SCL2 cryomodule development and test results

2023. 03. 02

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Contents

- Cryomodule development
- IHEP cryomodule test results (VT, HT)

Requirements for cryomodule

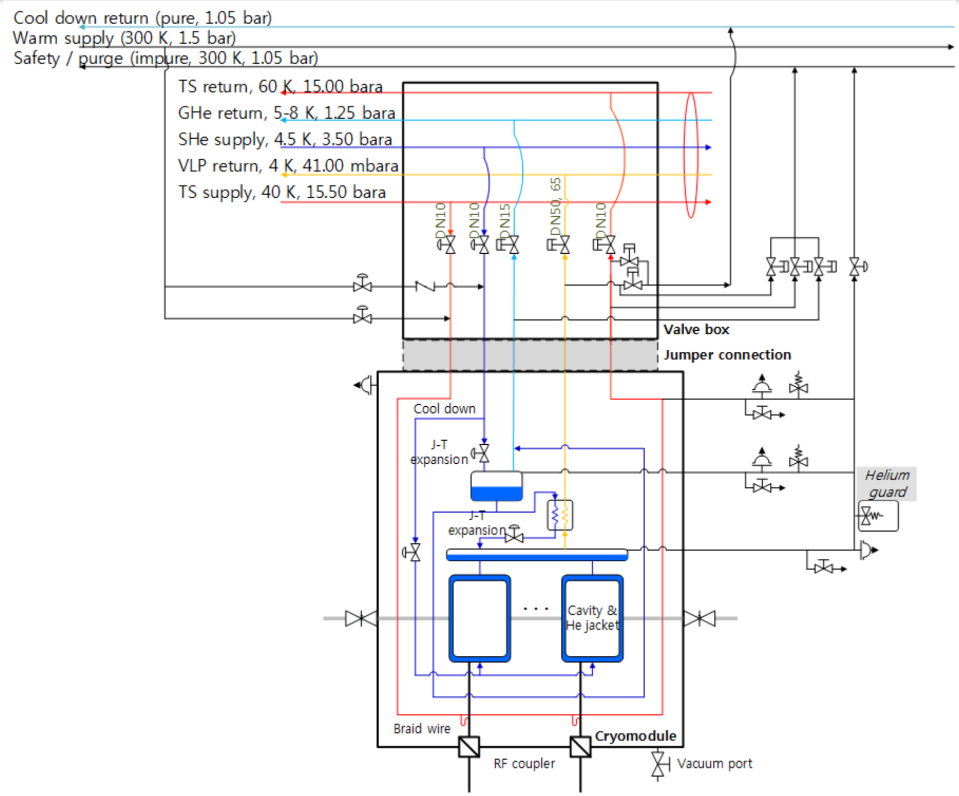
		SSR1	SSR2
Size	Width	Less than 1.6 m	
	Length, mm	**1852**	**4390**
	Height	Less than 3.5 m	
Operating Temp.	THS	40 K	
	Pipe lines	4.5 K or 2.05 K	
	Cavity	4.5 K	2.05 K
Alignment	x, y	± 1 mm	
	z (beam direction)	± 1 mm	
	tilt	± 5 mrad	
Magnetic shield		15 mG	
Vacuum	Cavity	Less than 10^{-9} mbar at cold	
	Vacuum vessel	Less than 10^{-5} mbar at cold	
Total thermal load	2.05 K	29.6 W	122.7 W
	4.5 K	12.2 W	19.1 W
	40 K	73.2 W	138.5 W

Cylindrical cavity (IHEP)

	Balloon type		Cylindrical type
	SSR1	SSR2	SSR2
Optimum β	0.3	0.51	0.51
f $[MHz]$	325	325	325
$L_{eff}(=\beta_o\lambda)[mm]$	276.9	470.8	470.8
R/Q $[\Omega]$	233	290	**247.6**
E_{peak}/E_{acc}	4.1	3.7	3.75
B_{peak}/E_{acc} $[mT/(MV/m)]$	6.9	7.7	**9.43**
E_{acc} $[MV/m]$	8.5	8.7	8.7
V_{acc} $[MV]$	2.35	4.1	4.1

- Cylindrical SSR2 cavity and dedicated coupler, tuner, cryomodule was developed by IHEP, China
- Vertical tests of cavities were done by IHEP
- Assembly of cryomodule were done by IHEP personnel at SRF test facility of RISP
- Horizontal test were done by RISP

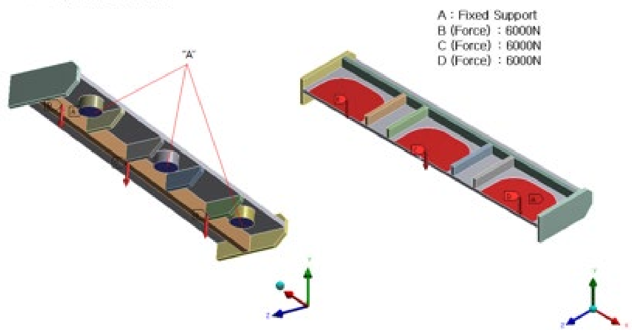
P&ID of cryomodule



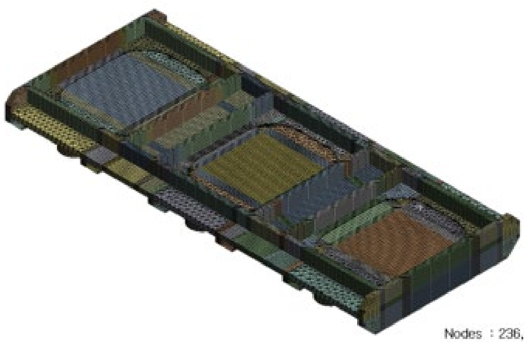
- Thermal shield cooled by GHe (SRF test facility: LN2)
- 2 reservoirs for 4.5 K and 2.05 K liquid helium
- Thermal intercepts
  - 4 K intercepts: loop thermosiphon connected with 4 K reservoir
  - 40 K intercepts: copper braid wire connected with thermal shield
- 3 cryogenic valves: 1 for cool-down and 2 for JT expansion
- Heat exchanger to pre-cool the liquid helium before expansion

Thermal & structural design

- Boundary Condition
  - 1/2 Model 적용

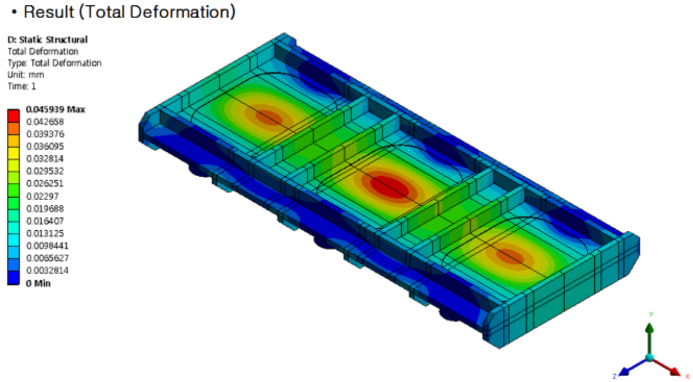


- FE Model

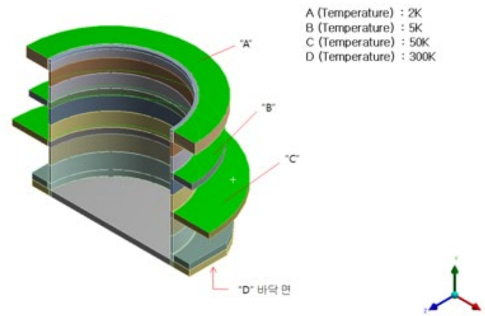


Nodes : 236,555
Elements : 59,253
Types : Tetra, Hexa

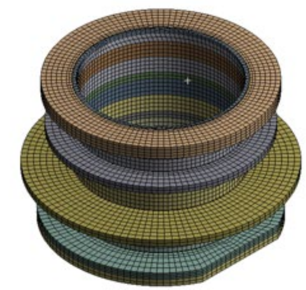
- Result (Total Deformation)



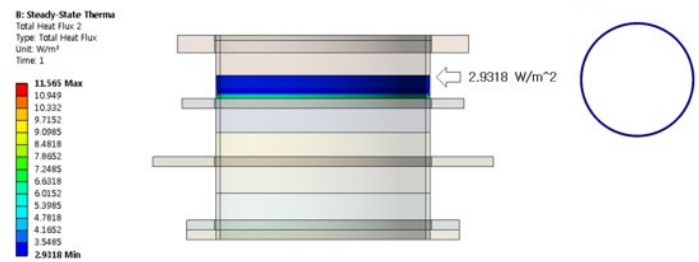
Max Deformation : 0.045939 mm



- FE Model



Nodes : 55,477
Elements : 10,448
Types : Tetra, Hexa



Case 1) 2K-5K			3
Ansys 값		계산 값 Q=K*A*∇T/L	
Heat Flux [W/m^2]	2.9318	Thermal Conductivity 평균 값 [W/m^2*K]	0.0512
Area [m^2]	0.0013503	L [m^2]	0.047
열량 [W]	0.0039588	열량 [W]	0.0044099

