S1-G Cryomodule Thermal Performance Summary

S1-G Cryomodule Group

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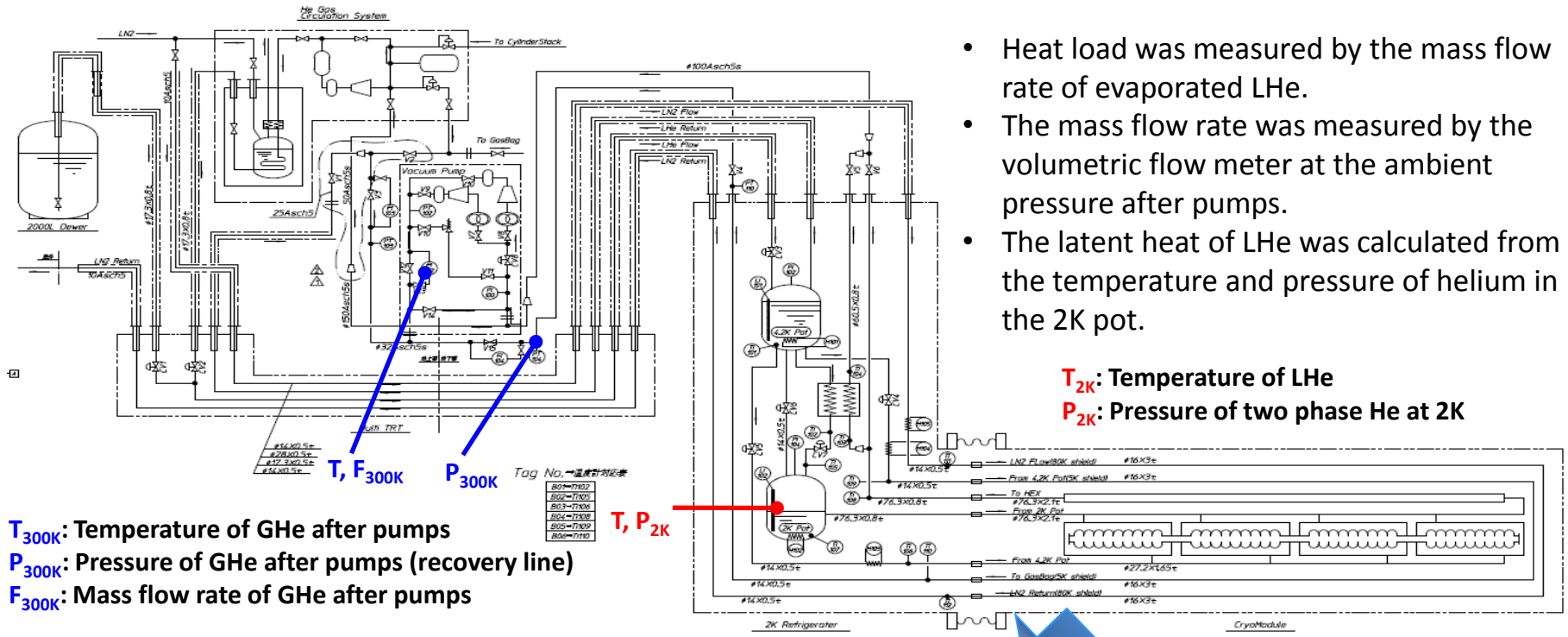
Introduction
(Planned thermal measurements)

- Heat load measurements
  - Heat loads of the modules were measured in order to compare the measured losses with those in RDR.
  - The static and dynamic losses were measured.
    - Static heat loss of Module A and C at 2 K, 2.5 K and 4 K.
    - Dynamic losses of DESY, FNAL and KEK cavities and input couplers
  - These losses were mainly measured by the flow rate of the evaporated 2K LHe.
- Temperature profile measurements in the cryomodules
  - The temperature profiles of the components were measured during all test period and these thermal data are analyzed for getting the heat losses of the components .
    - Cool-down and warm-up stages (two times)
    - Static and dynamic conditions of modules.
  - Temperatures were measured by the three types of thermal sensors of Cernox and Pt-Co resistance thermometers and Copper-Constantan thermo-couples.

Overall test schedule (thermal measurements)

2010 June	July	Aug.	Sept.	Oct.	Nov.	Dec.	2011 Jan.	Feb.
June 8 : The 1st cool-down started. June 16-17 : Static loss meas. at 4K. June 18 : Cool-down to 2K.	July 12-16 : Static loss meas. at 2K. Warm-up and maintenance		Sept. 6 : The 2nd cool-down started. Sept. 16-17 : Static loss meas. at 4K and cool-down to 2K. Sept. 28- : High grad. tests	-Oct. 22 : High grad. Tests and Lorentz detuning.	Nov. 8-12: Lorentz detuning. Nov. 16-Dec.10 : Dynamic loss meas.	Dec. 20-24: Static loss meas. Warm-up	Jan. 18 : The 3rd cool- down started.	DFRS tests

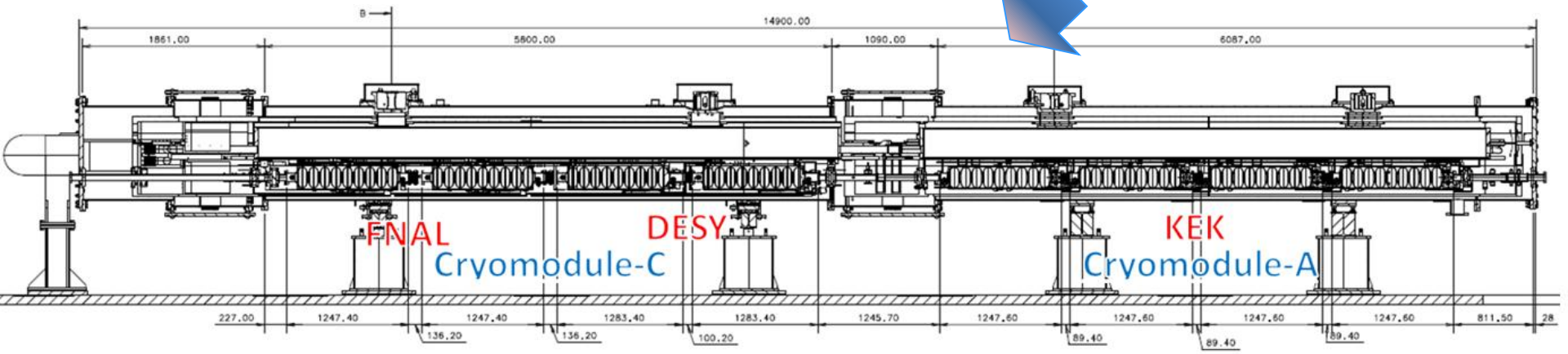
Static loss measurement



- Heat load was measured by the mass flow rate of evaporated LHe.
- The mass flow rate was measured by the volumetric flow meter at the ambient pressure after pumps.
- The latent heat of LHe was calculated from the temperature and pressure of helium in the 2K pot.

T_{2K}: Temperature of LHe
P_{2K}: Pressure of two phase He at 2K

T_{300K}: Temperature of GHe after pumps
P_{300K}: Pressure of GHe after pumps (recovery line)
F_{300K}: Mass flow rate of GHe after pumps



Test schedule (Static loss measurements)

July 12	July 13	July 14	July 15	July 16
1. Heat loss meas. of S1G module and 2 K pot @ 2.5 K. 2. Cooling the S1G module to 2K.	1. Heat loss meas. of S1G module and 2 K pot @ 2.5 K. 2. Heat loss meas. of S1G module and 2 K pot @ 2 K. 3. Calibration meas. by heater.	1. Heat loss meas. of S1G module and 2 K pot @ 2.5 K. 2. Heat loss meas. of S1G module and 2 K pot @ 2 K. 3. Calibration meas. by heater.	1. Heat loss meas. of S1G module and 2 K pot @ 2 K. 2. Heat loss meas. of S1G module @ 2 K by evaporating all LHe in 2 K pot. 3. Heat loss meas. of S1G module and 2 K pot @ 2 K (reproducibility).	1. re-cooling the S1G module to 2 K. 2. Heat loss meas. of S1G module and 2 K pot @ 2 K (reproducibility).

