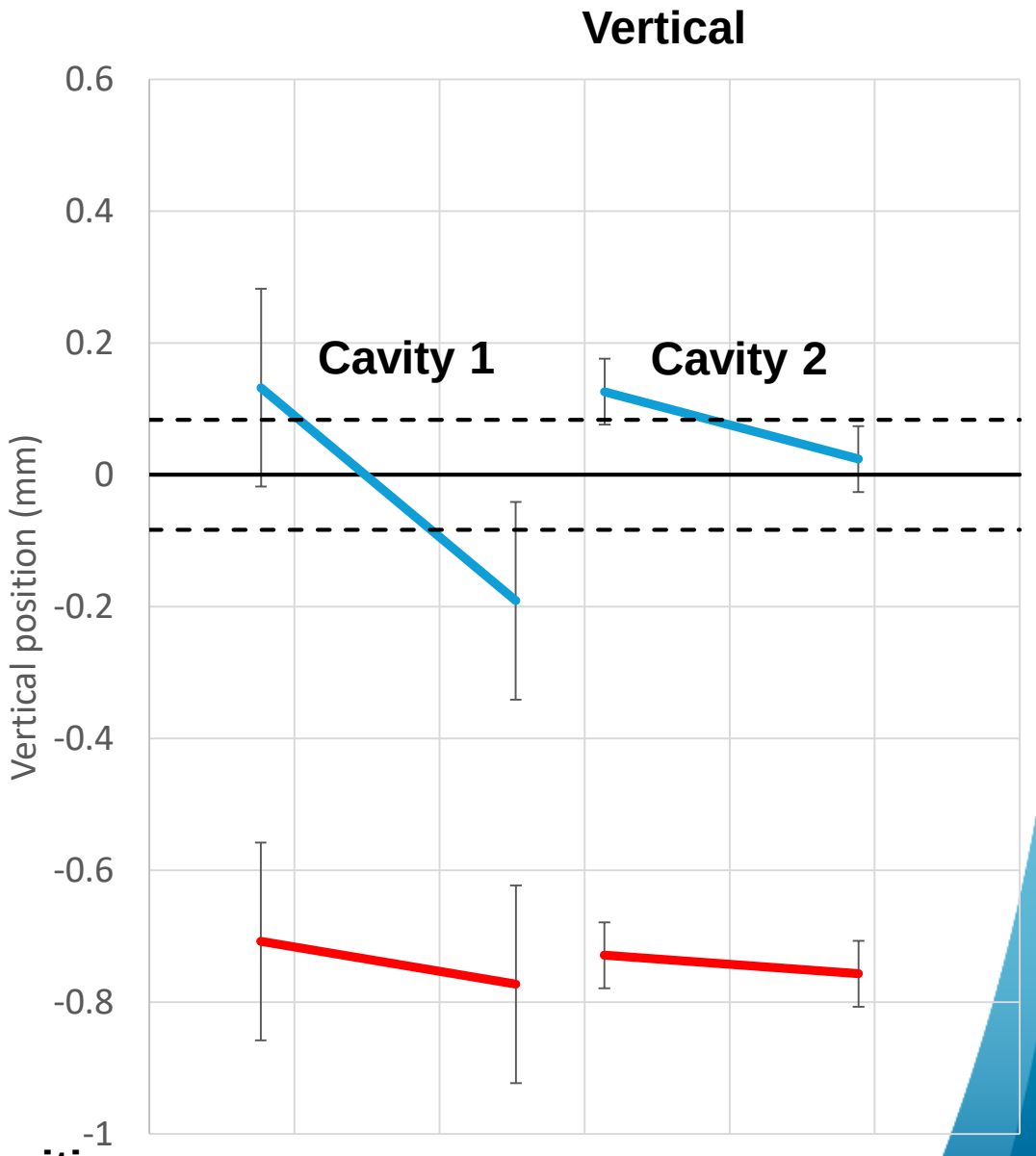
The current uncertainties for cavity 2 stay within the objective


Position of the cavities inside the cryomodule (SM18)30-Jul-2024 10:23
Nominal position at cold
Accuracy cavity (1 sigma)
cavity position (from FSI, SM18)
Vertical plane
Objective at cold
Cavity 1
Cavity 2
Horizontal plane
Objective at cold
Z (mm)
Vertical position
X (mm)
Radial position
Temperatu
K
Roll Cav 1 = -0.292 m
Roll Cav 2 = -0.115 m
FUV =1.7
Max Residu =0.04


Vertical position of Cavity 2 inside the cryomodule
during the cooling down on : RFD-PROTO
IN (cav 2)
OUT (cav 2)
Pumping
Objective : 0 mm +/- 0.1 mm
Cooling down
Temperature
FSI : IN
FSI : Center
FSI : OUT
Temperature [K]
Vertical position [mm]
Date
330
300
270
240
210
180
150
120
90
60
30
0
0.3
0.15
0
-0.15
-0.3
-0.45
-0.6
-0.75
-0.9
-1.05
-1.2
-1.35
30 Jul
04 Aug
09 Aug
14 Aug
19 Aug
24 Aug
29 Aug
03 Sep
08 Sep
13 Sep
18 Sep
23 Sep
28 Sep

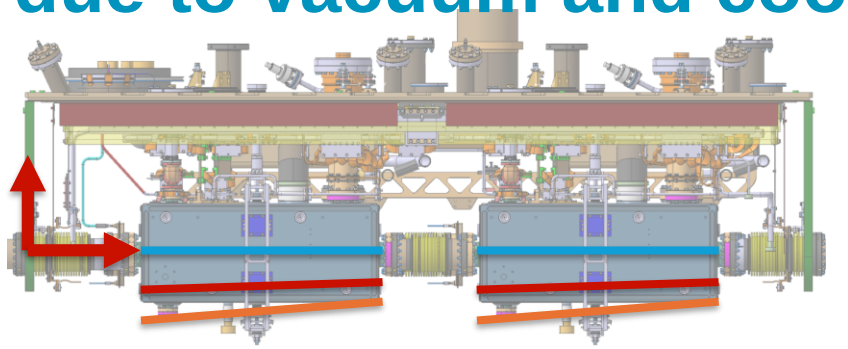
Current positions at cold (Sept 2024)