Thermal and structural design with ANSYS

Assembly

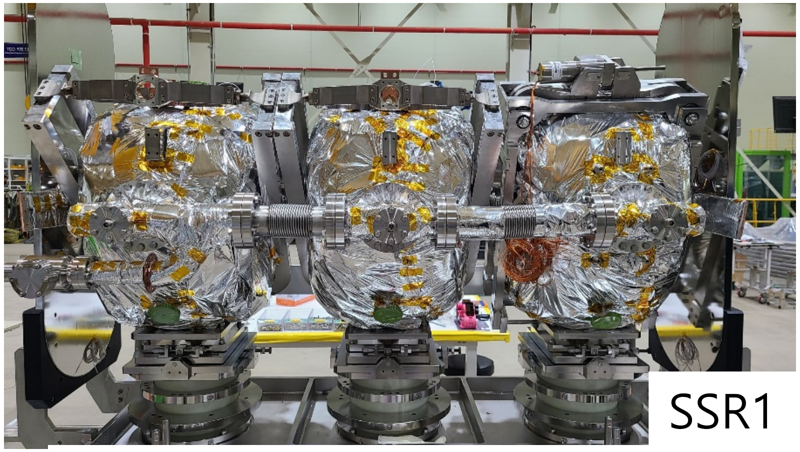
Vacuum chamber

Assembly

SSR2

Cavity string

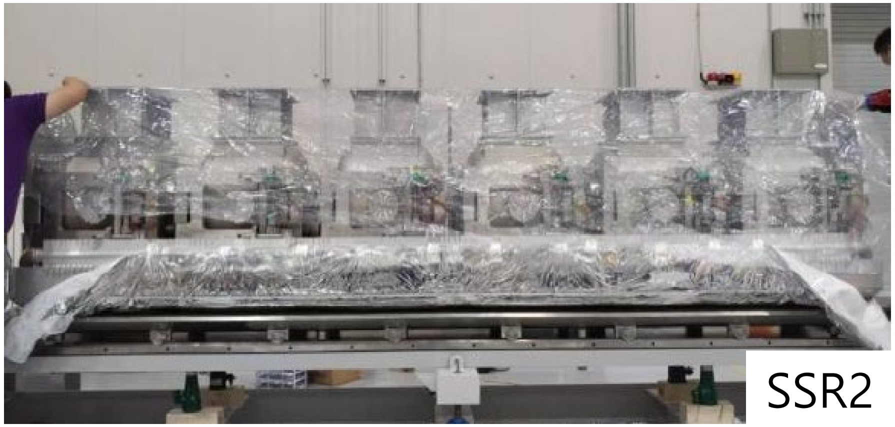
Cavity string assembly in cleanroom



SSR1

Tuner assembly

Room T. motor: 2set, Cryo. Motor: 1 set

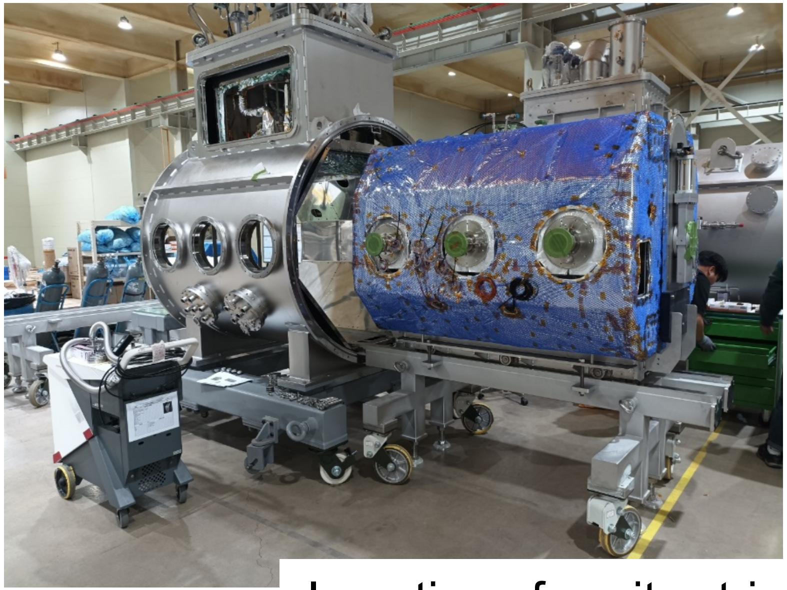


SSR2

Cavity string

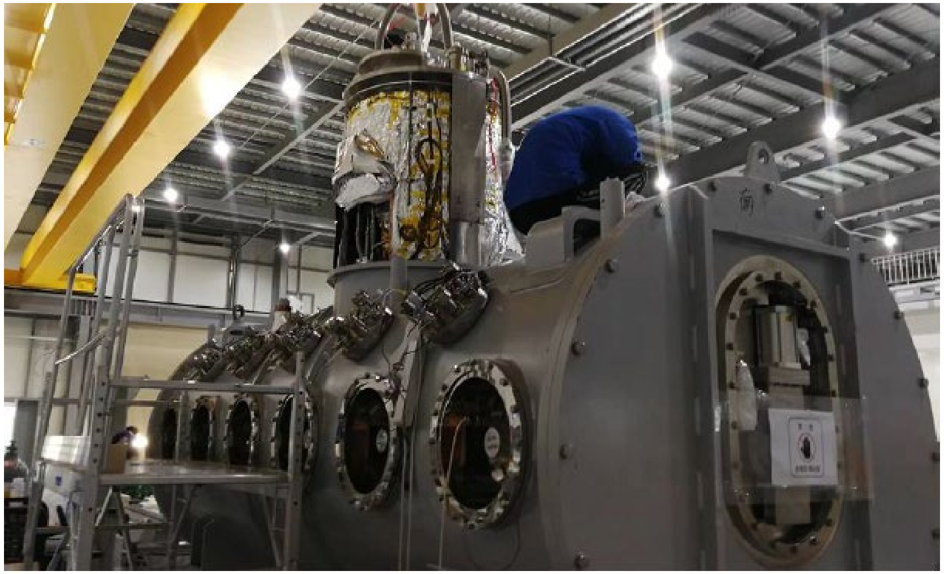
Assembly

3D measurement for cavity string



Insertion of cavity string into vacuum chamber

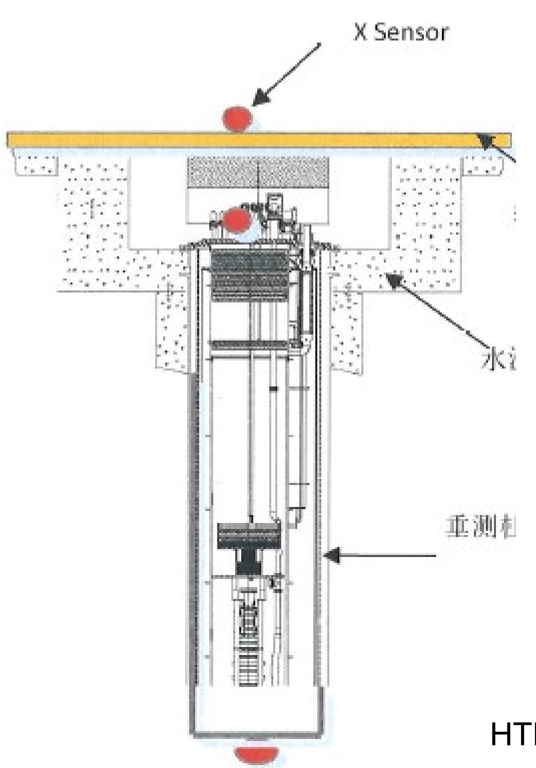
Assembly



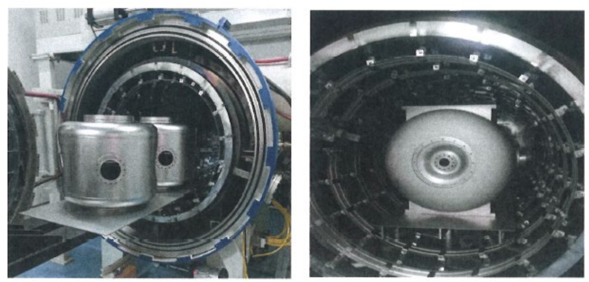
Cryogenic pipe line assembly

- SSR1/SSR2 cryomodules by RISP are not tested yet.
- SSR2 cryomdoule by IHEP was tested.