Module-A had windows for laser position sensors, which were able to see from 300 K to 2 K.

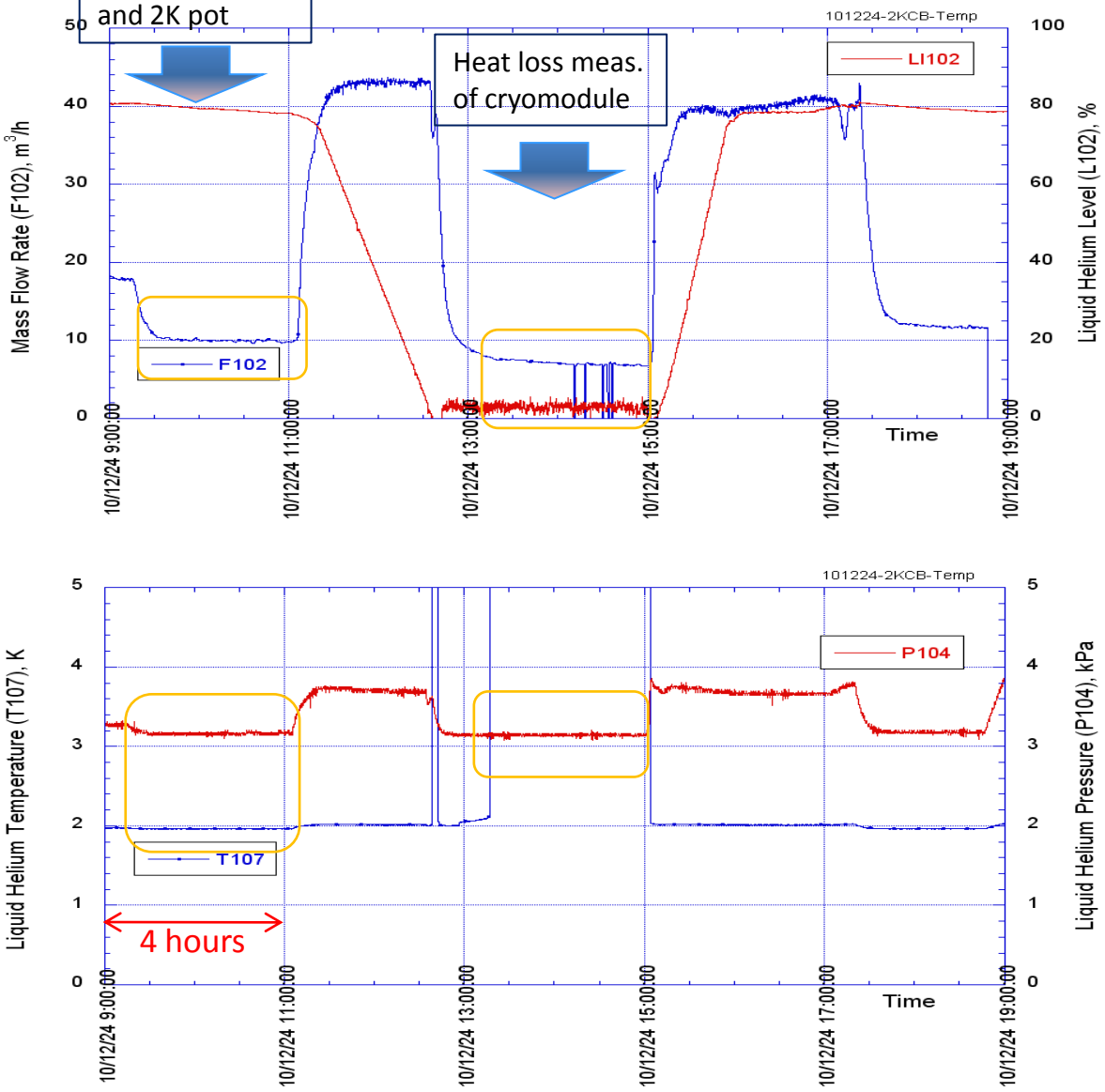
Non-stop 2K cooling

Dec. 20	Dec. 21	Dec. 22	Dec. 23	Dec. 24
1. Cooling cavities to 2 K.	1. Heat loss meas. of S1G module and 2 K pot @ 2.5 K. 2. Heat loss meas. of S1G module and 2 K pot @ 2 K. 3. Calibration meas. by heater.	1. Heat loss meas. of S1G module and 2 K pot @ 2.5 K. 2. Heat loss meas. of S1G module and 2 K pot @ 2 K. 3. Calibration meas. by heater.	1. Heat loss meas. of S1G module and 2 K pot @ 2 K. 2. Heat loss meas. of S1G module @ 2 K by evaporating all LHe in 2 K pot.	1. Heat loss meas. of S1G module and 2 K pot @ 2 K. 2. Heat loss meas. of S1G module @ 2 K by evaporating all LHe in 2 K pot. 3. Heat loss meas. of S1G module and 2 K pot @ 2 K (reproducibility).

The windows of Module-A were closed.

Non-stop 2K cooling

Measured static heat loss at 2 K



Measured static heat loss

- Cryomodule and 2 K pot
  - 10.4 W [Average: 10:00~11:00]
    - Mass flow rate= 0.453 g/s
    - Temperature = 1.96 K
    - Pressure = 3.17 kPa
- Cryomodule
  - 7.2 W [Average: 14:00~15:00]
    - Mass flow rate= 0.314 g/s
    - Temperature = NA (No liquid)
    - Pressure = 3.14 kPa

Summary of static heat loss measurements

	Cryomodule + 2 K pot	Cryomodule + 2 K pot	Cryomodule
Temperature	2.5 K	2 K	2 K
1st cool-down (Date)	11.8 W (2010.7.14)	11.4 W (2010.7.15)	7.5 W (2010.7.15)
2nd cool-down (Date)	11.4 W (2010.12.22)	10.4 W (2010.12.24)	7.2 W (2010.12.24)

Calculated heat loads to cavities

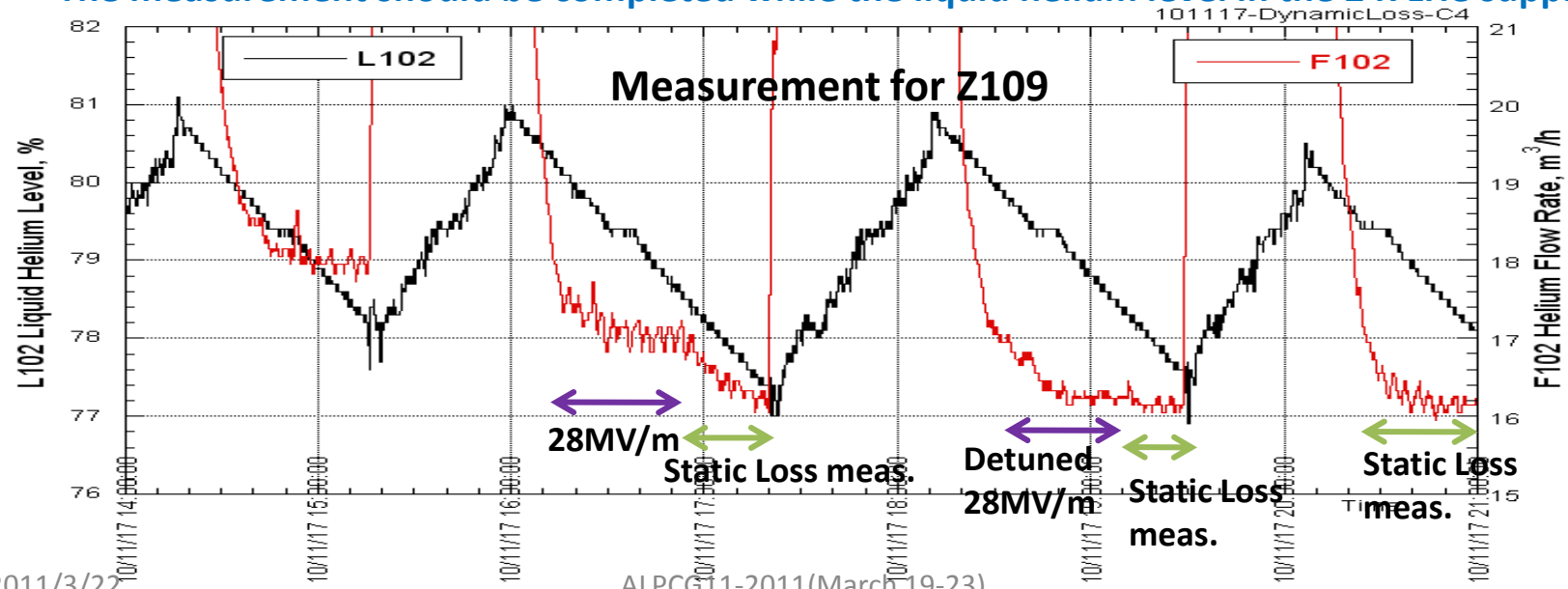
	Module-A	Module-C
Four cavities (wires of temp. sensors)	0.18	0.18
Four cavities (WPM wires)	0.90	0.0
Four cavities (Pin diode wires)	0.82	0.82
WPM connection pipe to the end flange	0.17	~0.0
Four tuner driving shafts	0.48	0.0
HOM RF cables	1.24	0.02
Piezo cables, etc.	0.84	0.03
Four input couplers	0.29	0.25
Thermal radiation (from 5 K shield)	~0.0	~0.0
Total of each module	4.92	1.30
Total	6.22	

