Cryostat performance

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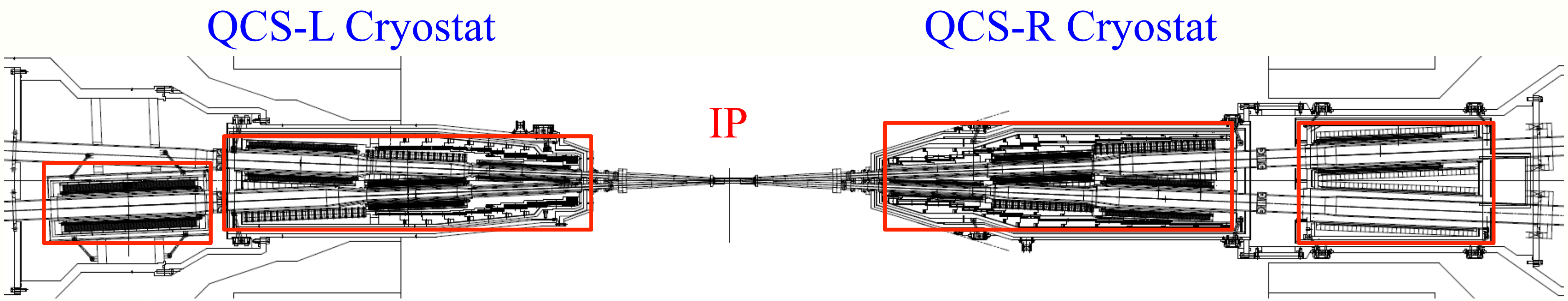
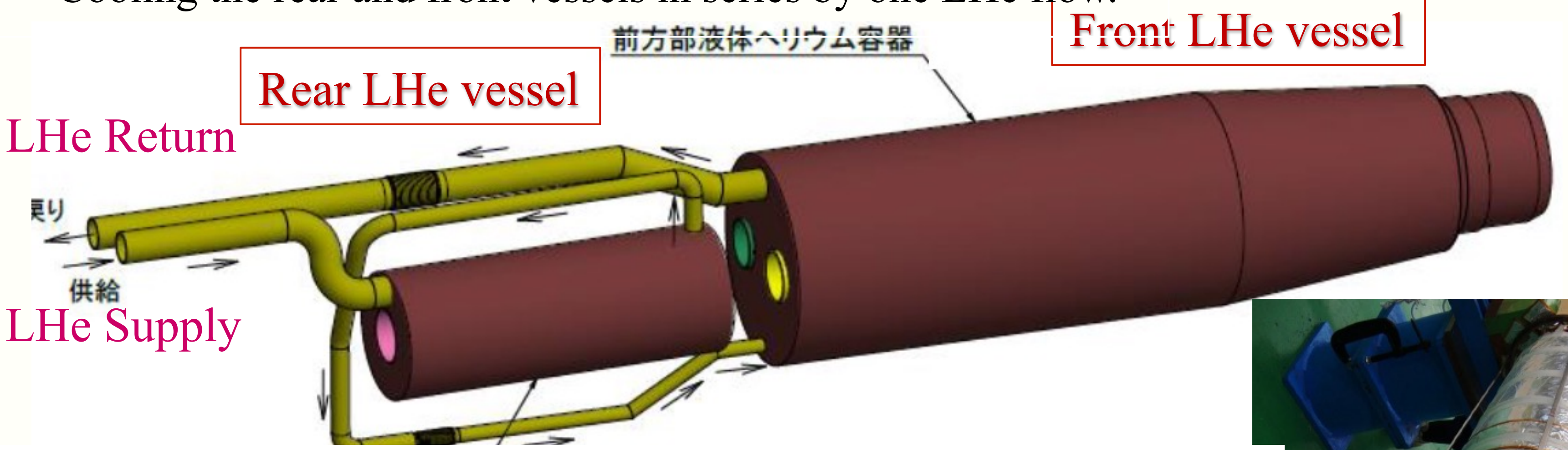
SC magnets and cryostats of the SuperKEKB IR