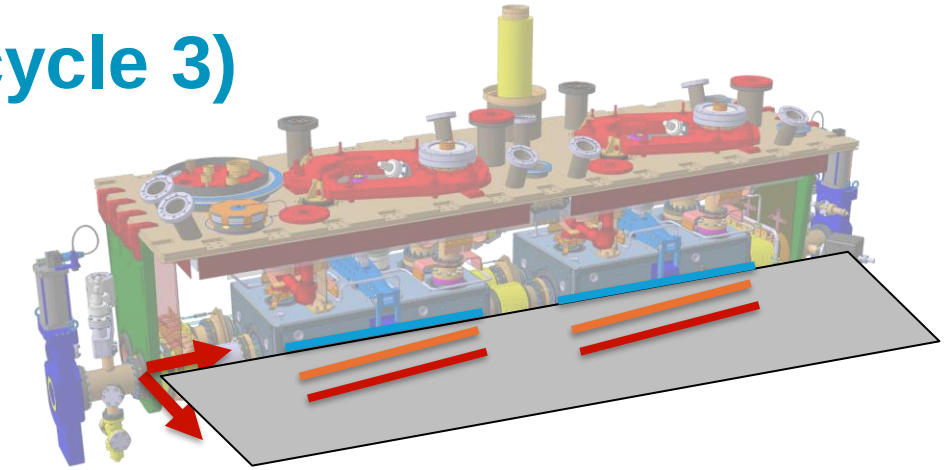


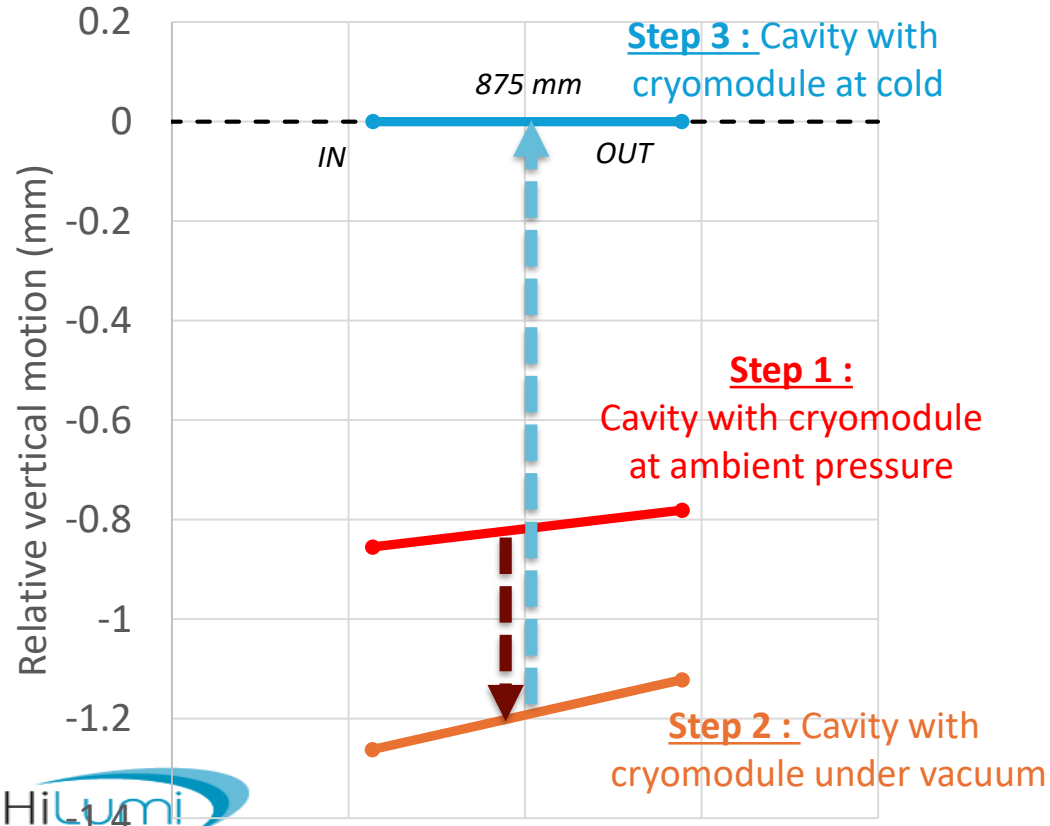


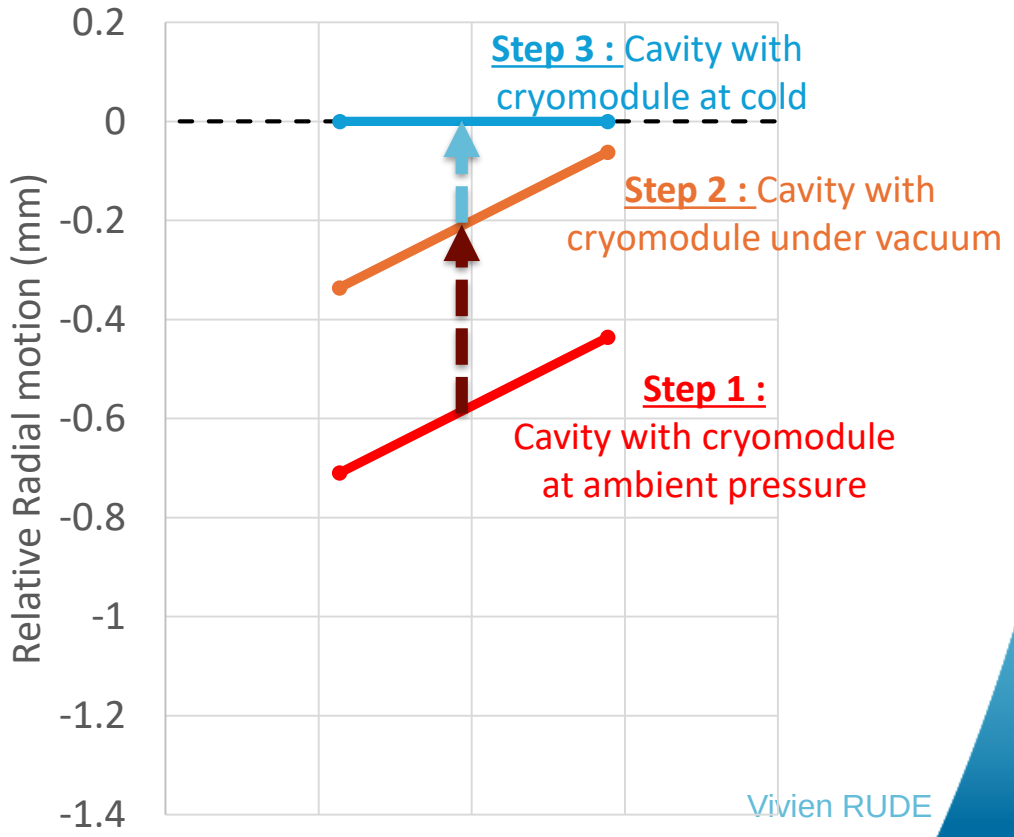
Warm position
Cold position

Relative Motions of the cavities due to vacuum and cooling down (cycle 3)









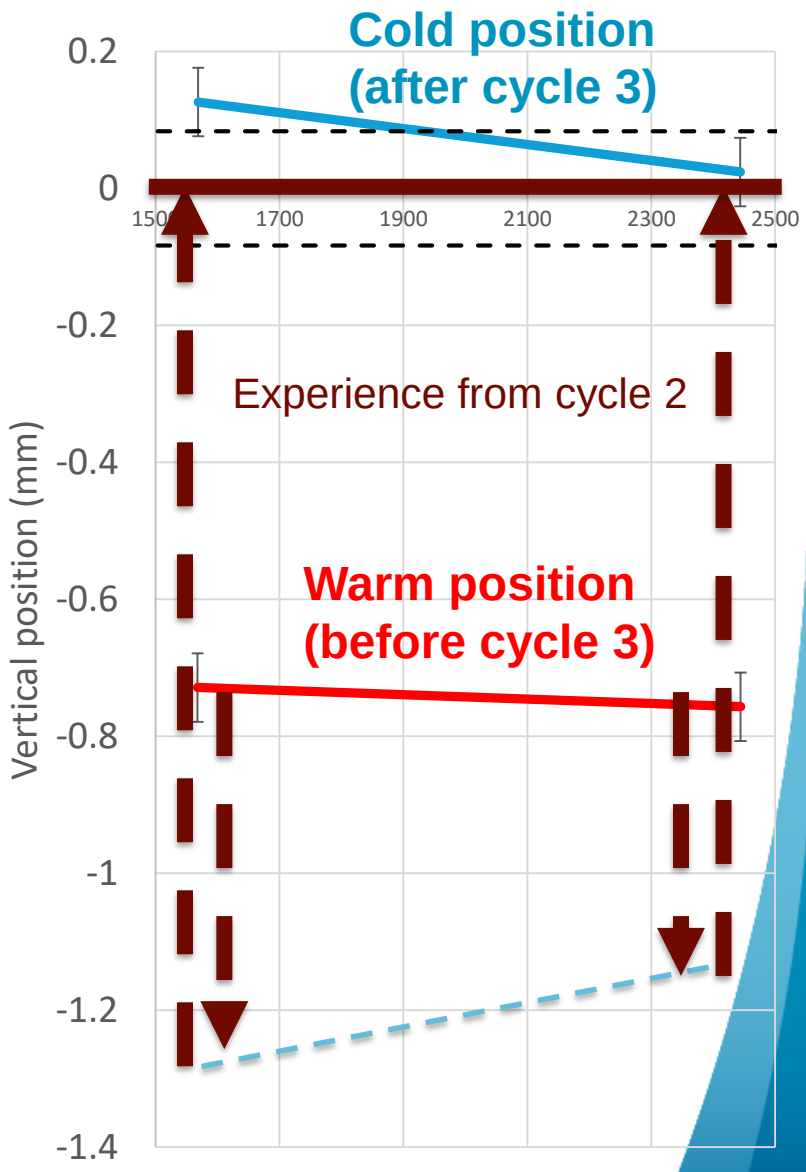
Repeatability on the motions

- Cycle 2 : 15/16 FSI observations are operational
- Cycle 3 : 16/16 FSI observations are operational