Wires of temperature sensors on the cavities : wire dimension = (ϕ0.15mm $\times$ 7) $\times$ 112, L=12.5 m, no thermal intercept.
Wires of WPM and Pin Diode : HUBER+SUHNER RG_178_B/U, Cross section of Cu=0.8482mm2 and Fe=0.0755mm2, L=5m (The actual length is 10m, but the part which has temperature gradient for conducting heat is 5m.), and 32 cables.

Dynamic loss measurement-1

- Dynamic loss was measured as follows:
  - Dynamic loss measurement : Q_{D1}
  - Static loss measurement after the operation of cavities : Q_{S1}
  - Dynamic loss measurement at the detuned condition : Q_{D2}
  - Static loss measurement after the operation of cavities : Q_{S2}
    - **Dynamic loss at cavities and couplers : $Q_D = Q_{D1} - Q_{S1}$**
    - **Dynamic loss at detuned condition : $Q_{D\text{-}det} = Q_{D2} - Q_{S2}$**
    - **Dynamic loss at cavities : $Q_{D\text{-}cav} = Q_D - Q_{D\text{-}det}$**

The measurement should be completed while the liquid helium level in the 2 K LHe supply line.



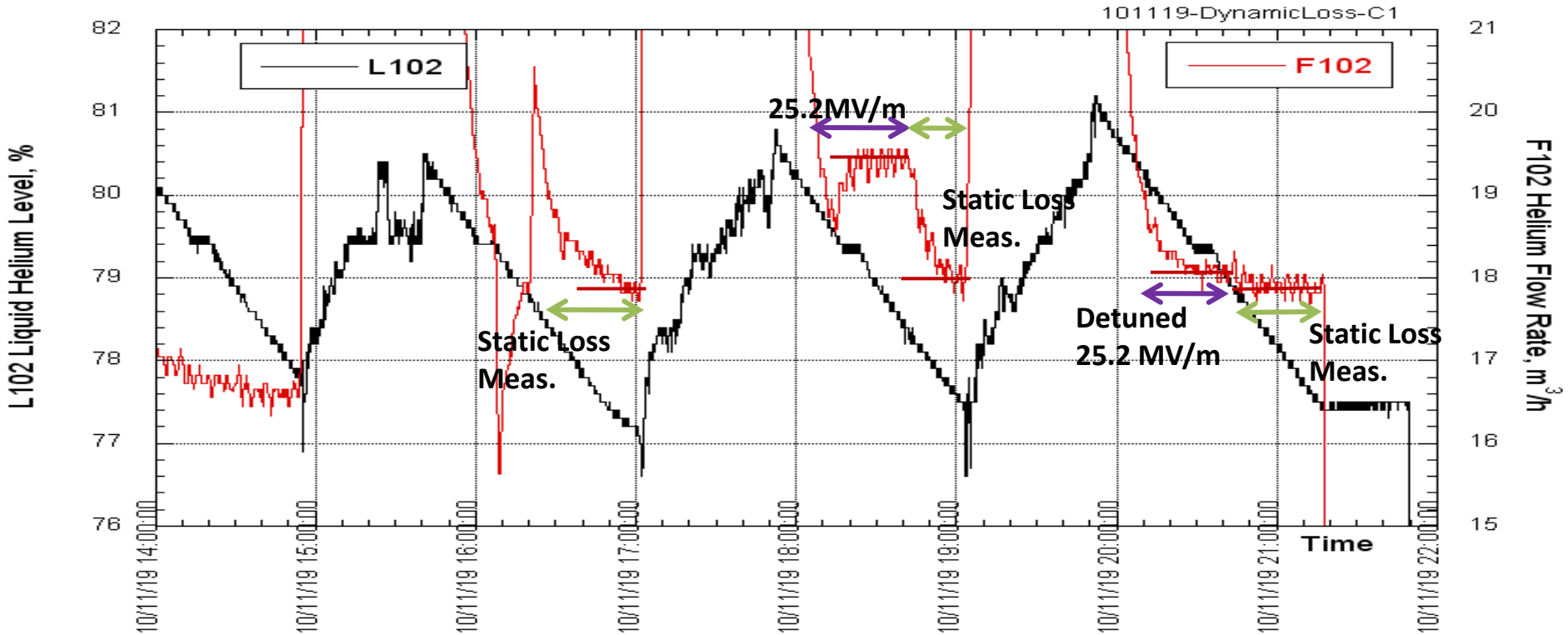
Dynamic loss measurements-2

- Dynamic losses of all cavities were planed to be measured, however, by troubles of the power supply and the cryogenic system, two cavities in each Module were tested at the continuously operational maximum gradient over one hour.
  - C-4 (Z109): 28 MV/m
  - C-1 (AES004): 25.2 MV/m
  - A-3 (MHI07): 32.3 MV/m
  - A-2 (MHI06): 38 MV/m, 32 MV/m
- Four cavities in each module were operated at the same time, and the dynamic losses were measured.
  - Module-C (AES004, ACC011, Z108, Z109) at the average gradient of 20 MV/m
  - Module-A (MHI05, MHI06, MHI07, MHI09) at the average gradient of 26.9 MV/m
- Seven cavities in S1-G cryomodule were operated at the same time, and the dynamic losses were measured.
  - 7 cavities (AES004, Z108, Z109, MHI05, MHI06, MHI07, MHI09) at 25.4 and 20.4 MV/m
- Four cavities in each module were operated under the detuned condition of 32 MV/m.

Summary of dynamic loss measurements

	C-4 Z109	C-1 AES004	A-3 MHI07	A-2 MHI06	A-2 MHI06	4 C Cavities	4 A Cavities	4 C Cavities	4 A Cavities	7 Cavities	7 Cavities
Date	Nov. 17	Nov. 19	Nov. 23	Nov. 24	Nov. 25	Nov. 26	Nov. 30	Dec. 2	Dec. 3	Dec. 9	Dec. 10
Gradient, MV/m	28	25.2	32.3	38	32	32 Detune	32 Detune	20 .0 Average	26.9 Average	25.4 Average	20.4 Average
Q_D, W	0.84	1.4	2.8	4.8	2.6			2.7	6.9	9.6	4.8
$Q_{D\text{-}det}$, W	0.09	0.18	0.7	1.8	1.2	0.5	4.6	0.2	2.5	2.6	1.6
$Q_{D\text{-}cav}$, W	0.8	1.3	2.0	2.9	1.3			2.5	4.4	7.0	3.2
Q_0	8.8E9	4.3E9	4.3E9	4.2E9	6.5E9						
								C1=22.2 C2=18.9 C3=14.9 C4=24.3	A1=15.8 A2=37.6 A3=32.9 A4=21.4	C1=25.2 C2=NA C3=17.6 C4=28.8 A1=15.3 A2=37.4 A3=32.4 A4=20.9	C1=20.1 C2=NA C3=14.1 C4=23.0 A1=12.3 A2=30.4 A3=26.0 A4=16.7