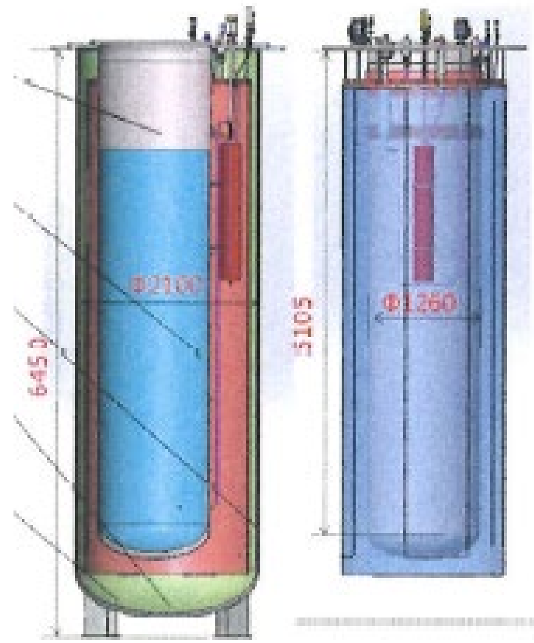
VT results of cylindrical SSR2



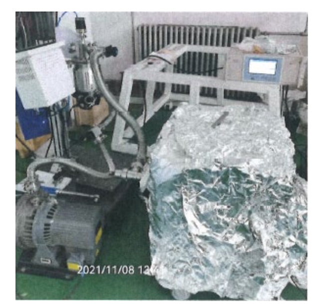
BCP (150 um + 15 um)



HTB: 3 hours at 800°C, 200°C/hour, 1e-3 Pa during HTB

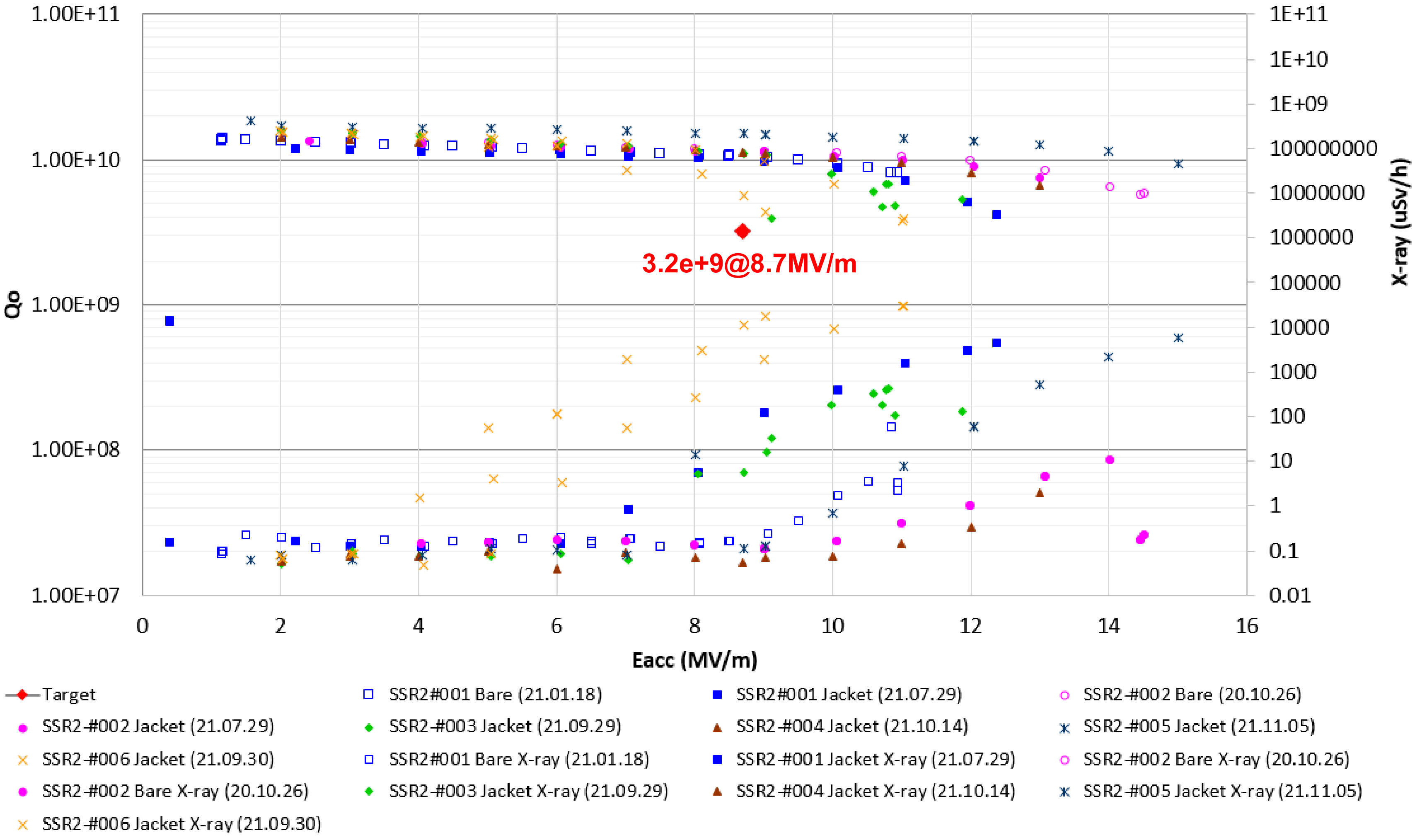


HPR: 100bar, 30mm/min., 10L/min.



Baking: 120~150°C, 48hours

VT results of cylindrical SSR2

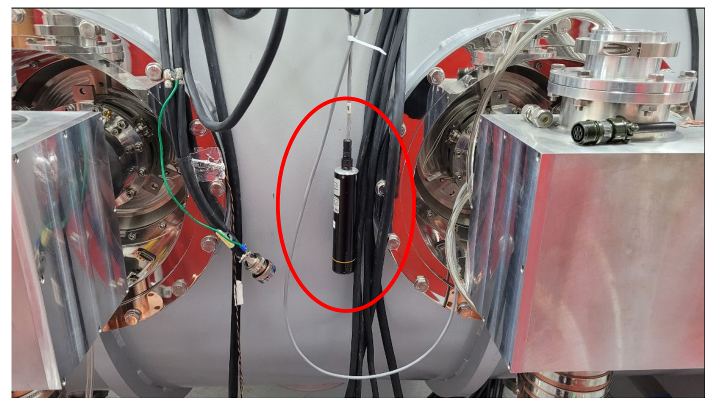


Horizontal test

Cryogenic transfer line

RF transmission line

Vacuum pump for cavity



X-ray sensor: installed between
Coupler #3 and #4

HT History

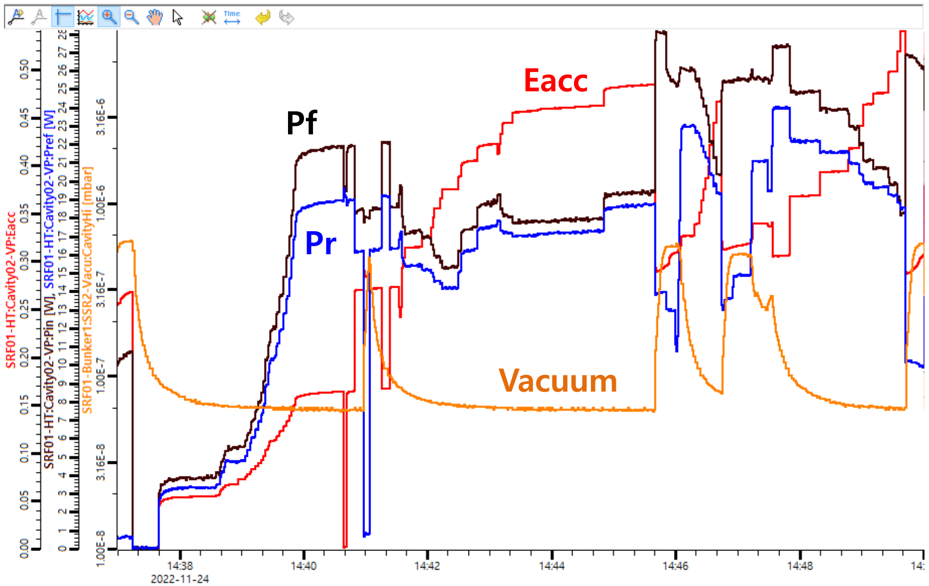
- Test schedule

Time	Contents
‘22. 11.14	LN2 Supply
11.17	LHe Supply
11.18	Line calibration, Q_{ext} measurement
11. 22	Cavity #6, #5, Static thermal load measurement
11. 23	Cavity #4, #3
11. 24	Cavity #2, #1, Static thermal load measurement DC bias* installation
11. 25	Interruption of LHe supply (resumed at 11.26)
11. 28	2 K pumping Static/total thermal load measurement (cavity #2)