	Cavity 2	
Impact of cold	**Cycle 2**	**Cycle 3**
Tx [mm] (radial translation)	0.60 *+/-0.10*	0.57 *+/-0.08*
Ty [mm] (longi translation)	0.15 *+/-0.15*	0.27 *+/-0.10*
Tz [mm] (vertical translation)	0.76 *+/-0.05*	0.81 *+/-0.05*
Rx [mrad] (Pitch angle)	0.05 *+/-0.05*	-0.08 *+/-0.05*
Ry [mrad] (Roll angle)	-0.74 *+/-0.40*	-0.41 *+/-0.40*
Rz [mrad] (Yaw angle)	0.45 *+/-0.15*	0.31 *+/-0.10*
Scale [mm/m]	-2.22 *+/-0.20*	-2.14 *+/-0.20*

Difference between motion of cavity 2 on cycle 2 and cycle 3

Radial : 30 µm Uncertainty : 100 µm	Repeatable
Longitudinal : 120 µm Uncertainty : 150 µm	Repeatable
Vertical : 50 µm Uncertainty : 50 µm	Repeatable
Pitch : 130 µrad Uncertainty : 50 µrad	Close to be repeatable
Roll : 320 µrad Uncertainty : 400 µrad	Repeatable
Yaw : 140 µrad Uncertainty : 150 µrad	Repeatable



Conclusion

Cryomodule

- The shape of the cryomodule must be repeatable at ambient pressure with an uncertainty of less than 40 µm.
- The shape of the cryomodule must be repeatable under vacuum with an uncertainty of less than 40 µm.
- The shape of the cryomodule must be repeatable under vacuum with an uncertainty of less than 40 µm.

Crab-cavities

- The movement of the two cavities between warm (ambient pressure) and cold should be repeatable with an uncertainty of less than 40 µm
  → 50 µm for cavity 2 (Translations)
  → 150 µm for cavity 1 (difficult to confirm due to lack of accuracy for cavity 1
- The accuracy of each FSI measurement must be validated within 40 µm
  → FSI targets holders to be improved

Next steps

RFD prototype : SPS installation

- The installation of the cryomodule in the SPS is scheduled for the technical stop (TS) in 2024-2025
- The impact of transport of the cryomodule will be tested to ensure that it does not affect the alignment
- A new alignment of the cavities will be carried out in the SPS during this period (with experience results of cycle 3)
- The position of the radio-frequency axis will be analysed using the beam, confirming the alignment and validating the assumption that the radio-frequency axis can be approximated to the mechanical axis of the capacitive plates.

Series

- FSI targets holders will be improved

Conclusion

The RFD prototype is ready to go into the SPS accelerator !

Many thanks to STFC team :

- Nik
- Ed
- Luke
- Ryan
- Carlos
- Andy
- …

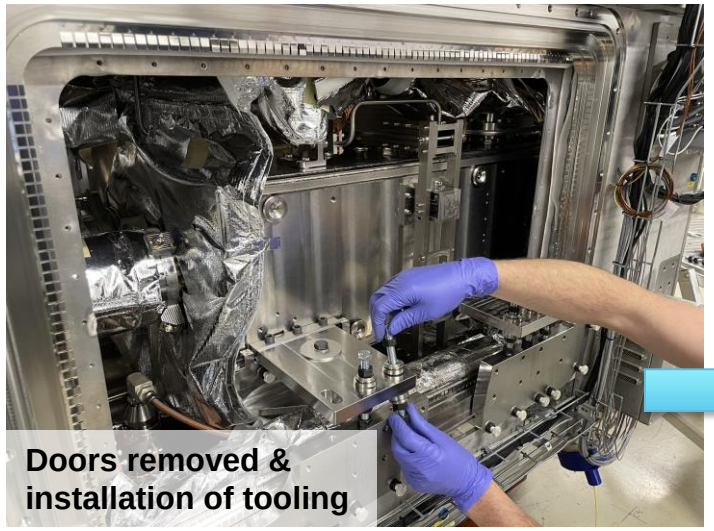
Many thanks to CERN team :

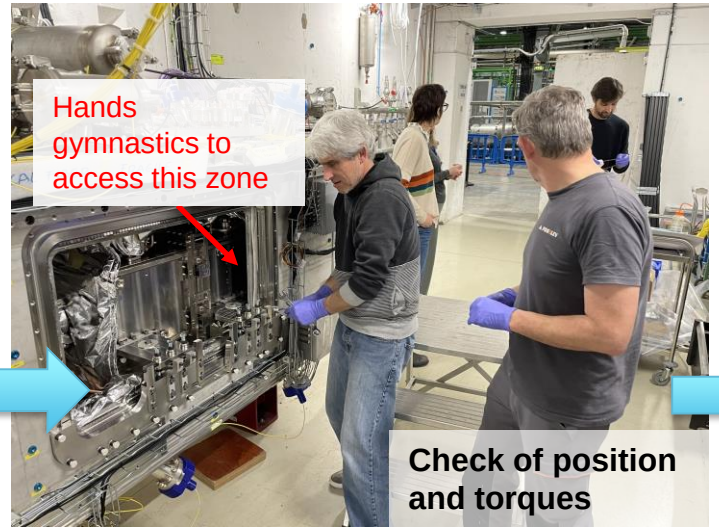
- Teddy
- Simon
- Marco
- Nuria
- Katarzyna
- Kurt
- Rama
- Raphael
- Luca
- Ofelia
- Julien
- …