C1(AES004) dynamic loss measurement



Q_{D1} @ 25.2 MV/m = 20.58 W

Q_{S1} = 19.14 W

$Q_D = Q_{D1} - Q_{S1}$ = 1.44 W

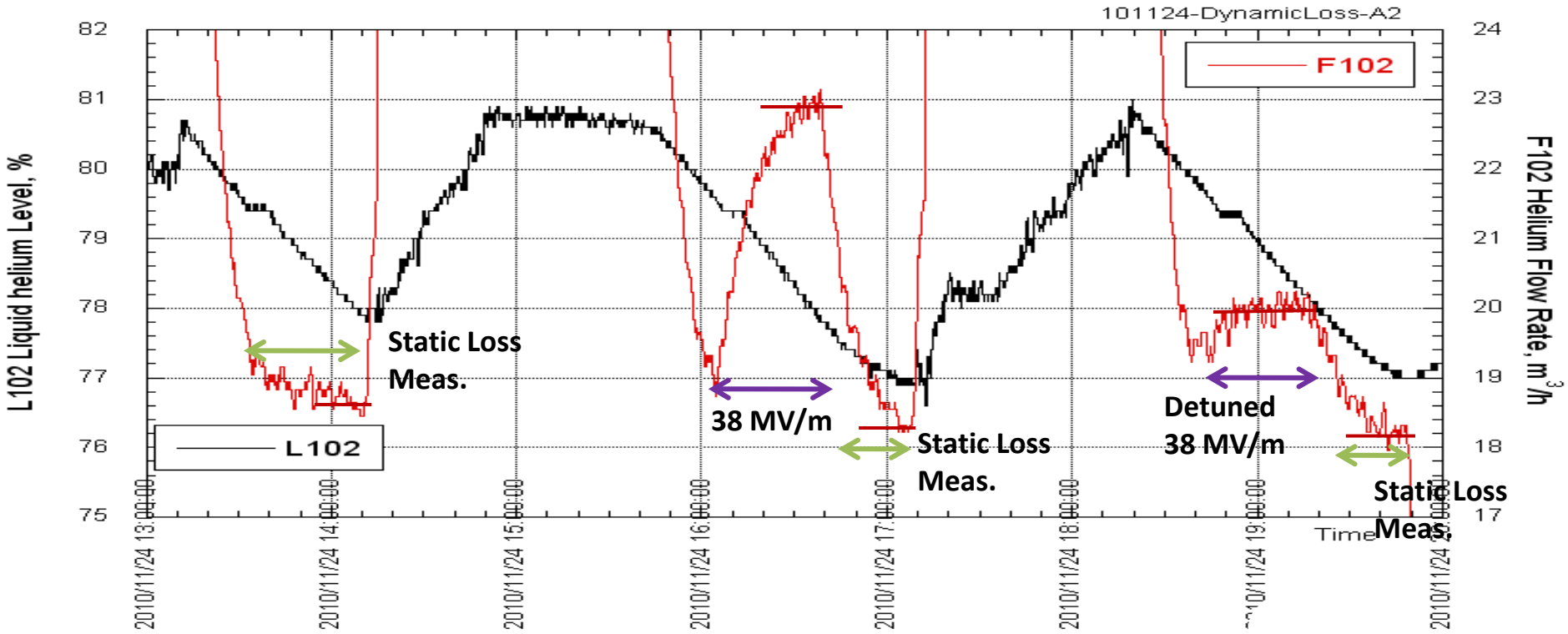
Q_{D2} @ 25.2 MV/m = 19.16 W

Q_{S2} = 18.99 W

$Q_{D\text{-}det} = Q_{D2} - Q_{S2}$ = 0.17 W

$Q_{D\text{-}cav}$ @ 25.2 MV/m = 1.3 W

A2(MHI06) dynamic loss measurement



Q_{D1} @ 38 MV/m = 24.29 W

Q_{S1} = 19.52 W

$Q_D = Q_{D1} - Q_{S1}$ = 4.77 W

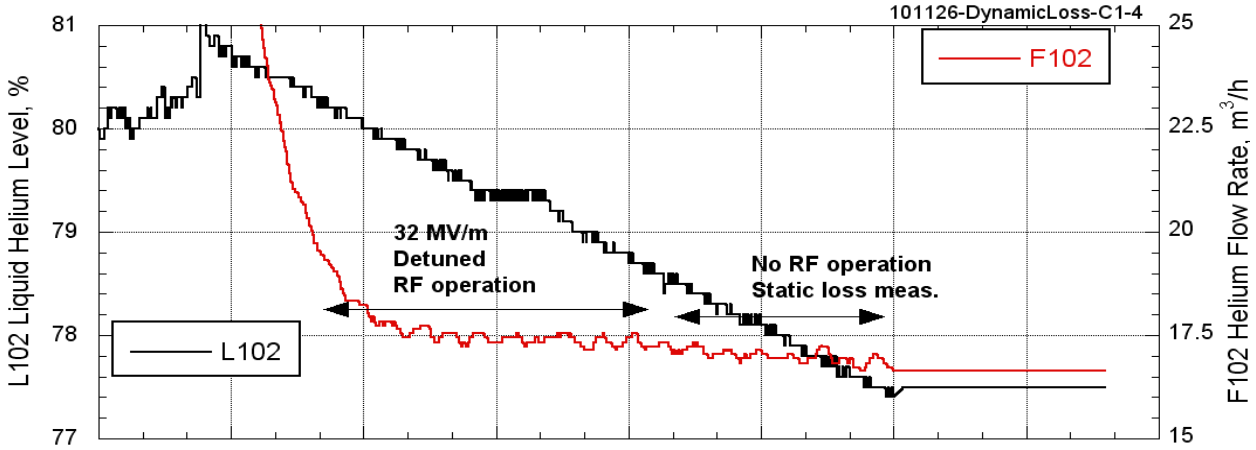
Q_{D2} @ 38 MV/m = 21.20 W

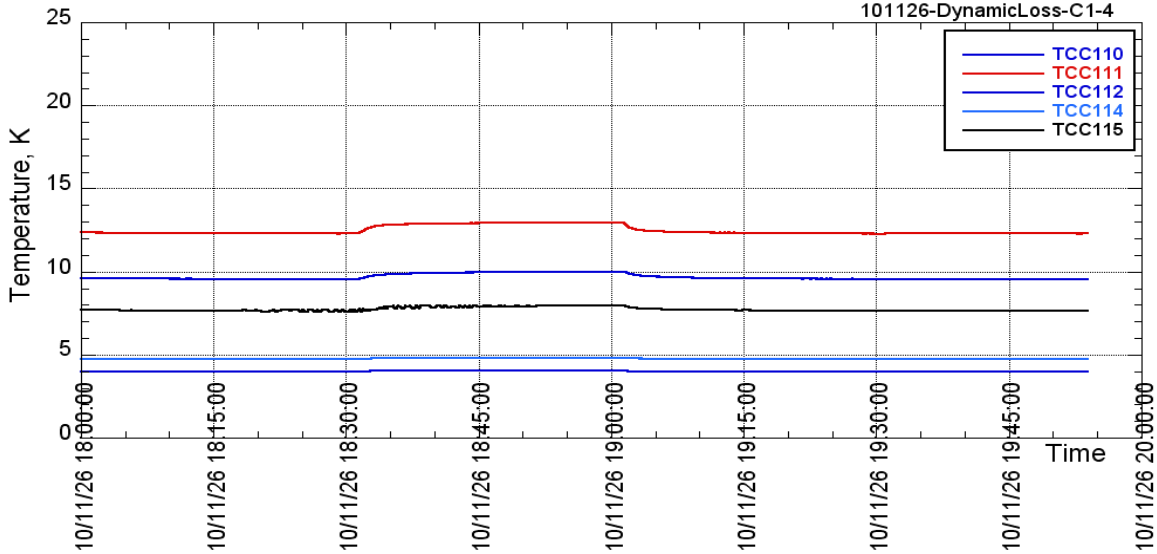
Q_{S2} = 19.36 W