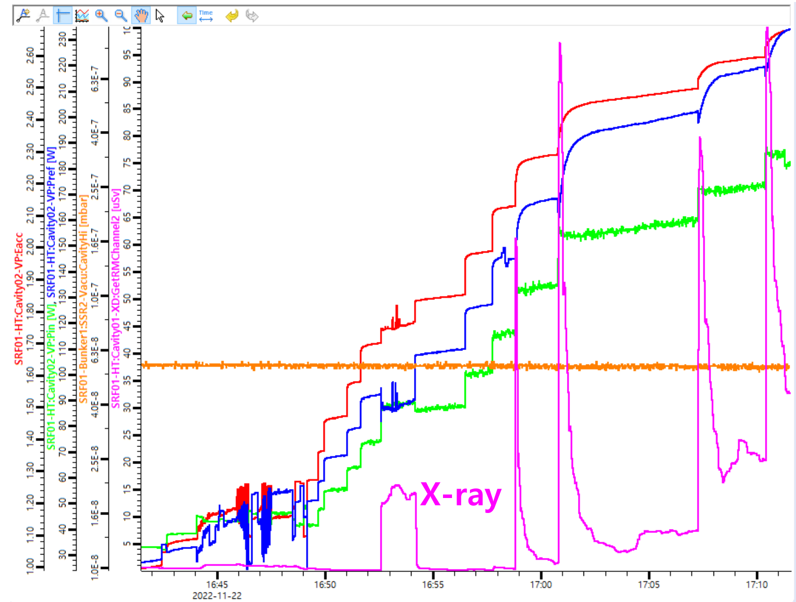
* DC bias

- 1 kV DC voltage
- DC bias Installed before Cavity #1 test
- No MP of FPC below 10 kW

Multipacting conditioning



MP starts at 0.35 MV/m



X-ray generation by MP above ~2 MV/m

- MP band upto approximately 4.5MV/m
  (IHEP: 3.5 MV/m at VT)
- MP band is wide, but conditioning is possible within 2~3 hours.
- MP is sometimes reactivated.

➔ Difficult to distinguish the cause of X-ray whether by MP or FE.

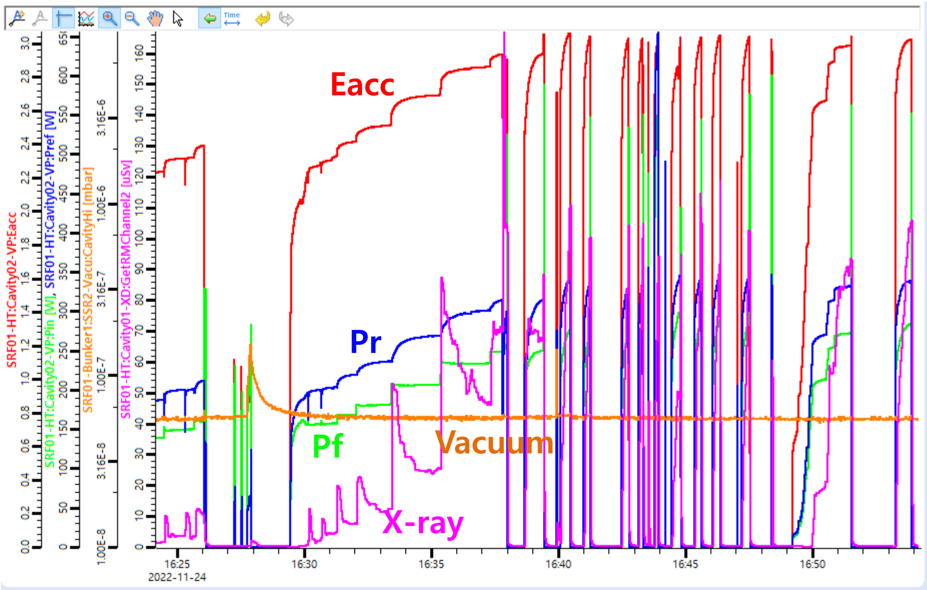
➔ Difficult to check the FE turn-on E_{acc}.

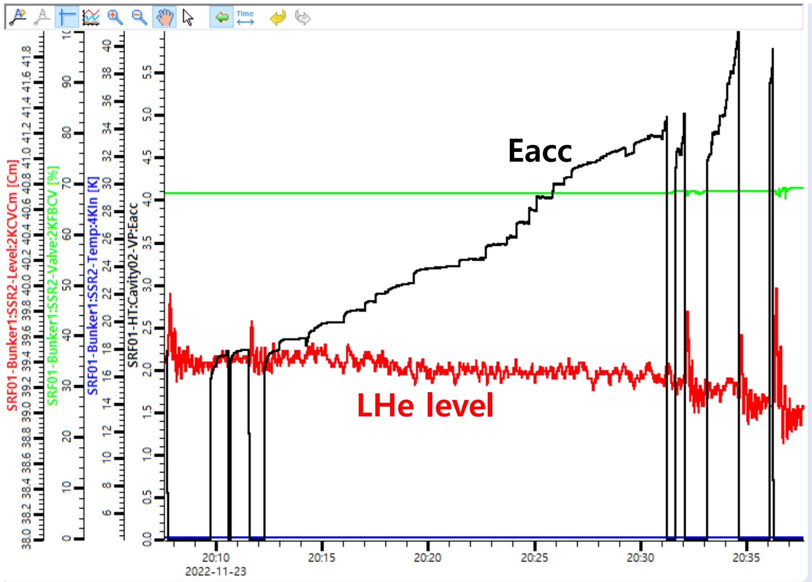
➔ MP conditioning procedure needs to be established.

Summary of HT results

Cavity	Summary	비고
#1	▪ Repeated quench at 3MV/m	
#2	▪ 7.5MV/m, (X-ray: 180 uSV/hr) but degraded after quench ▪ Repeated quench around 5.7 MV/m and 7.1MV/m ▪ Degradation after Pulse conditioning	
#3	▪ Repeated quench around 2.3MV/m ▪ X-ray: 2200 uSv/hr	
#4	▪ 7.0MV/m reached but strong FE ▪ X-ray : 2.55e+4uSV/hr ▪ Degradation after Pulse conditioning	
#5	▪ 6.55Mv/m reached but strong FE ▪ X-ray: 4000 uSv/hr	
#6	▪ Repeated quench around 5.1MV/m ▪ X-ray: ~300 uSv/hr	

Cavity #1





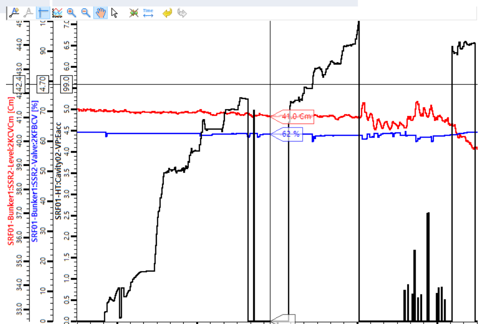
Repeated quench at 3MV/m

LHe level fluctuation at the time quench

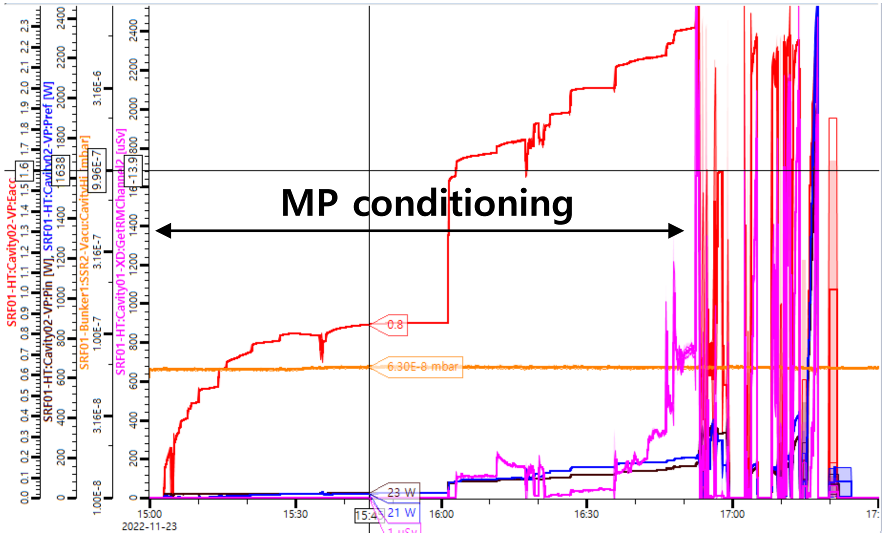
Cavity #2

Eacc(MV/m)	4	4.5	5	5.5	6	6.5	7	7.5	**Quench / Eacc**
11.23	11.6	150							5
		80							5
			0.7	1					5.9
									5.8
				0	0	30	70	180	7.5
11.24			1000						5.7
			500						5.7
			500	2100					5.7
				2100					5.7
				2100					5.7
				500	1600	2800	**7000**		7.1
			80	270	1100	2800	6000		7.1
					580	1800	6000		
						1700			
11.24 17:47 **(Add DC bias)**	0.5		35	170	800	2200			7.1
pulse cond.						1400			