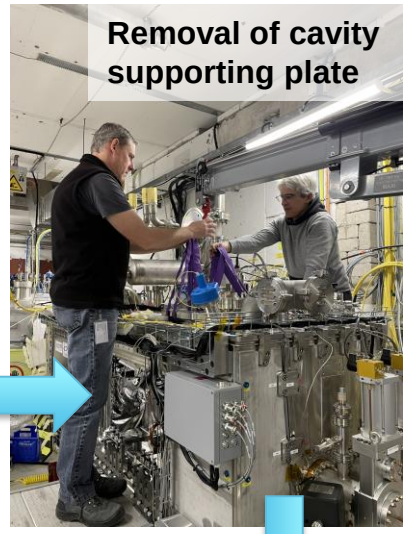
Thank you for your attention

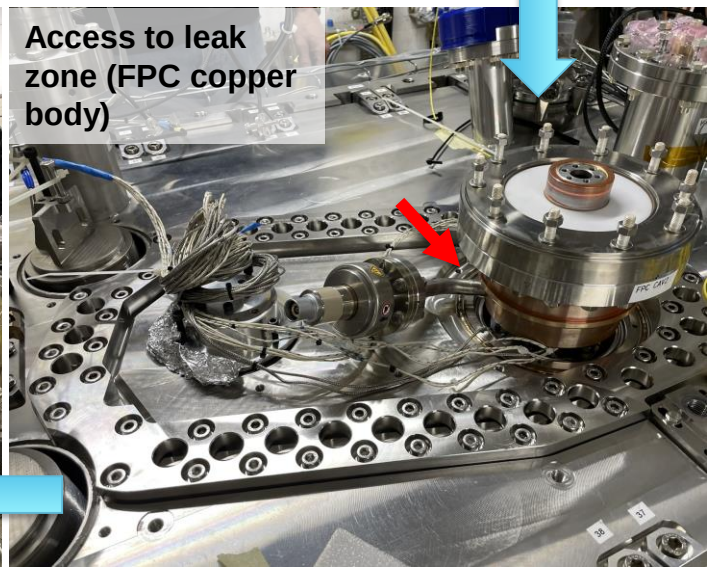
FSI following Cavity 2 repair

Survey measurement on load charge transfer of TANK2



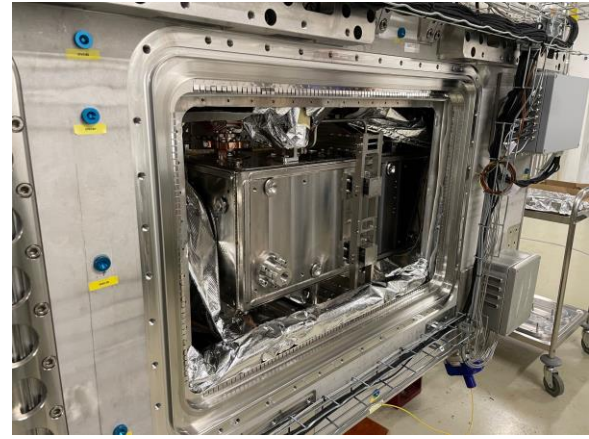






Situation before installation of tooling support of cavity 2
8 March 2024

EDMS : 3065222



08-Mar-2024 09:50:14
FUV =0.6
Max residual =24 microns

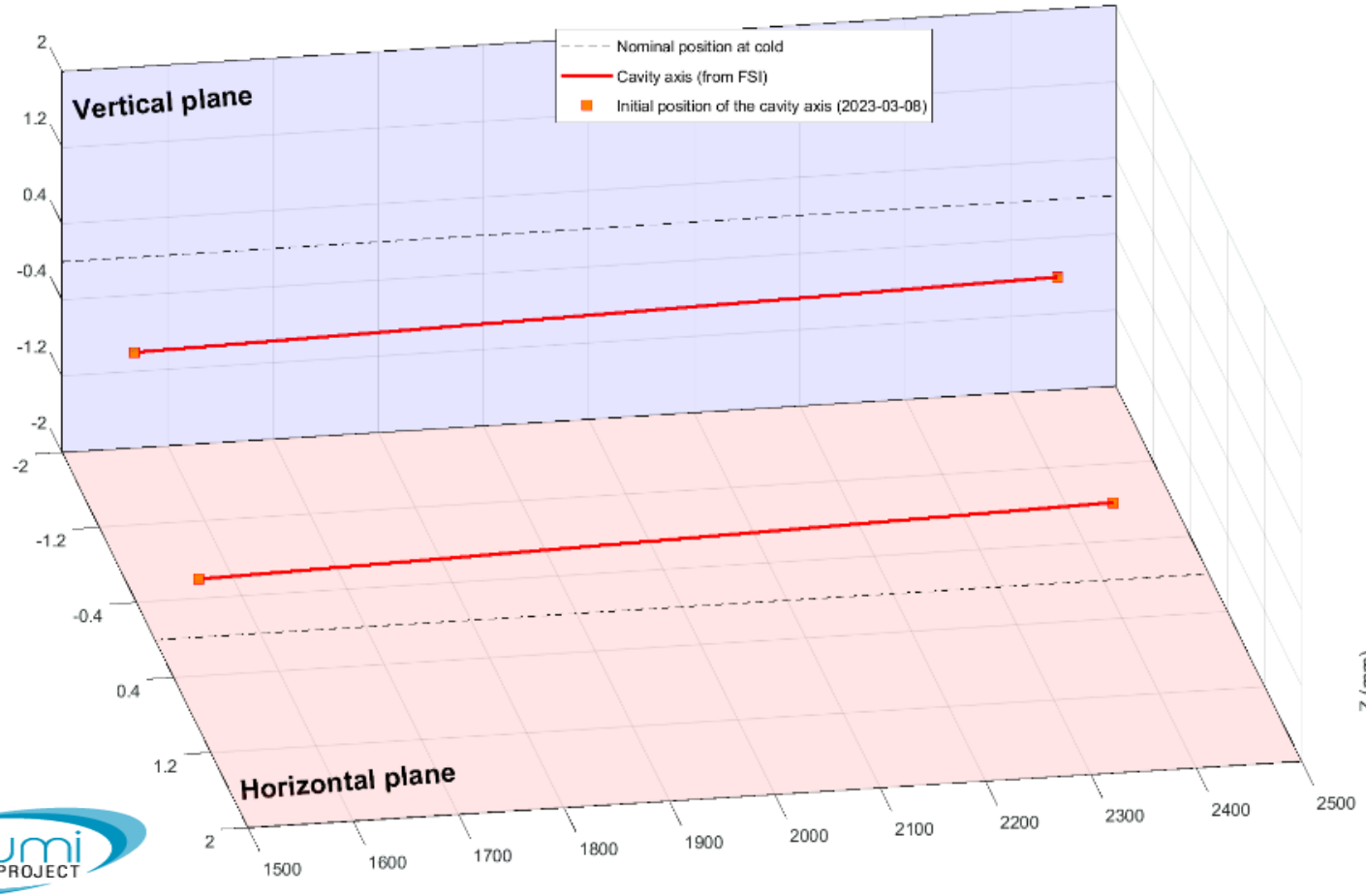
Roll initial =-0.785 mrad
Roll actual =-0.785 mrad
Difference roll =0.000 mrad

IN : X initial =-0.601 mm
IN : X actual =-0.601 mm
Difference IN (X) =0.000 mm

IN : Z initial =-0.998 mm
IN : Z actual =-0.998 mm
Difference IN (Z) =-0.000 mm

OUT : X initial =-0.799 mm
OUT : X actual =-0.799 mm
Difference OUT (X) =-0.000 mm

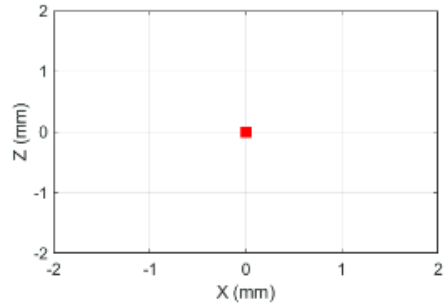
OUT : Z initial =-0.816 mm
OUT : Z actual =-0.816 mm
Difference OUT (Z) =-0.000 mm

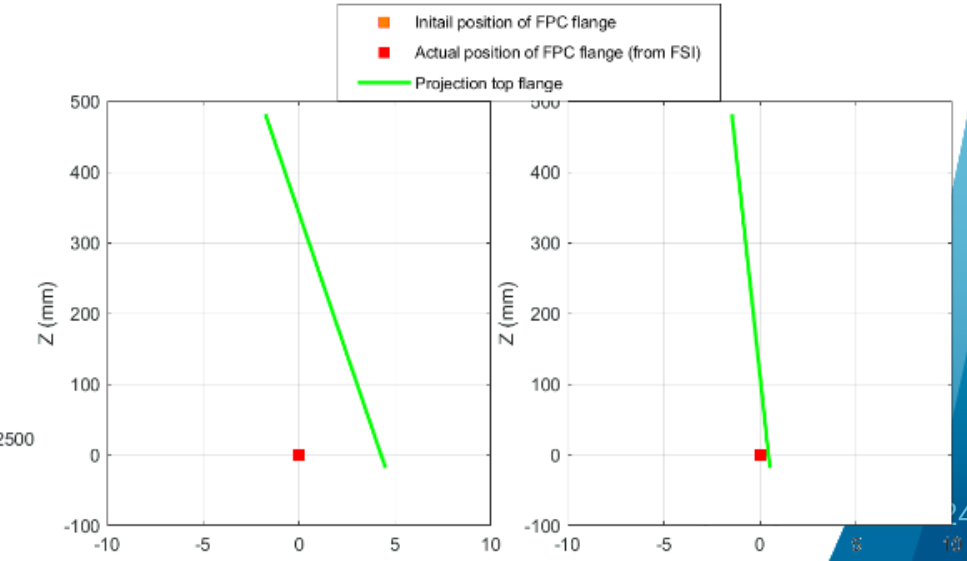


FPC : X initial =99.159 mm
FPC : X actual =99.159 mm
Difference FPC (X) =0.000 mm

FPC : Y initial =2294.623 mm
FPC : Y actual =2294.623 mm
Difference FPC (Y) =-0.000 mm