$Q_{D\text{-}det} = Q_{D2} - Q_{S2}$ = 1.84 W

$Q_{D\text{-}cav}$ @ 38 MV/m = 2.9 W

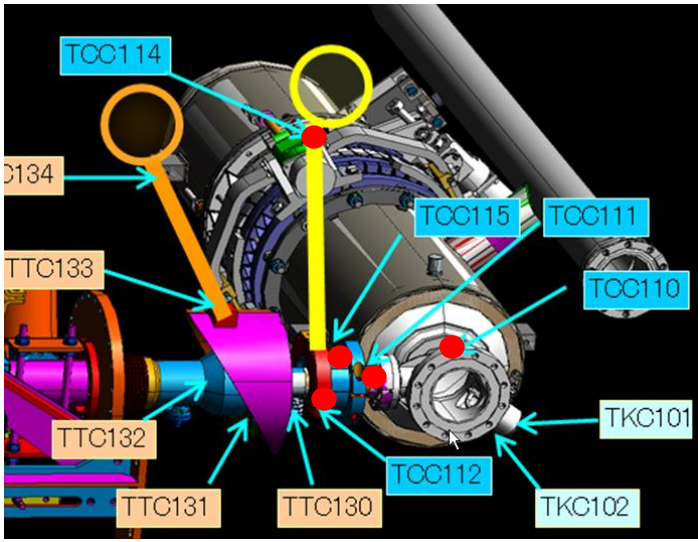
Module-C heat loss measurement at 32 MV/m detuned condition (four cavities)



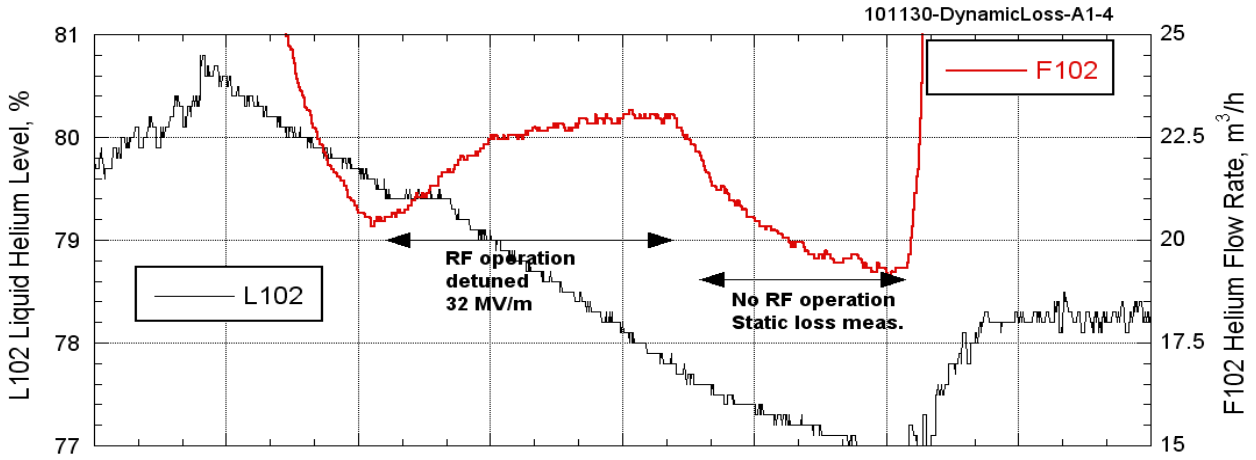


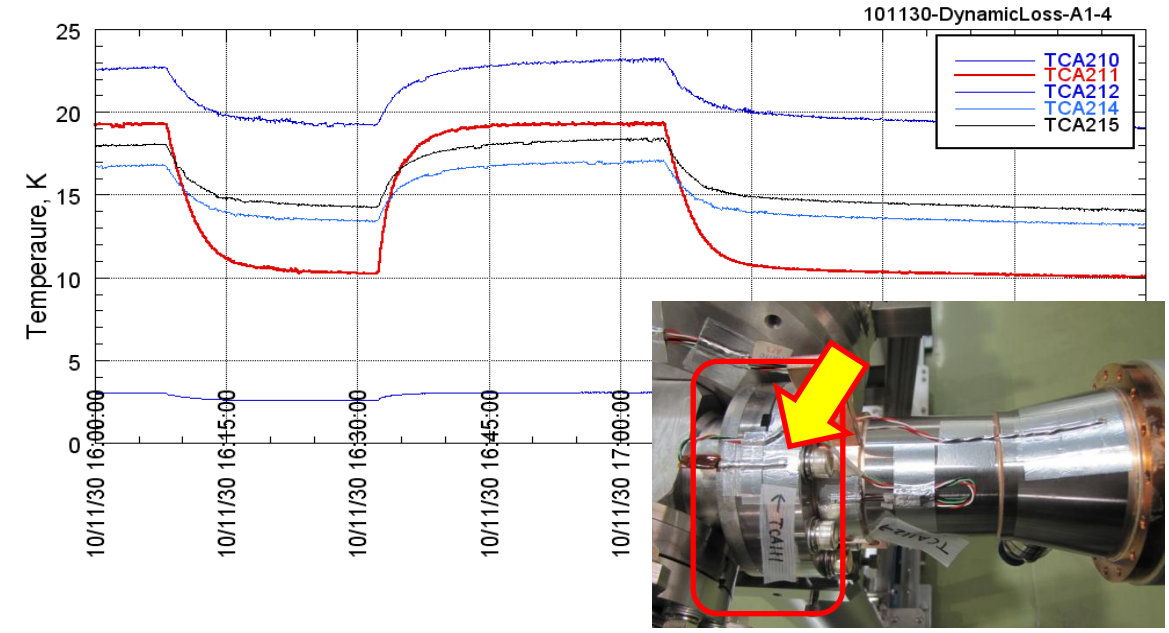
Q_{D2} = 18.42 W
Q_{S2} = 17.92 W
$Q_{D\text{-}det}$ = 0.5 W

ΔTCC110= 0.03 K
ΔTCC111= 0.61 K
ΔTCC112= 0.42 K
ΔTCC114= 0.09 K
ΔTCC115= 0.28 K



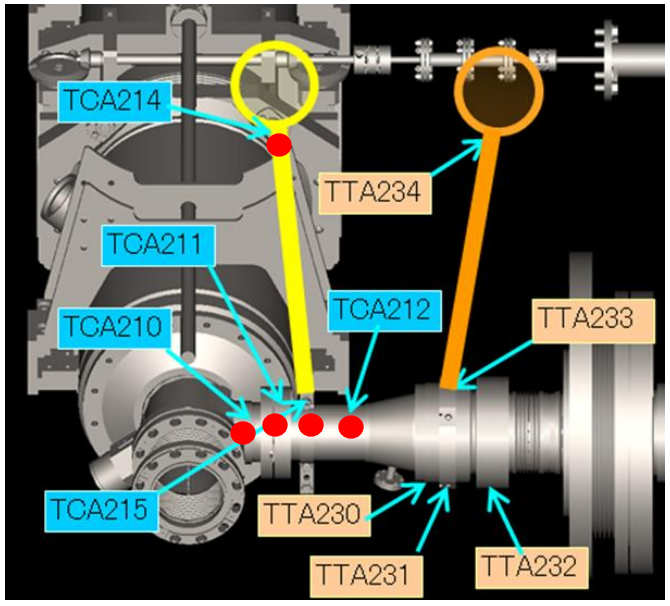
Module-A heat loss measurement at 32 MV/m detuned condition (four cavities)