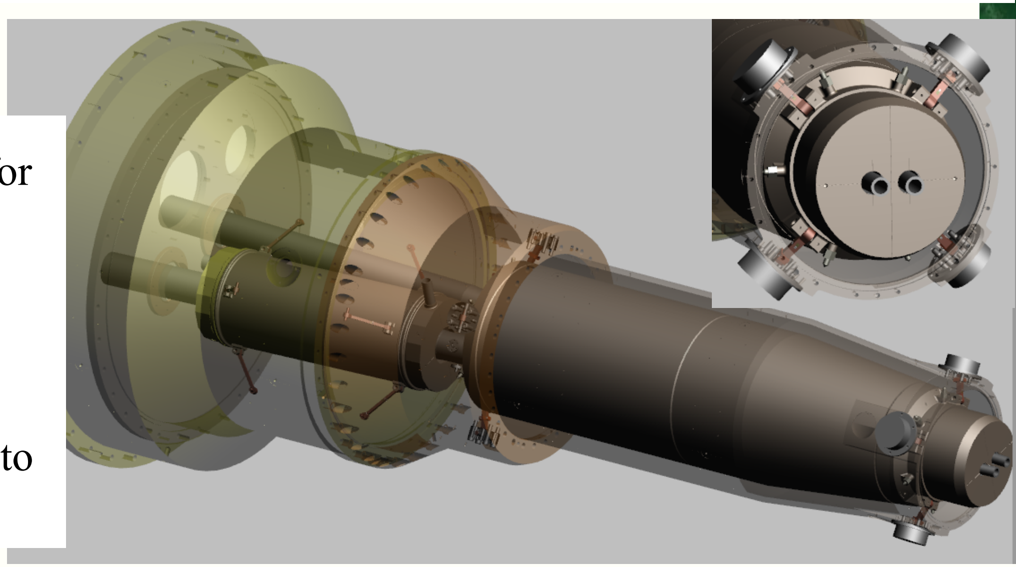
Cryostats	QCS-L		QCS-R	
Helium vessels	Rear	Front	Front	Rear
Main quadrupoles	QC2LE	QC1LP QC2LP QC1LE	QC1RP QC2RP QC1RE	QC2RE
Compensation solenoids	-	ESL	ESR1	ES2/ES3
Correction/Cancel coils	4	16	19	4
Cold mass at LHe (kg)	273.5	1460	1981.3	1152.1

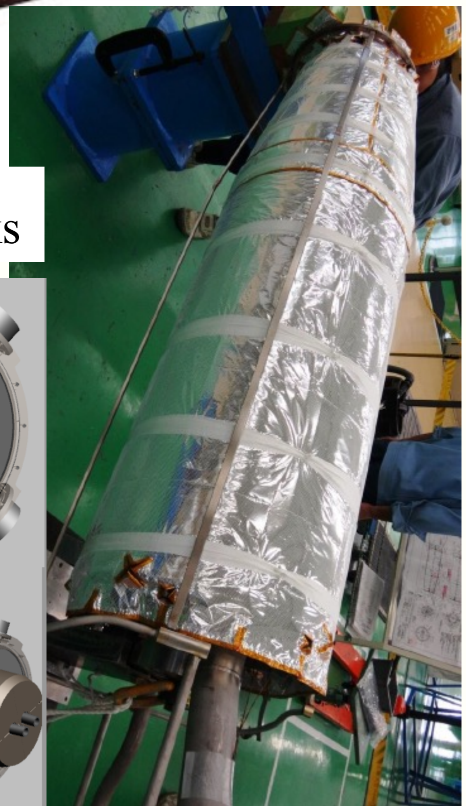
Cryostat of the SC magnets

- Cooling the rear and front vessels in series by one LHe flow.