FPC : Z initial =188.823 mm
FPC : Z actual =188.823 mm
Difference FPC (Z) =0.000 mm



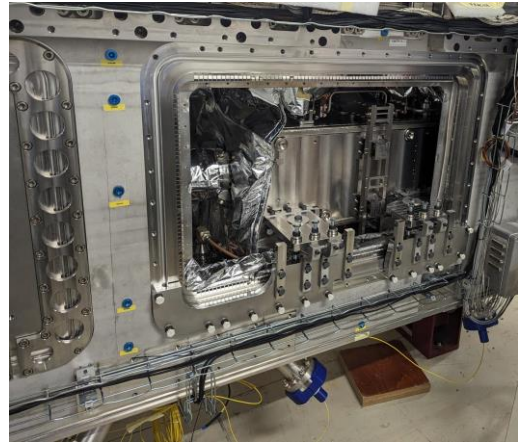


Situation after installation of tooling support of cavity 2
13 March 2024 : 9h12

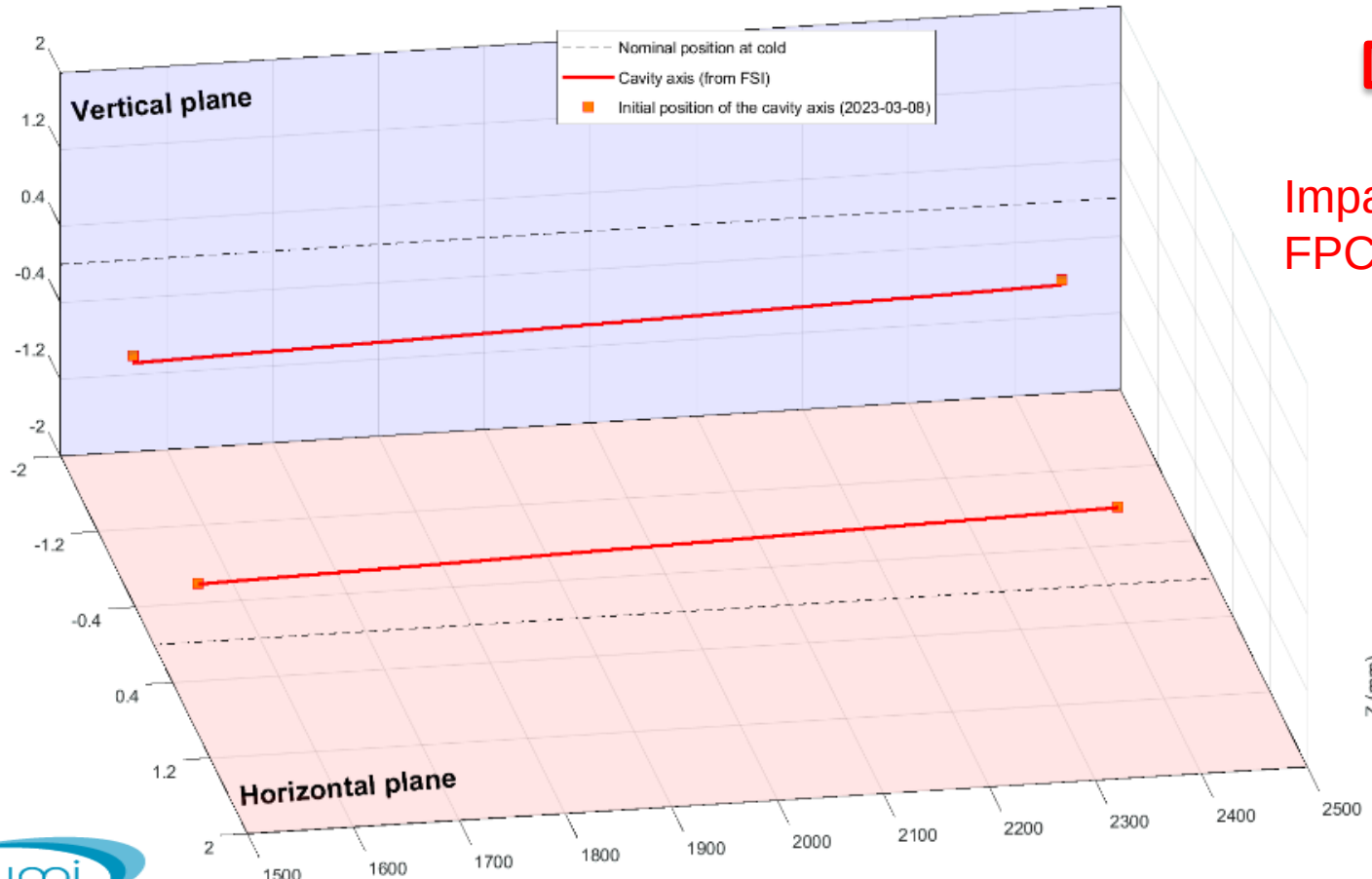
EDMS : 3065222

Impact of installation tooling system : < 0.1 mm

Impact on cavity

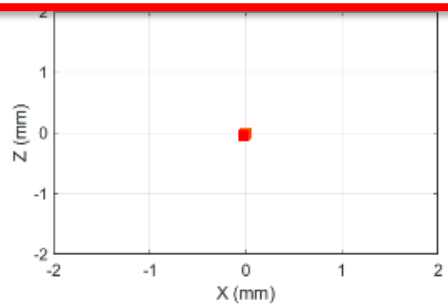


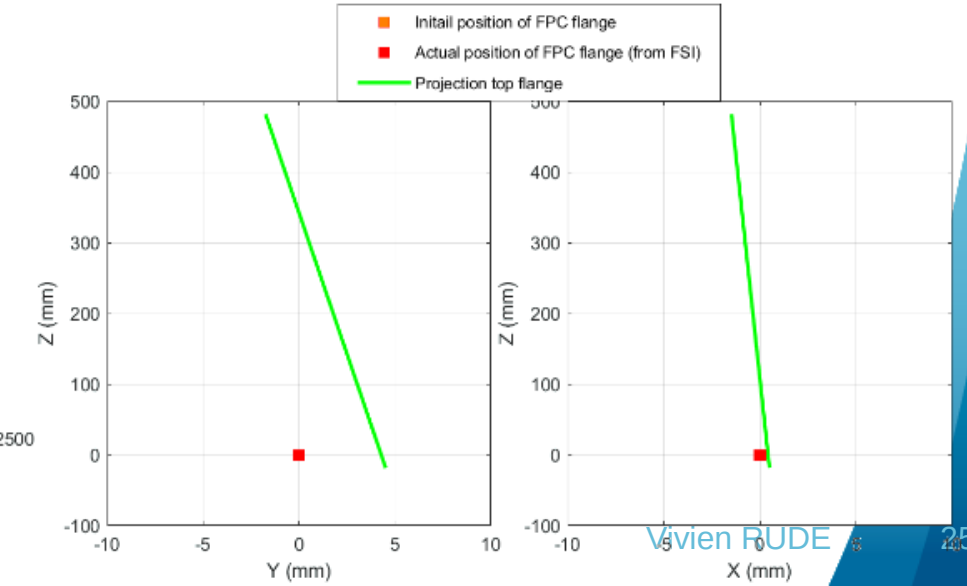
13-Mar-2024 09:12:53	Roll initial =-0.785 mrad	IN : X initial =-0.601 mm	IN : Z initial =-0.998 mm	OUT : X initial =-0.799 mm	OUT : Z initial =-0.816 mm
FUV =0.9	Roll actual =-0.855 mrad	IN : X actual =-0.594 mm	IN : Z actual =-1.077 mm	OUT : X actual =-0.788 mm	OUT : Z actual =-0.870 mm
Max residual =32 microns	**Difference roll =-0.071 mrad**	**Difference IN (X) =0.006 mm**	**Difference IN (Z) =-0.079 mm**	**Difference OUT (X) =0.011 mm**	**Difference OUT (Z) =-0.054 mm**