Q_{D2} = 24.38 W
Q_{S2} = 19.77 W
$Q_{D\text{-}det}$ = 4.6 W

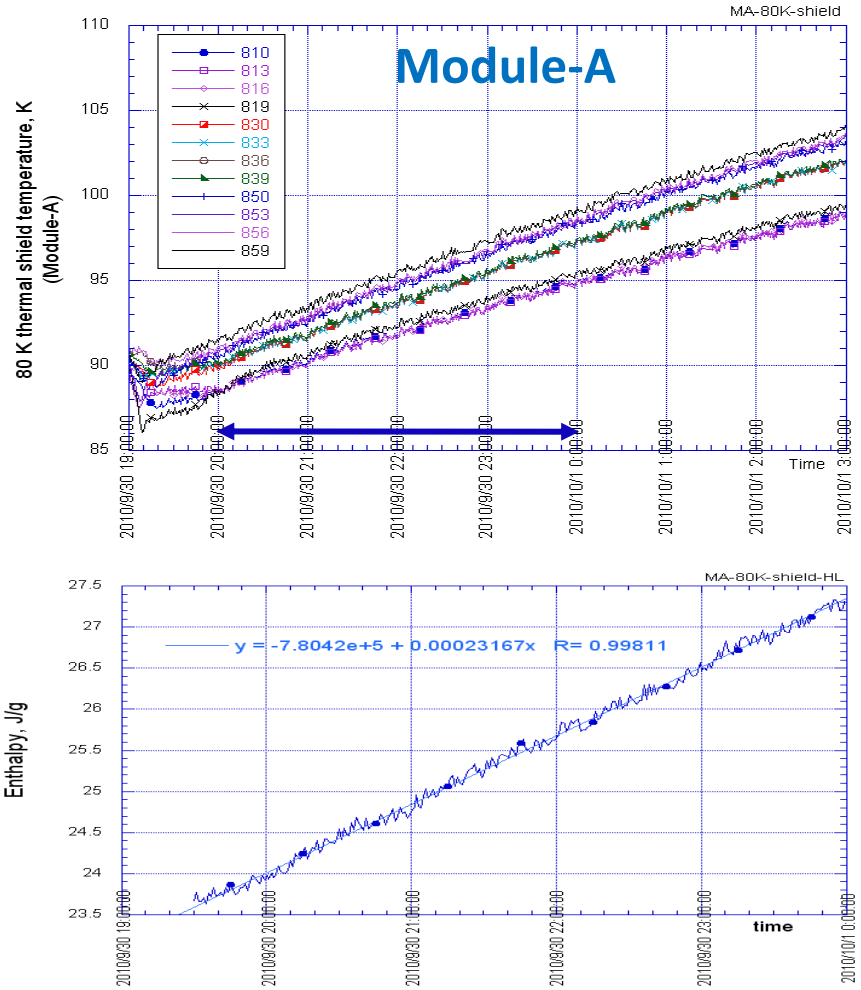
ΔTCA210= 0.49 K
ΔTCA211= 9.05 K
ΔTCA212= 3.92 K
ΔTCA214= 3.59 K
ΔTCA215= 4.13 K



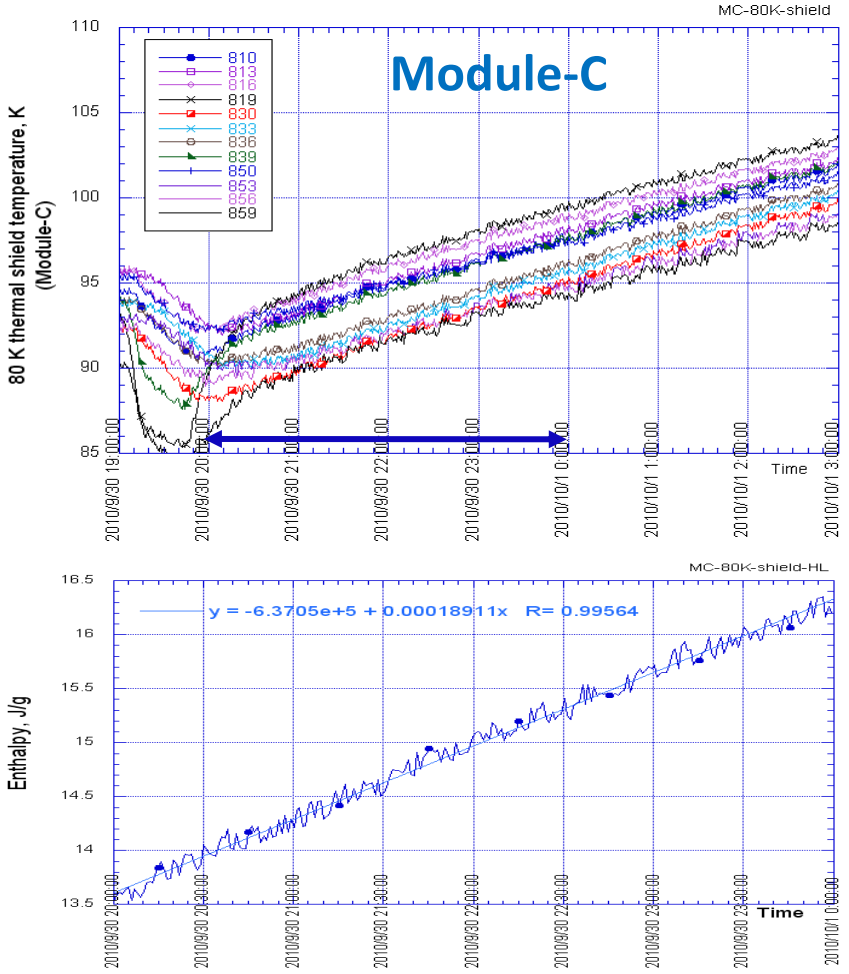
Temperature profile in S1-G cryomodule

- Temperature profiles of the components were measured during the cool-down and warm-up of S1-G cryomodule, and the heat load measurements.
- The measured temperature profiles are compared with thermal calculation of the components.
- Temperature sensors for Module-A and C:
  - Cernox (2K – 100K) : 54
  - Calibrated carbon resistor (2K – 100K) : 32
  - PtCo (2K – 300K) : 53
  - Cu-Constantan thermocouple (70K – 300K) : 75
    - Cavities : 104
    - GRPs : 16
    - Support posts : 20
    - Thermal shields : 59
    - Cooling channels and beam pipes : 15