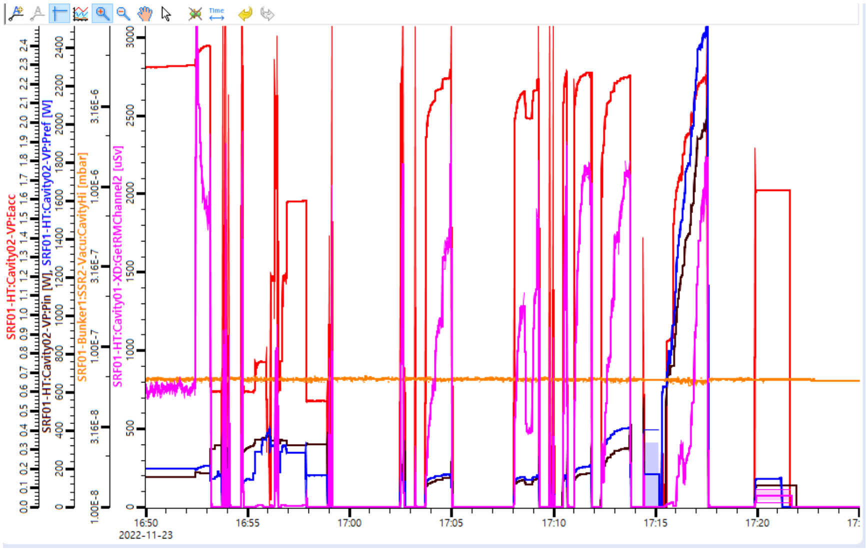
- At 6.6MV/m, the LHe level drops rapidly even with the valve open more than 60% ➔ Large heat load



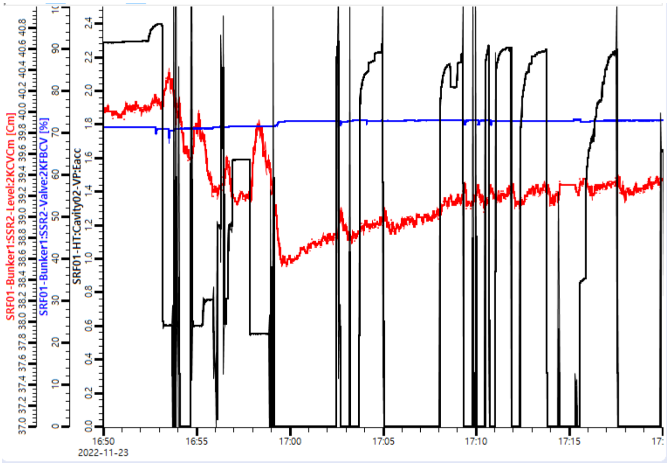
Cavity #3



MP conditioning

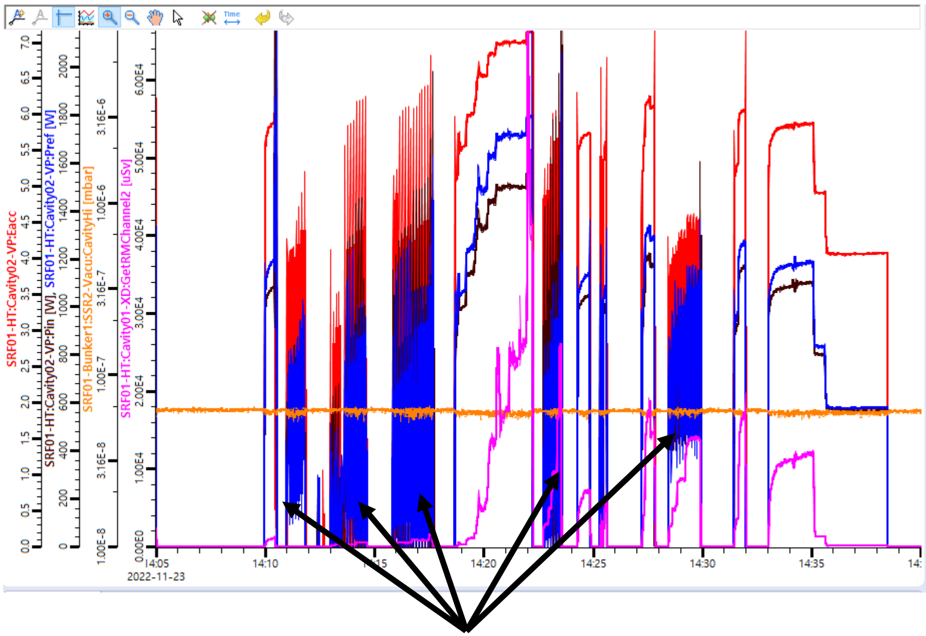


Repetitive quench at 2.3MV/m



Fluctuation of the LHe level due to repetitive quench around 2.3 MV/m.

Cavity #4

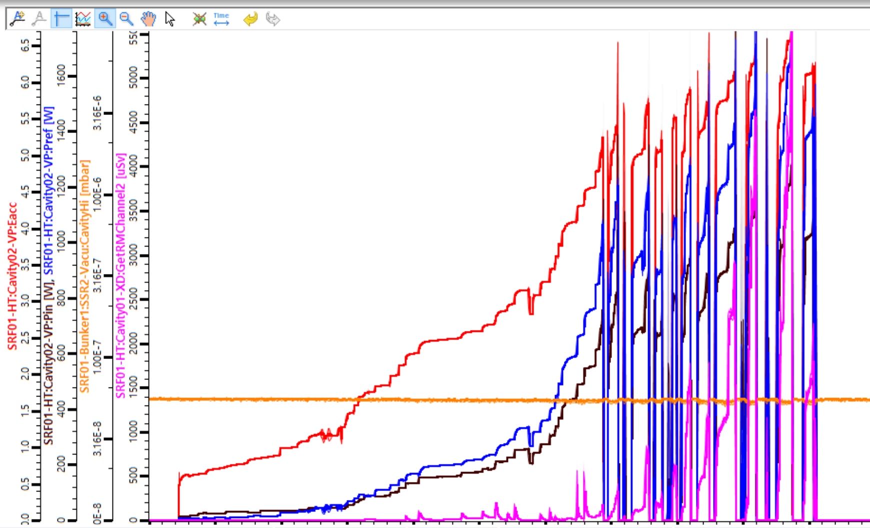


Pulse conditioning

Eacc(MV/m)	4	4.5	5	5.5	6	6.5	7
	350	1400	3100	950			
				530			
				350			
pulse cond.				250	1000	5000	17000->23000
pulse cond.					14000		
					16000		

RF supply process of the cavity #4 and performance change according to pulse conditioning.

Cavity #5 & #6



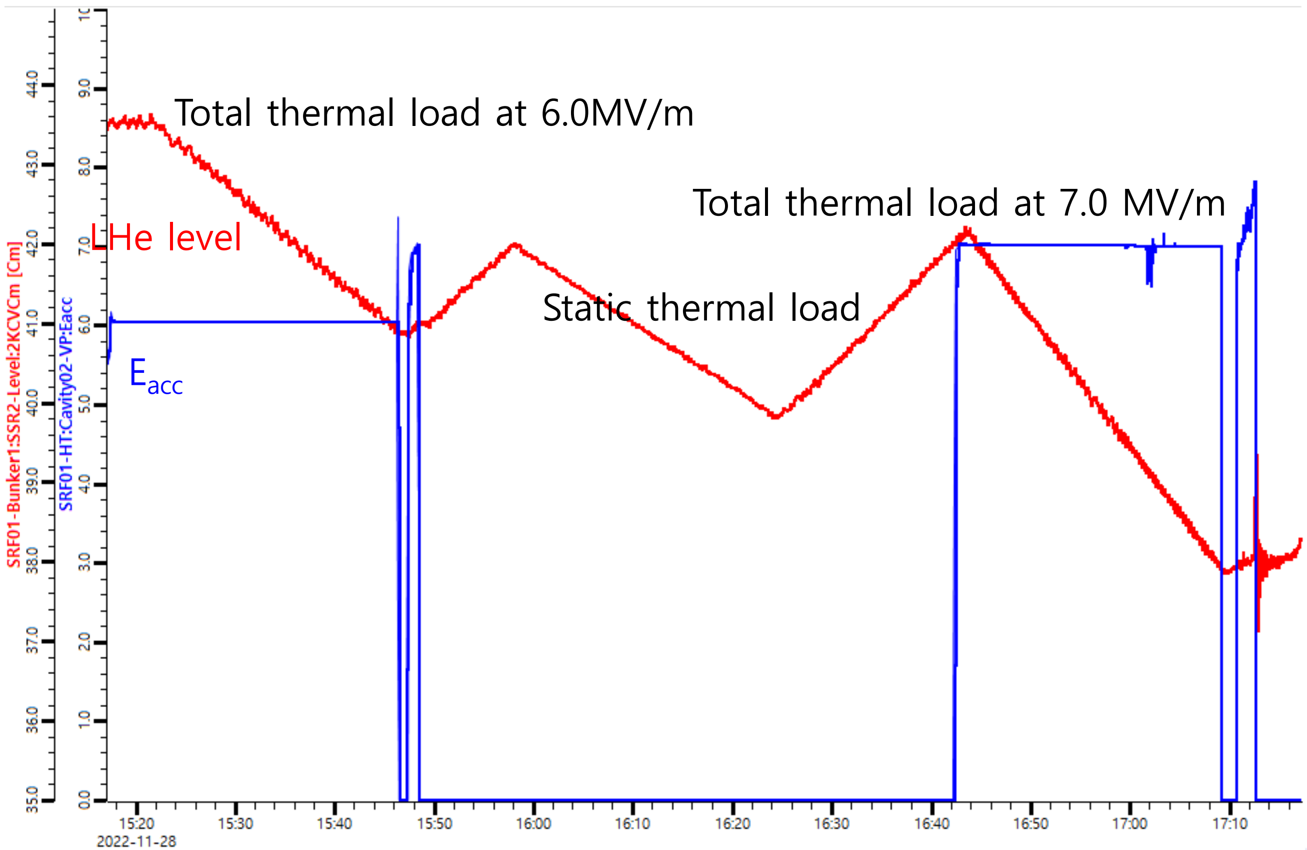
RF supply process of the cavity #5 and quench due to FE (X-ray: ~5000 usV/hr) around 6.3MV/m.