FPC : X initial =99.180 mm	FPC : Y initial =2294.614 mm	FPC : Z initial =188.815 mm
FPC : X actual =99.156 mm	FPC : Y actual =2294.615 mm	FPC : Z actual =188.772 mm
Difference FPC (X) =-0.024 mm	**Difference FPC (Y) =0.002 mm**	**Difference FPC (Z) =-0.043 mm**

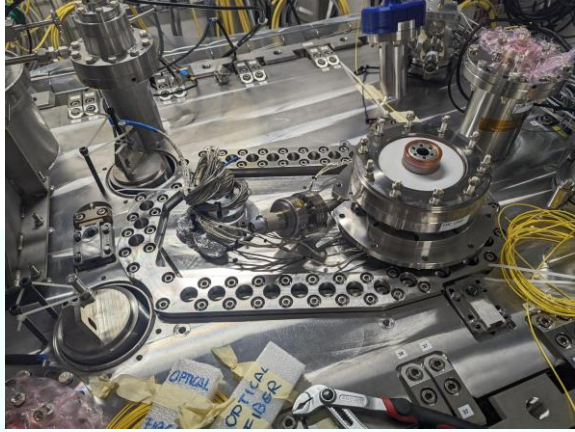
Impact on FPC flange





Movie during the load charge transfer

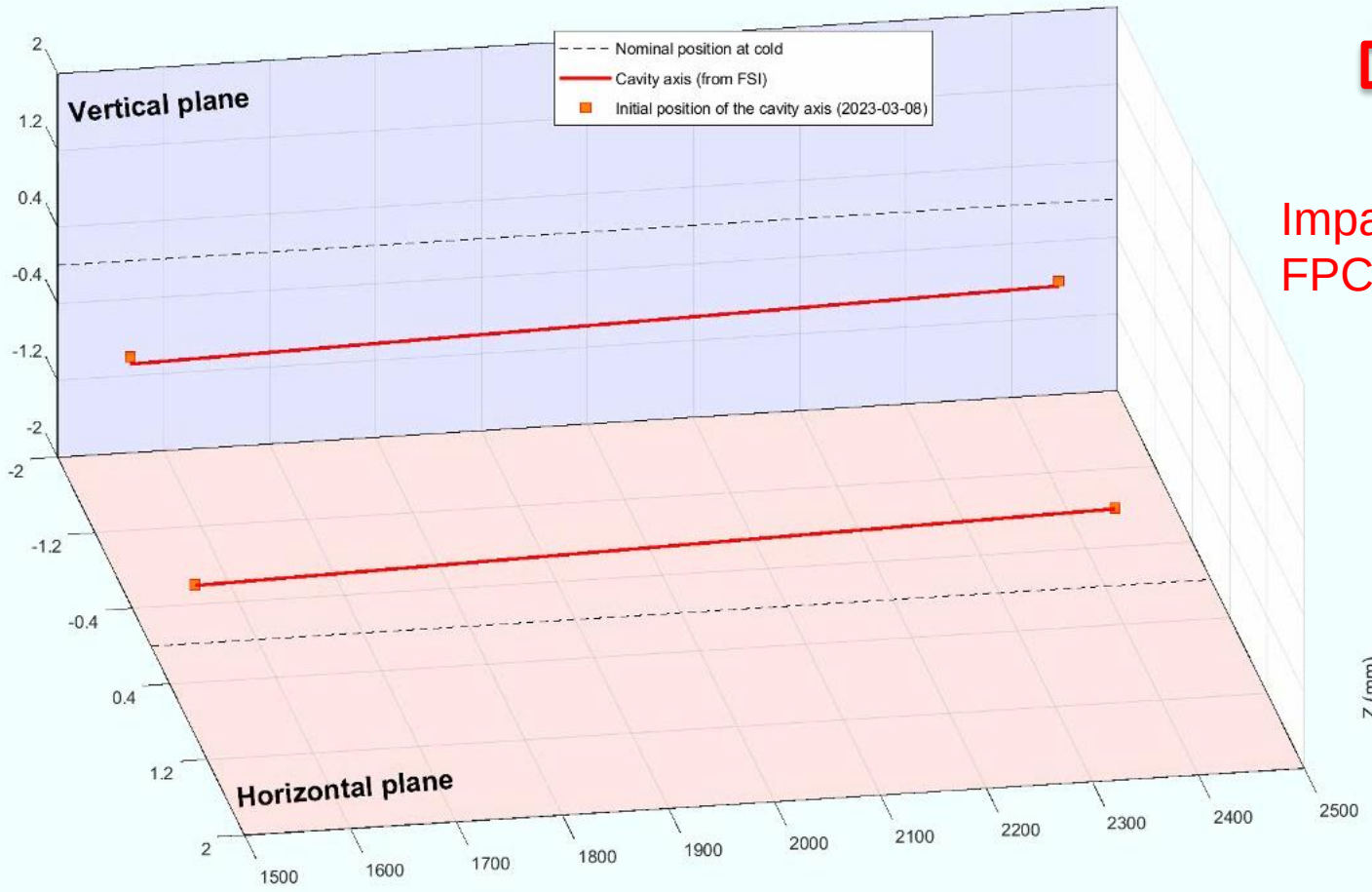
EDMS : 3065222



Impact on cavity

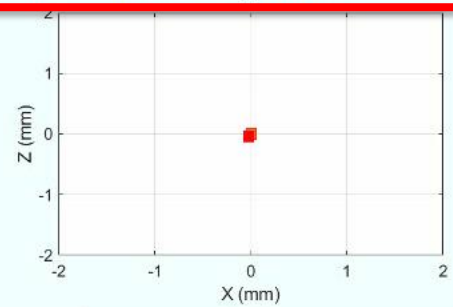
Impact of load transfer : ~0.35 mm in vertical

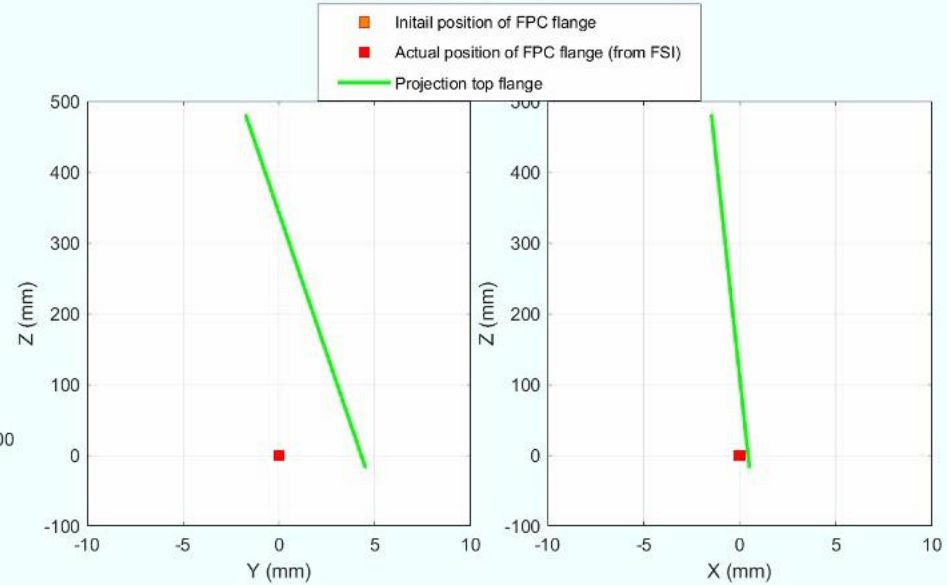
13-Mar-2024 09:12:53	Roll initial =-0.785 mrad	IN : X initial =-0.601 mm	IN : Z initial =-0.998 mm	OUT : X initial =-0.799 mm	OUT : Z initial =-0.816 mm
FUV =0.9	Roll actual =-0.855 mrad	IN : X actual =-0.594 mm	IN : Z actual =-1.077 mm	OUT : X actual =-0.788 mm	OUT : Z actual =-0.870 mm
Max residual =32 microns	**Difference roll =-0.071 mrad**	**Difference IN (X) =0.006 mm**	**Difference IN (Z) =-0.079 mm**	**Difference OUT (X) =0.011 mm**	**Difference OUT (Z) =-0.054 mm**