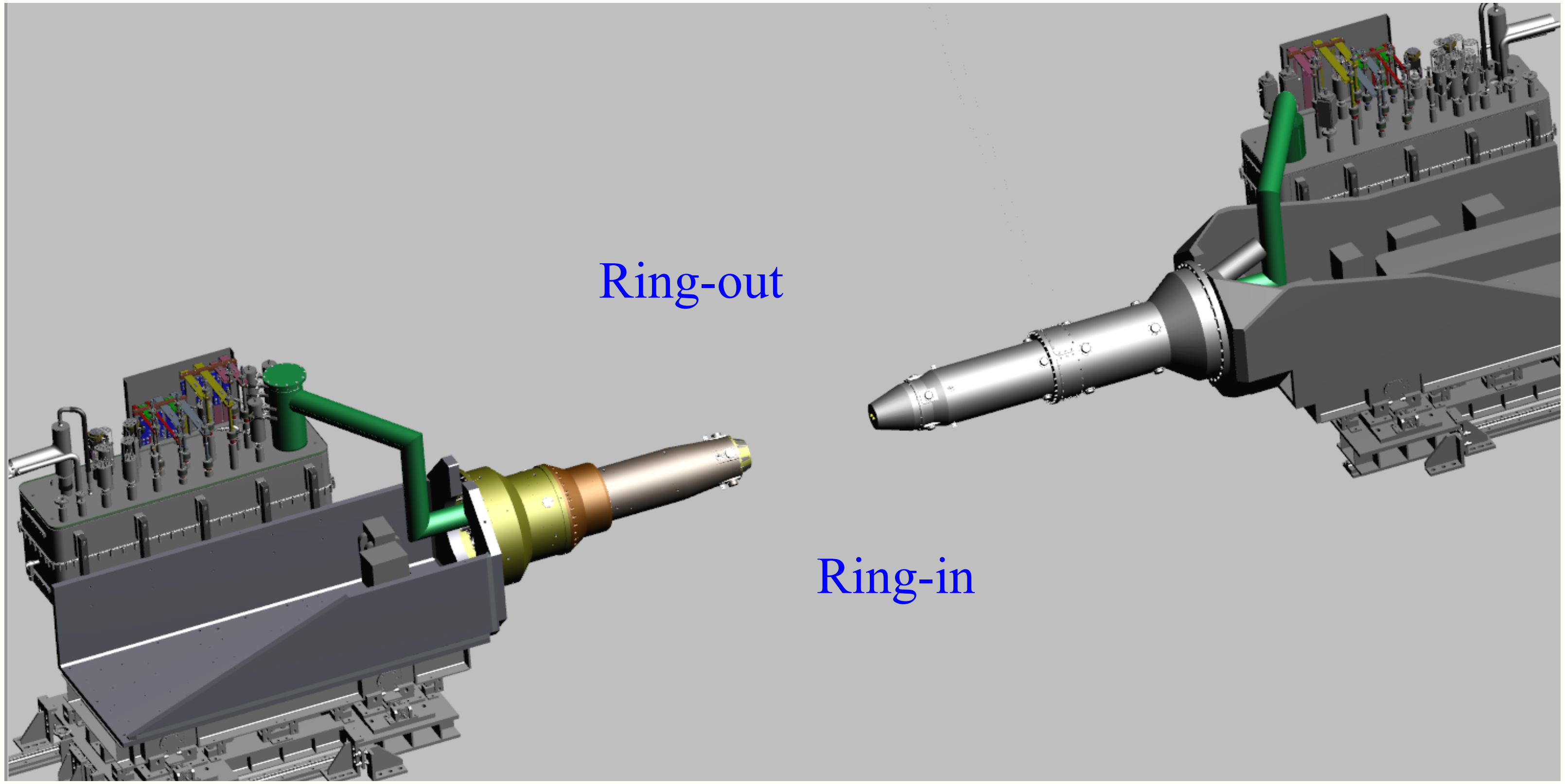


- Multi-layer insulation and LN_2 shields applied to intercept heat leaks
- Support rods
  - 8 rods/vessel (16 for each cryostat)
  - Made of Ti-6Al-4V(ELI)
  - Largest heat leaks to the LHe vessels





Service cryostats of the SuperKEKB IR SC magnets



Cryostats	QCS-L	QCS-R
Service cryostats	To access cryogenic multi-channel lines, and to accommodate cryogenic control valves, signal wires, current leads	

Cooling requirements of SC magnets

- Vapor cooled current leads for the SC magnets
  - Large lead number (**111 leads**) and total current (**33.1 kA to/from**): 51 leads for the left, 16.2 kA and 60 for the right to transfer 16.9 kA.
  - Rated at 2.0 kA, 1.8 kA, 1.35 kA, 1.0 kA, 450 A and 60 A, for the main quadrupoles, compensation solenoids and SC correction/cancel coils.
  - The leads with large currents were commercially supplied. The compact units were developed at KEK.