	3.5	4	4.5	4.6	4.7	4.8	4.9	5	Quench / Eacc
9:49	18	110	230						Trip at 4.7MV/m MP reactivated
			180						5.0MV/m MP reactivated
			0						Trip occurs repeatedly at 5.0MV/m or trip while maintaining at 4.9MV/m
			150						X-ray increase after repeated trip at 5.0MV/m
10:22	9	44	160	200	250	300	350		Trip at 5.0MV/m
			80						When RF is supplied again, MP reactivated around 0.6Mv/m
10:55		21	77			180	225	300	Trip at 5.1Mv/m

X-ray change according to RF supply process of the Cavity #6 and repetitive quench around 5.0MV/m

Thermal load measurement at 2.05K

Cavity #2



E_{acc} (MV/m)	Q_s (W)	Q_t (W)	Q_d (W)	Q_0
6.0	35.6	46.7	11.1	2.89e+9
7.0		70.7	35.1	1.25e+9

- Static thermal load requirement: 14 W

Discussion with IHEP

- FE was generated in all cavities and the target E_{acc} was not achieved.
  - Contamination during cavity string assembly
  - No HPR before cavity string assembly
  - No coupler conditioning before cool down

- For Cavity #1, #3, #6, quench occurs repeatedly at low field.
  - Large static thermal load for the cavities at the both end.

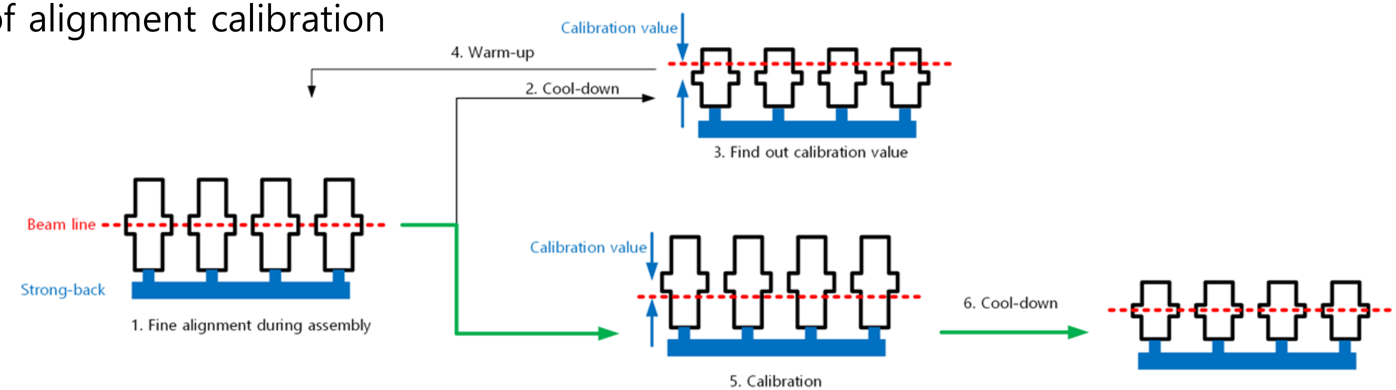
- Huge static thermal load (36 W)
  - No vacuum leak of vacuum chamber
  - Large conduction through the warm-to-cold transition beam pipes
  - Possibility of thermal contact between thermal shield or pipes and helium pipes

Thank you!

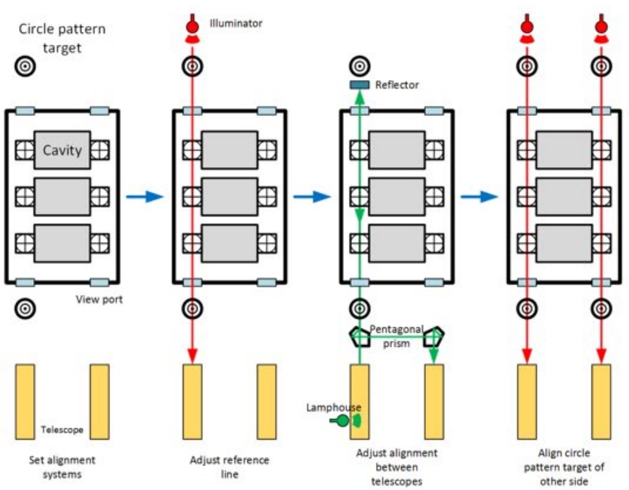
Cavity alignment

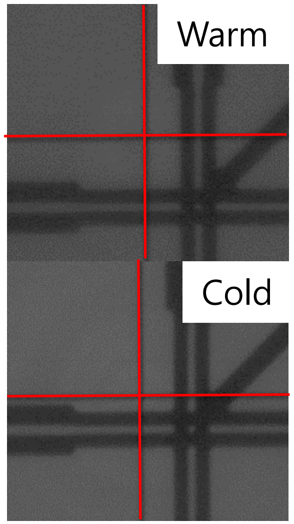
- Process of alignment calibration and measuring method are applied to SCL 3 cryomodules and it was verified.

Process of alignment calibration

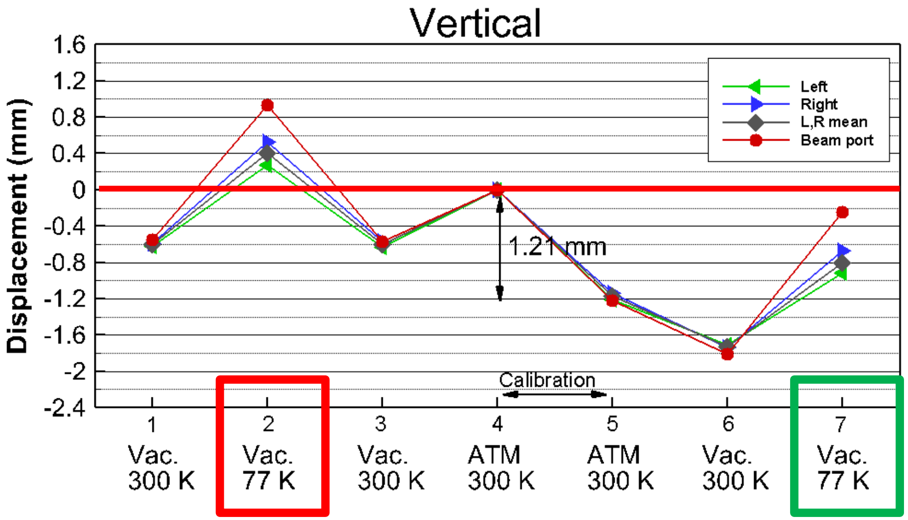


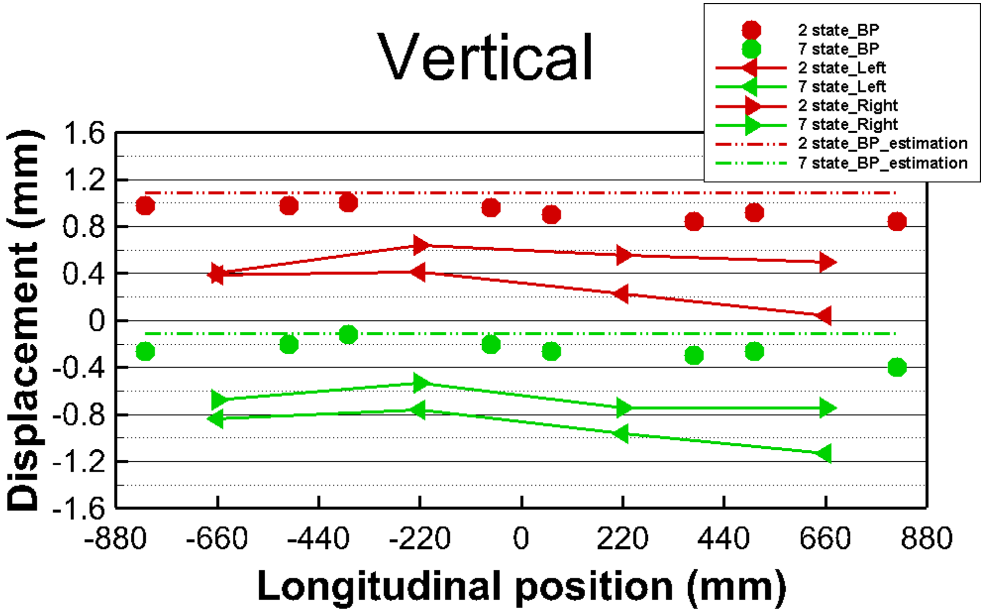
Measuring cavity displacement of room and cold temperatures with micro alignment telescope