Heat loads on 80 K thermal shields

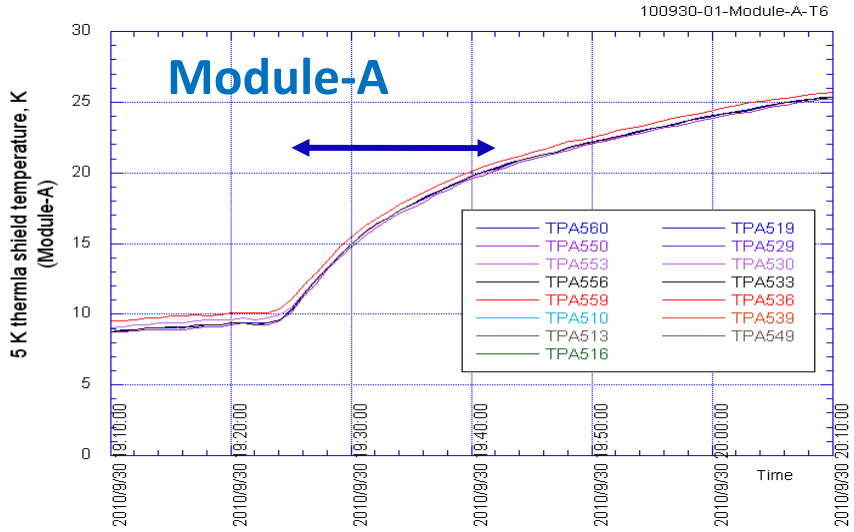


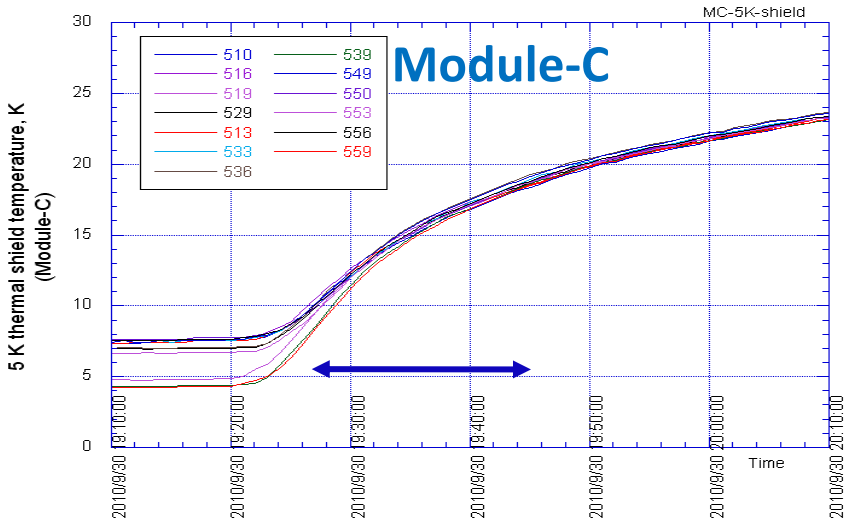
Cold mass=210 kg
Heat load= 48.7 W

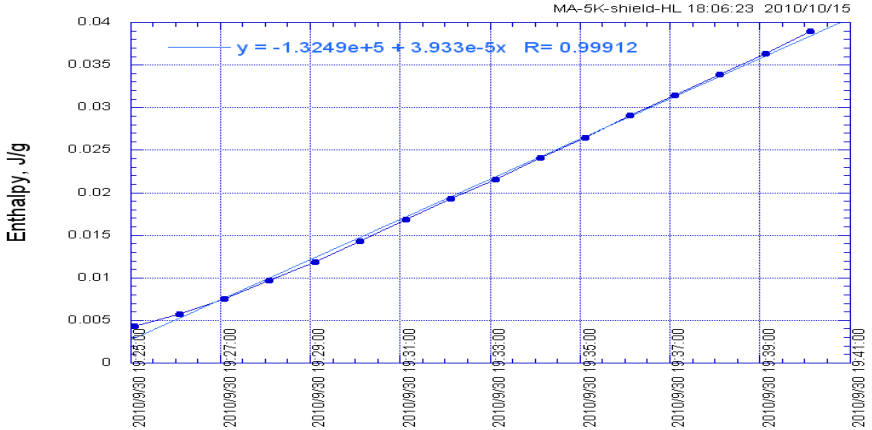


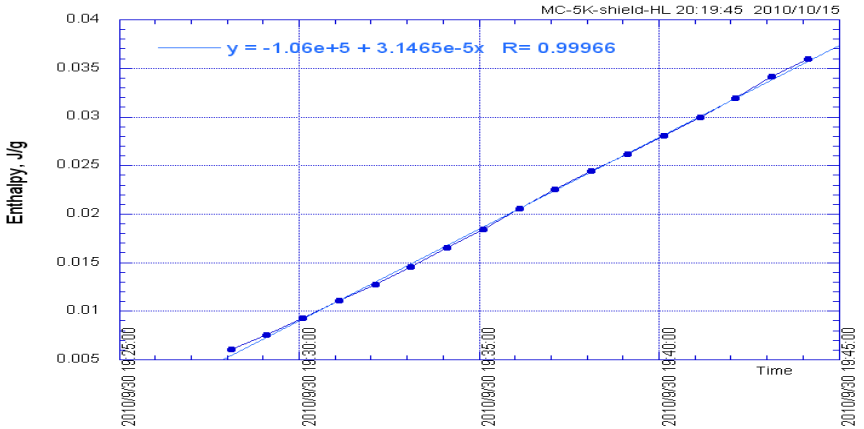
Cold mass=182 kg
Heat load= 34.4 W

Heat loads on 5 K thermal shields





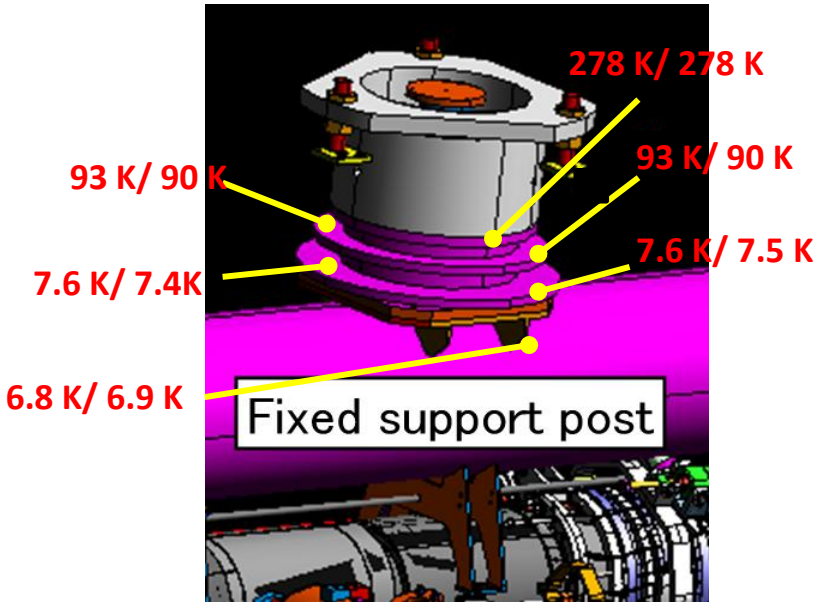


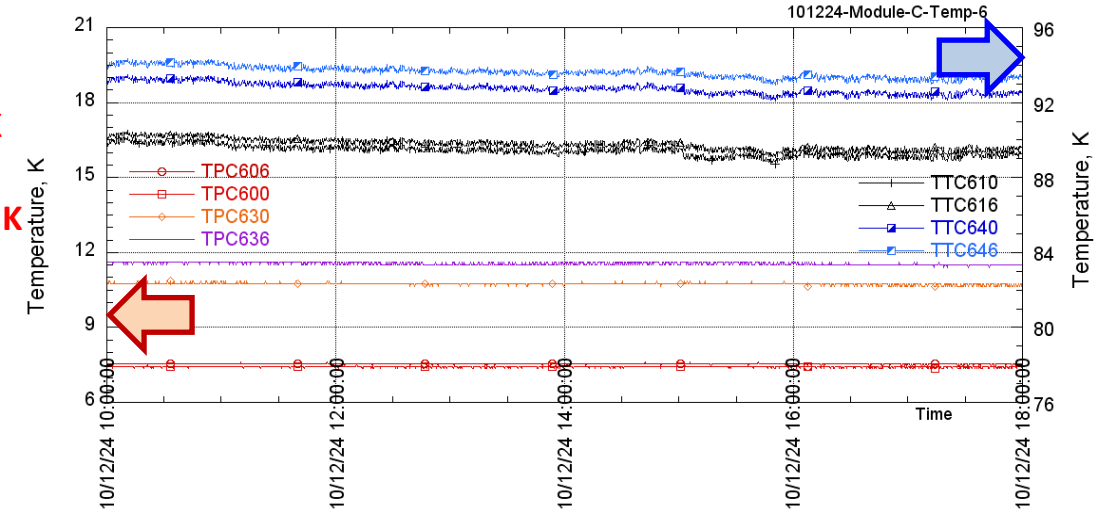


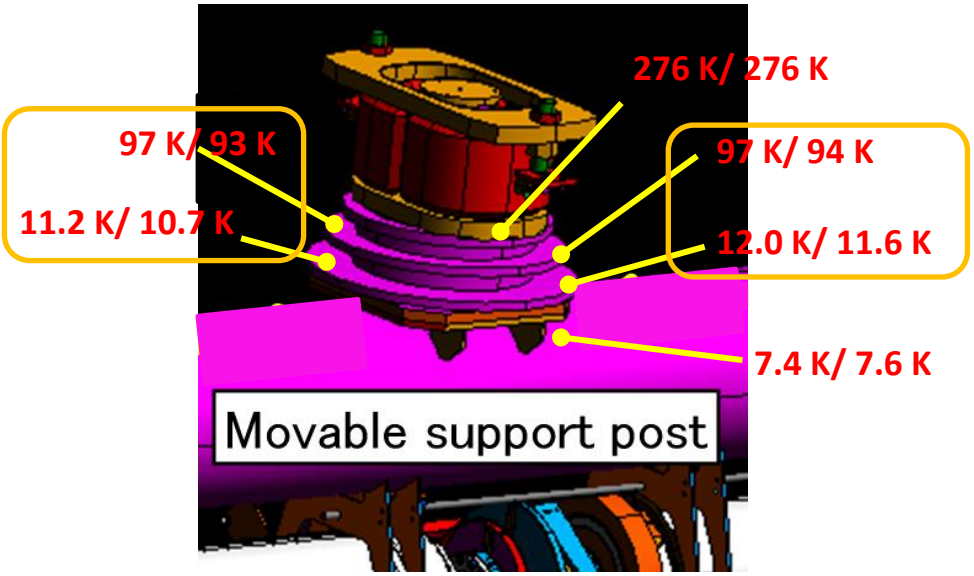
Cold mass=185 kg
Heat load= 7.3 W

Cold mass=167 kg
Heat load= 5.3 W

Temperature profile of Module-C support posts (July 15/Dec. 24)