FPC : X initial =99.180 mm	FPC : Y initial =2294.614 mm	FPC : Z initial =188.815 mm
FPC : X actual =99.156 mm	FPC : Y actual =2294.615 mm	FPC : Z actual =188.772 mm
Difference FPC (X) =-0.024 mm	**Difference FPC (Y) =0.002 mm**	**Difference FPC (Z) =-0.043 mm**

Impact on FPC flange



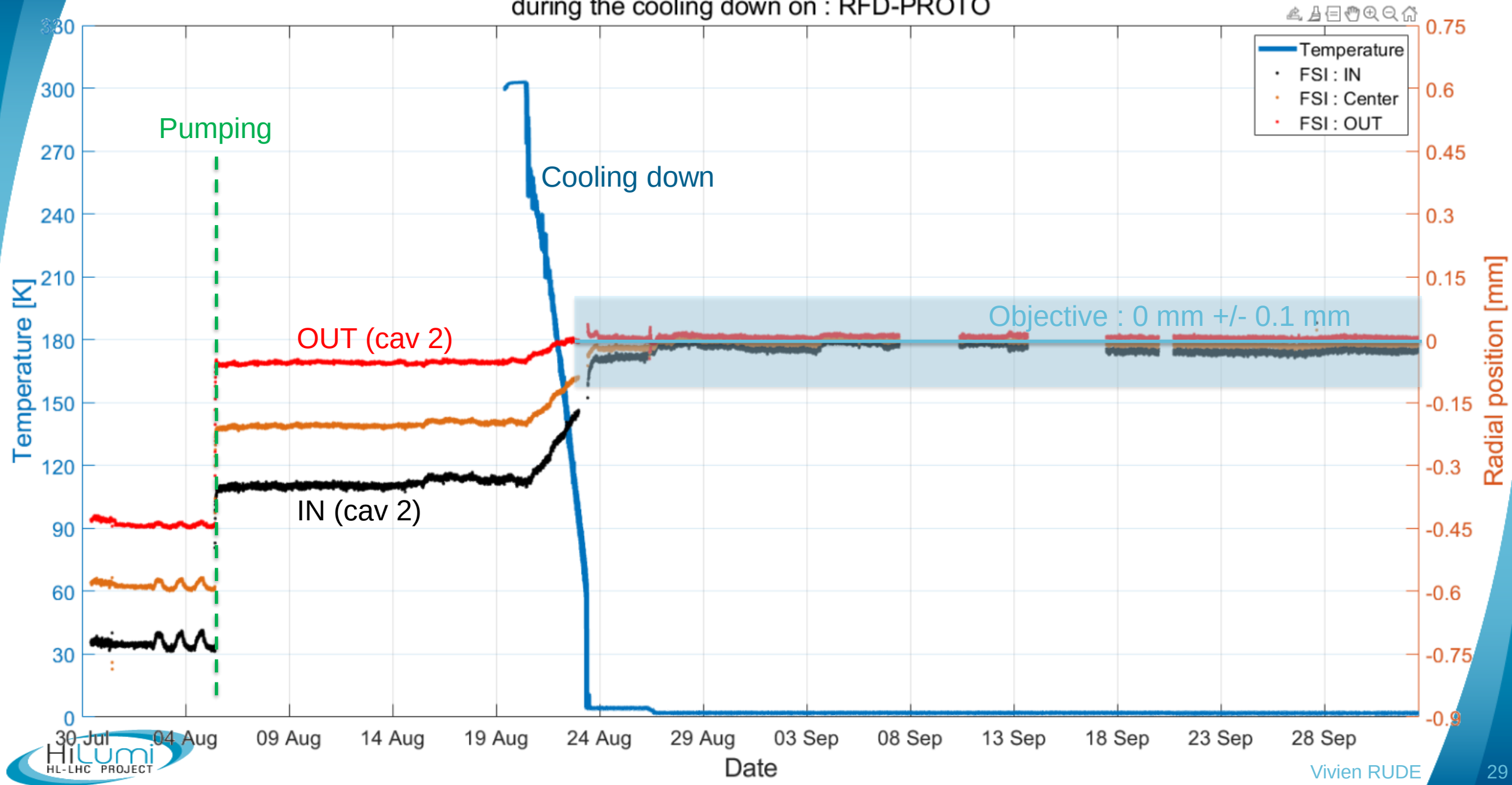


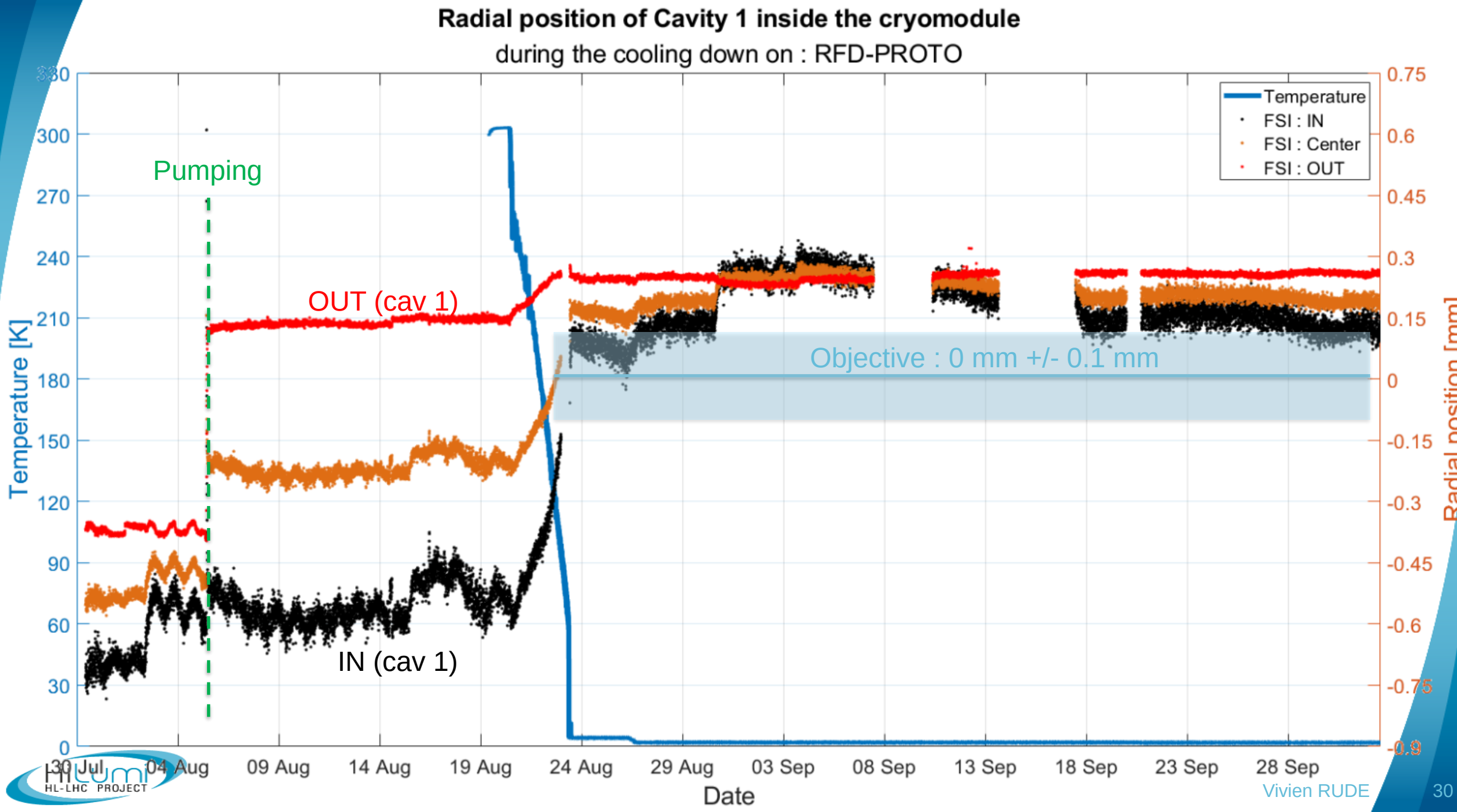
Spare

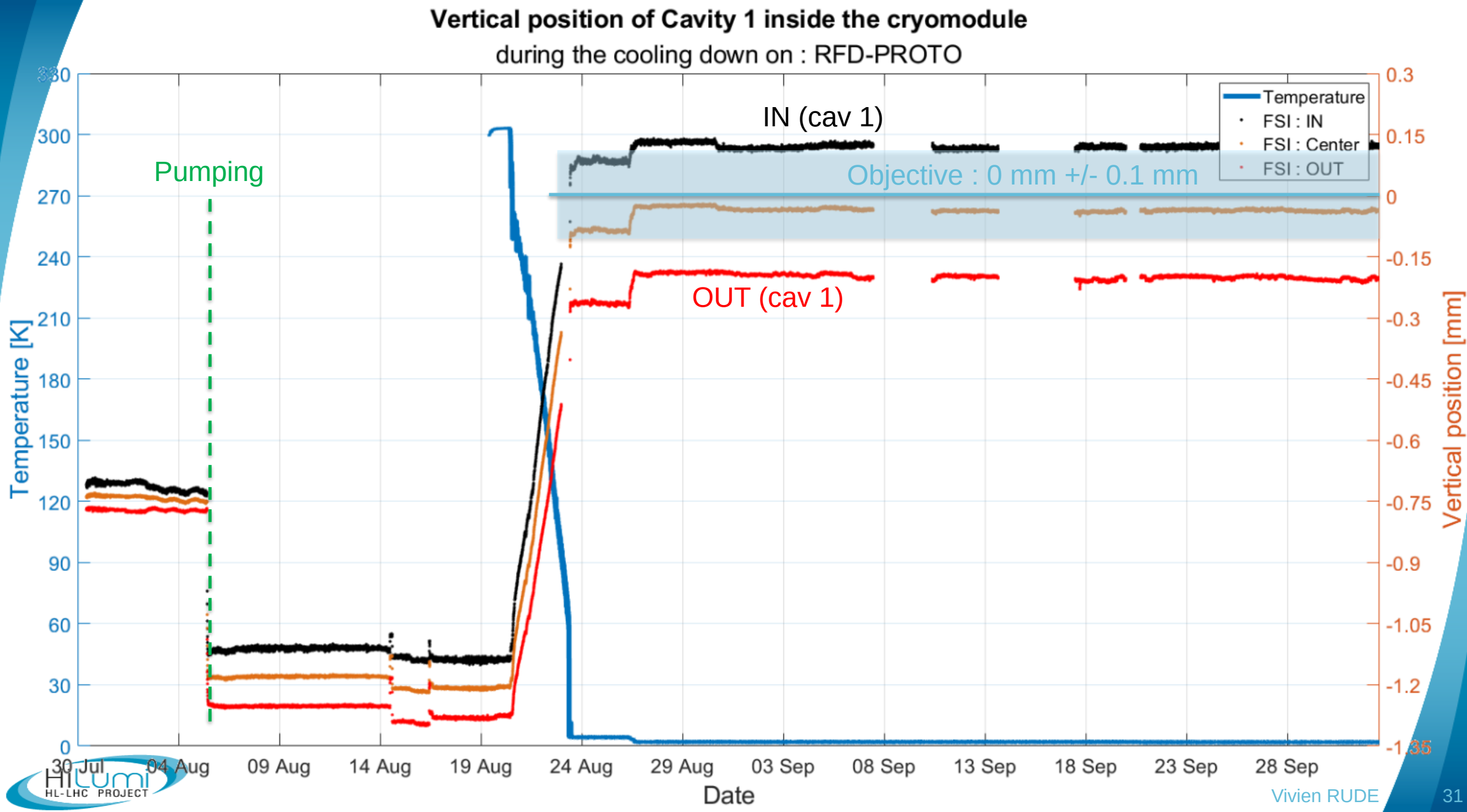
Repeatability on the motions

- Cycle 1 : 12/16 FSI observations are operational
- Cycle 2 : 15/16 FSI observations are operational
- Cycle 3 : 16/16 FSI observations are operational

	Cavity 1			Cavity 2		
Impact of cold	**Cycle 1**	**Cycle 2**	**Cycle 3**	**Cycle 1**	**Cycle 2**	**Cycle 3**
Tx [mm] (radial translation)	0.69 +/-0.30	0.87 +/-0.20	0.72 +/-0.20	0.37 +/-0.20	0.60 +/-0.10	0.57 +/-0.08
Ty [mm] (longi translation)	0.32 +/-0.30	0.35 +/-0.20	0.39 +/-0.20	0.39 +/-0.20	0.15 +/-0.15	0.27 +/-0.10
Tz [mm] (vertical translation)	0.75 +/-0.20	0.62 +/-0.15	0.71 +/-0.15	0.76 +/-0.10	0.76 +/-0.05	0.81 +/-0.05
Rx [mrad] (Pitch angle)	-0.36 +/-0.20	-0.40 +/-0.15	-0.30 +/-0.15	-0.11 +/-0.10	0.05 +/-0.05	-0.08 +/-0.05
Ry [mrad] (Roll angle)	-0.23 +/-1.00	-0.74 +/-0.70	-0.20 +/-0.70	-1.65 +/-1.00	-0.74 +/-0.40	-0.41 +/-0.40
Rz [mrad] (Yaw angle)	0.08 +/-0.35	0.41 +/-0.20	0.21 +/-0.50	0.12 +/-0.20	0.45 +/-0.15	0.31 +/-0.10