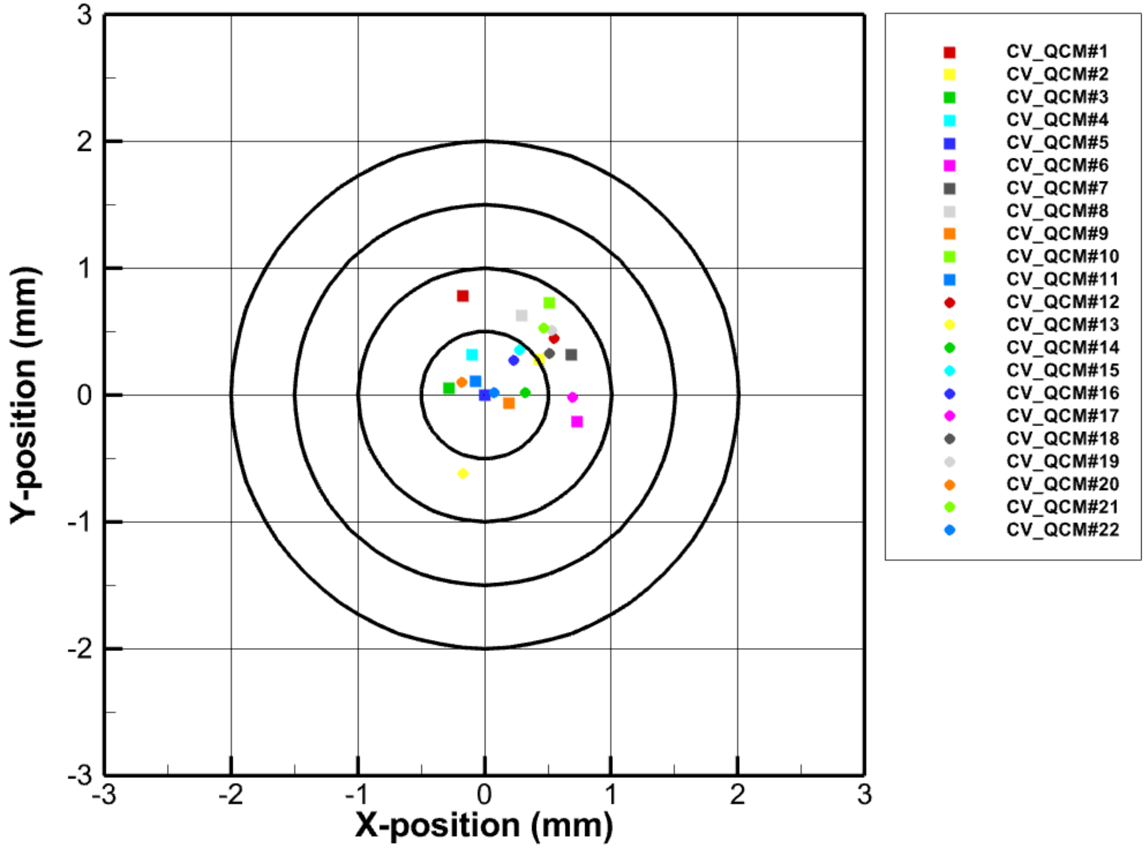
Cavity alignment



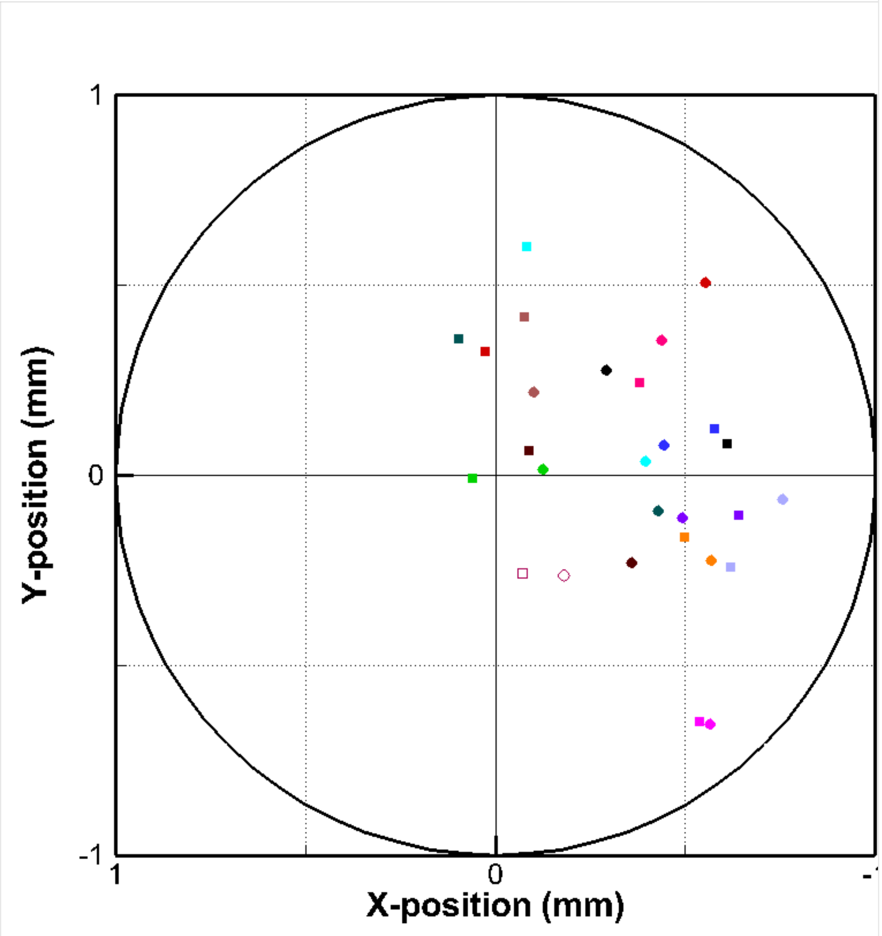


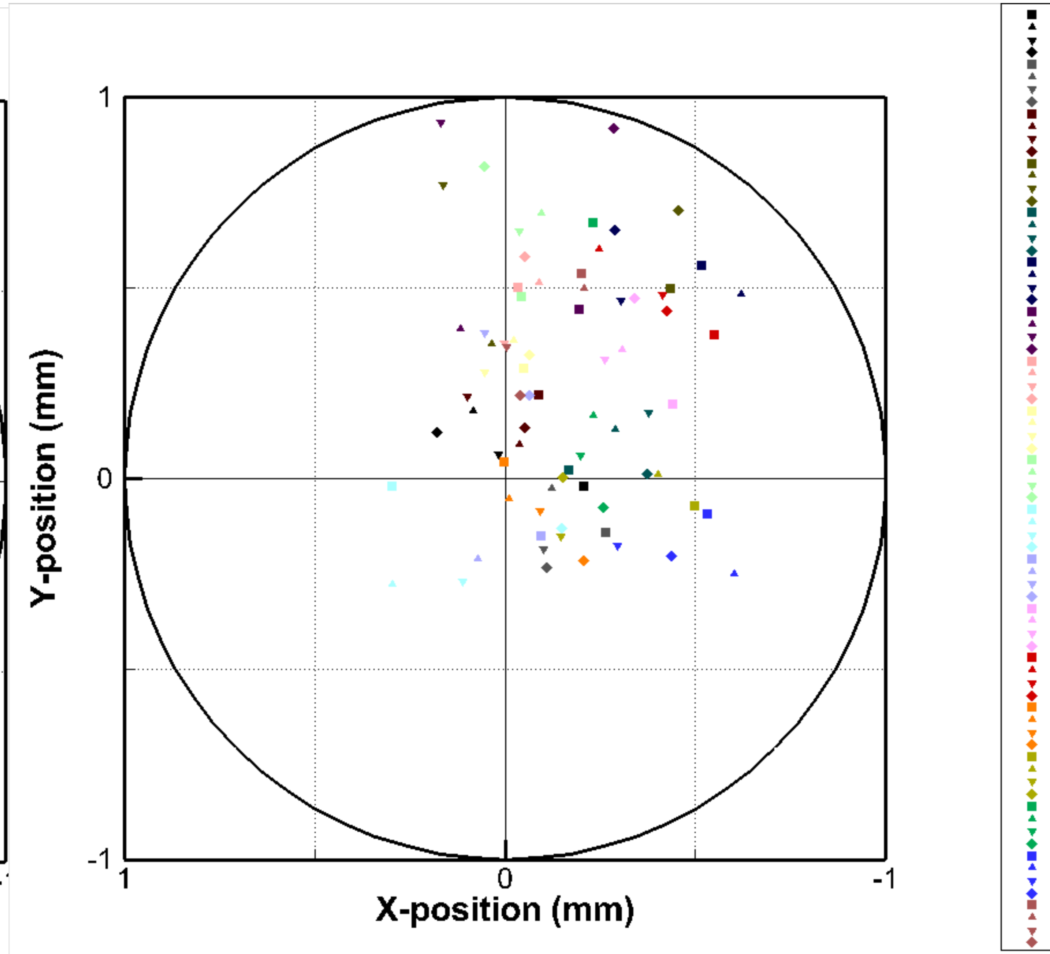
- Calibration method of cavity was confirmed in 1st prototype of HWR cryomodule B.
- Including deformation of vacuum chamber in vacuum and thermal contraction of vertical support and cavity, estimated calibration value in vertical direction is -1.21 mm.
- Measured displacement of beam port is located less then 0.29 mm of estimated displacement.
- Alignment of SSR1 cavities is easier than QWR&HWR cavities because SSR1 cavities are supported from below not hanging.