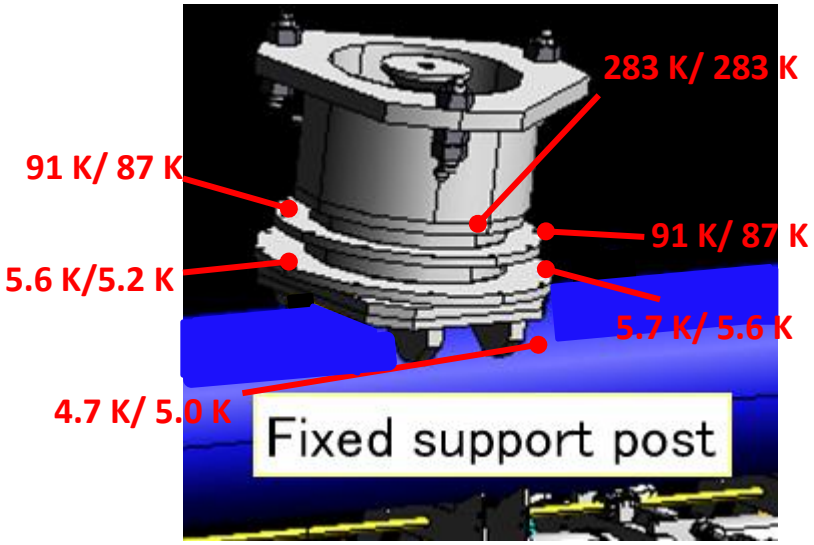


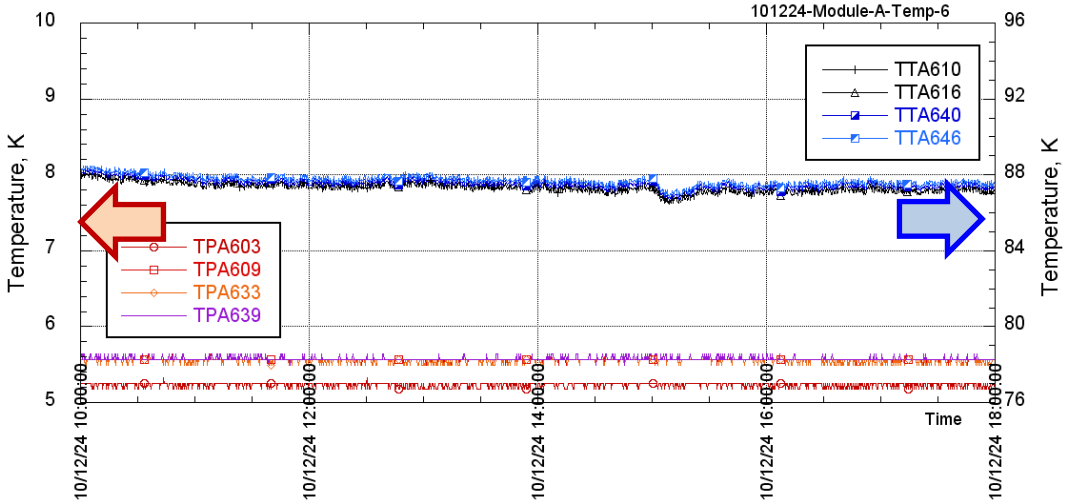
Heat loads of support posts, W

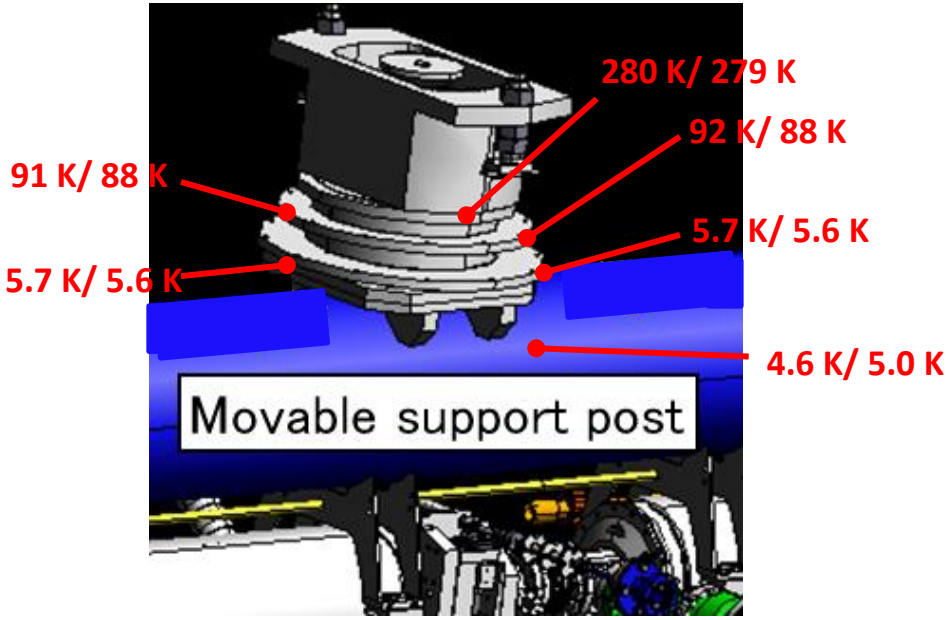
	Fixed	Movable
80 K	4.7	4.2
5 K	0.88	0.88
2 K	0.24	0.42

(Rough calculation)

Temperature profile of Module-A support posts (July 15/Dec. 24)







Heat loads of support posts, W

	Fixed	Movable
80 K	4.9	4.4
5 K	0.87	0.88
2 K	0.15	0.16

(Rough calculation)

Summary - 1

1. The S1-G cryomodule (Module-C and Module-A) was successfully cooled down to 2K and the thermal performances of different types of components were measured under the same thermal conditions.
2. The static heat loss to the eight cavities at 2 K was measured.
   - Measured static heat loss = 7.2 W, estimated static heat loss = 6.2 W
   - By calculation (excluding heat loss via signal wires), heat loss at four 2 K cavities:
     - Four cavities in Module-A = 2.85 W
     - Four cavities in Module-C = 0.3 W
     - Main source of static heat loss in Module-A was HOM RF cables.
3. The static heat losses at 80 K and 5 K were measured by temperature rise of thermal shields.
   - Heat loss at 80 K:
     - Module-A = 49 W, Module-C = 34 W
   - Heat loss at 5 K:
     - Module-A = 7.3 W, Module-C = 5.3 W
4. Flange temperatures of the movable support post in Module-C was 4 K higher than those of the other posts.
   - Need to strengthen the thermal intercepts for this post.

Summary - 2

5. Dynamic loss measurements
   - Dynamic losses of cavities were measured by the flow rate of evaporated LHe, and Q_0 was calculated.
     - Z109 : $Q_0 = 8.8\times10^9$ at 28 MV/m,
     - AES004 : $Q_0 = 4.3\times10^9$ at 25.2 MV/m,
     - MHI-06 : $Q_0 = 4.2\times10^9$ at 38 MV/m, $Q_0 = 6.5\times10^9$ at 32 MV/m,
     - MHI-07 : $Q_0 = 4.3\times10^9$ at 32.3 MV/m.
6. Dynamic loss measurement at 32 MV/m under the detuned condition
   - Heat loss of four input couplers at 32 MV/m:
     - Module-A = 4.6 W, Module-C = 0.5 W
   - Heat might be generated in the connection flanges of KEK input couplers.
     - The flange temperatures increased 9K.

Back-up slides

Measured static heat loss at 2.5 K