Scale [mm/m]	-2.06 +/-0.20	-2.22 +/-0.20	-2.14 +/-0.20	-2.06 +/-0.20	-2.22 +/-0.20	-2.14 +/-0.20


Radial position of Cavity 2 inside the cryomodule
during the cooling down on : RFD-PROTO
Temperature
FSI : IN
FSI : Center
FSI : OUT
Pumping
Cooling down
OUT (cav 2)
IN (cav 2)
Objective : 0 mm +/- 0.1 mm
Temperature [K]
Radial position [mm]
Date
330
300
270
240
210
180
150
120
90
60
30
0
0.75
0.6
0.45
0.3
0.15
0
-0.15
-0.3
-0.45
-0.6
-0.75
-0.9
30 Jul
04 Aug
09 Aug
14 Aug
19 Aug
24 Aug
29 Aug
03 Sep
08 Sep
13 Sep
18 Sep
23 Sep
28 Sep


Radial position of Cavity 1 inside the cryomodule
during the cooling down on : RFD-PROTO
Temperature
FSI : IN
FSI : Center
FSI : OUT
Pumping
OUT (cav 1)
IN (cav 1)
Objective : 0 mm +/- 0.1 mm
Temperature [K]
Radial position [mm]
Date
330
300
270
240
210
180
150
120
90
60
30
0
0.75
0.6
0.45
0.3
0.15
0
-0.15
-0.3
-0.45
-0.6
-0.75
-0.9
30 Jul
04 Aug
09 Aug
14 Aug
19 Aug
24 Aug
29 Aug
03 Sep
08 Sep
13 Sep
18 Sep
23 Sep
28 Sep


Vertical position of Cavity 1 inside the cryomodule
during the cooling down on : RFD-PROTO
Pumping
IN (cav 1)
Objective : 0 mm +/- 0.1 mm
OUT (cav 1)
Temperature
FSI : IN
FSI : Center
FSI : OUT
Temperature [K]
Vertical position [mm]
Date
30 Jul
04 Aug
09 Aug
14 Aug
19 Aug
24 Aug
29 Aug
03 Sep
08 Sep
13 Sep
18 Sep
23 Sep
28 Sep
0
30
60
90
120
150
180
210
240
270
300
330
0.3
0.15
0
-0.15
-0.3
-0.45
-0.6
-0.75
-0.9
-1.05
-1.2
-1.35