Cavity alignment



Cavity alignment

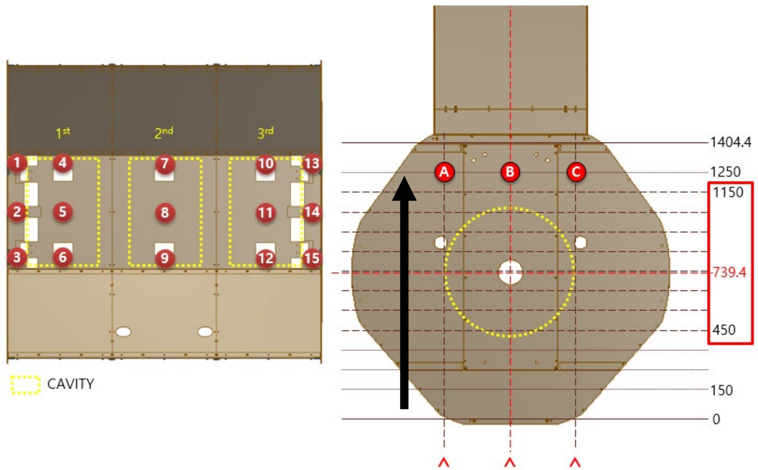




Magnetic field measurement

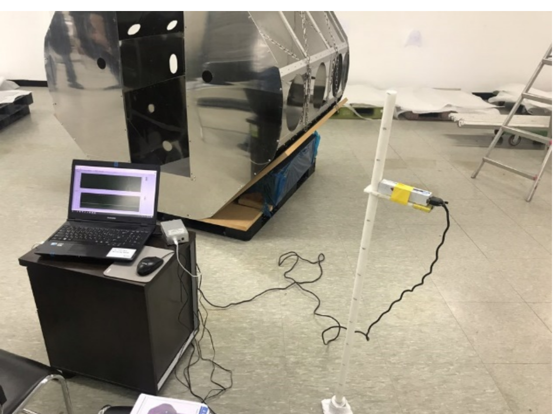
- Magnetic field near cavity is below 15 mG(avg. 7.6). It satisfice our requirement.

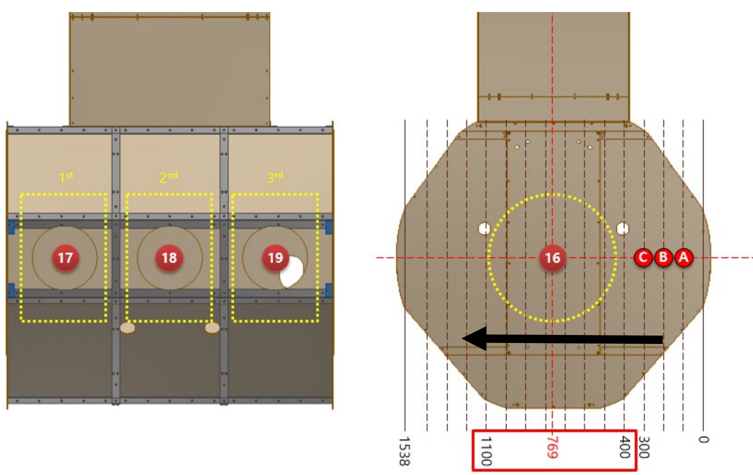
Test 1: 50 mm ~ 1250 mm, 150 mm interval



In test 1, points near top cover and tuner port (A7,10,13, B8,11,14, C9,12,15) are over 15 mG but under 27 mG(C12).

Test 2: 100 mm ~ 1400 mm, 100 mm interval





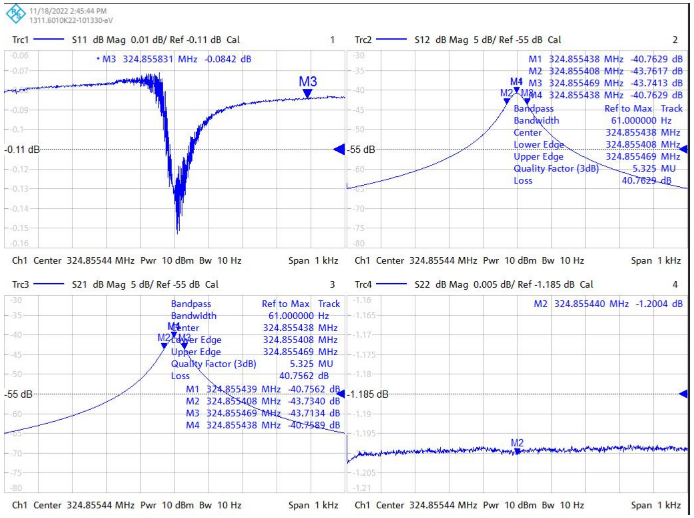
In test 2, maximum and minimum values at points near coupler port (A17~19, B18~19, C19) are 134 mG(A19) and 18 mG(C17).

* Background: 260 mG

Q_{ext} measured

CAV	#1	#2	#3	#4	#5	#6
Freq [MHz]	325	325	325	325	325	325
S21 (dB)	-40.9936	-45.6779	-41.108	-40.76	-40.45	-34.2772
S11 (dB)	-7.99E-02	-5.87E-02	-7.07E-02	-8.40E-02	-7.74E-02	-8.00E-02
S22 (dB)	-1.12E+00	-9.60E-01	-1.62E+00	-1.20E+00	-1.11E+00	-1.11E+00
QL	6.12E+06	**1.77E+06**	5.70E+06	5.30E+06	5.80E+06	**2.70E+07**
Qt	2.68E+11	**2.32E+11**	2.42E+11	2.18E+11	2.24E+11	**2.52E+11**
BW	53	**184**	57	61	56	**12**

$$Q_t = \frac{1}{Q_c}\left(\frac{2Q_L}{S_{21}}\right)^2$$



I. SCL2

1. 저온유지모듈 개별 열부하

Heat load		HWR2 (1 EA)			SSR1 (23 EA)			SSR2 (23+2 EA)			Remark
		2.05 K	4.5 K	35 – 55 K	2.05 K	4.5 K	35 – 55 K	2.05 K	4.5 K	35 – 55 K	
Without margin	Static	4.5	5.0	121.0	5.0	8.1	48.8	9.2	12.7	92.3	2016.04
	Dynamic	12.8	-	-	14.7	-	-	72.6	-	-	2016.04
	Total	**17.3**	**5.0**	**121.0**	**19.7**	**8.1**	**48.8**	**81.8**	**12.7**	**92.3**	2016.04
With margin	Static	6.8	7.5	181.5	7.5	12.2	73.2	13.8	19.1	138.5	2016.04
	Dynamic	19.2	-	-	22.1	-	-	108.9	-	-	2016.04
	Total	**26.0**	**7.5**	**181.5**	**29.6**	**12.2**	**73.2**	**122.7**	**19.1**	**138.5**	2016.04

2. 저온유지모듈 전체 열부하

Heat load		P2DT, SCL2, and Extension			Remark
		2.05 K	4.5 K	35 – 55 K	
Without margin	Static	349.5	508.8	3,550.9	2016.04
	Dynamic	2,165.9	-	-	2016.04
	Total	**2,515.4**	**508.8**	**3,550.9**	2016.04
With margin	Static	524.3	765.6	5,327.6	2016.04
	Dynamic	3,250.0	-	-	2016.04
	Total	**3,774.3**	**765.6**	**5,327.6**	2016.04