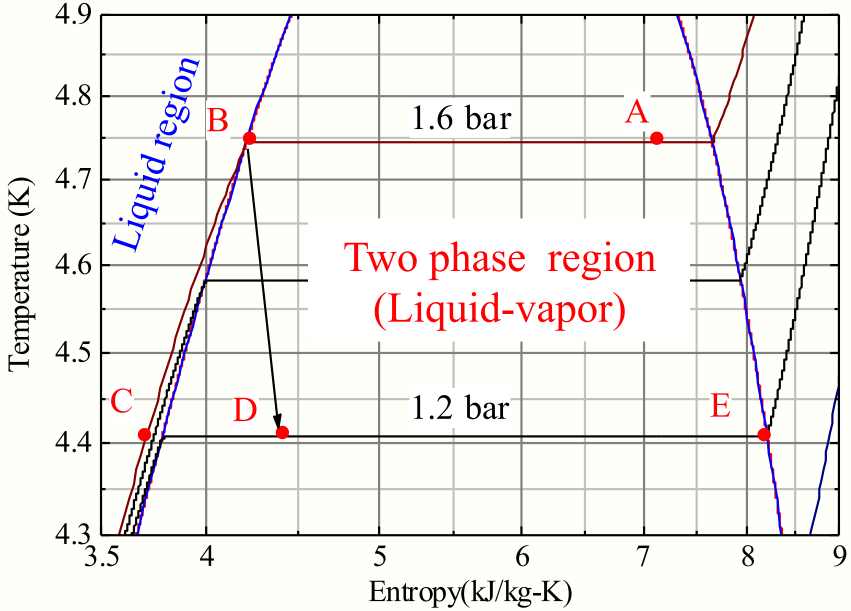
- Lead performance
  - Designed with the vapor cooled type.
  - Tested at the KEK lab with LHe before delivery to the factory.

Magnets		Unit	Solenoid	QC2P	QC2E	QC1P	QC1E	Corr./cancel coil
Current		kA	0.45	1.0	1.35	1.8	2.0	<0.070
Lead	NO.	-	8	4	4	4	4	70/16
	Type	-	Helium vapor cooled current lead (VCCL)					VCCL+HTS tape
Heat leak	Design	W	<0.72	<1.6	<2.16	<2.16	<2.4	<0.58(Ref.)
	Meas.	W	<0.63	<1.35	<1.84	<2.16	<2.3	<0.55/8-lead
Helium vapor	Design	g/s	0.031	0.068	0.089	0.106	0.117	0.027
		SLPM	10	22.9	29.9	35.6	39.3	9
	Meas.	SLPM	<10	<22.0	~30	~35.0	~37	<10
LHe	meas.	L/h	<0.86	<1.88	<2.14	~3.04	~3.32	0.77

  - Heat load for each side: <30 L/hour (LHe)

Cooling requirements of the SC magnet cryostats

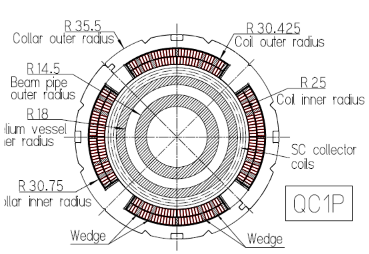
- Cooled by sub-cooled single phase LHe at the normal operation
  - The magnet cryostats were designed under the stringent space constraints, especially in the radial direction, and the annular helium channels in the cryostats are slim.
  - The cryostats are cooled by sub-cooled single-phase LHe, to avoid the instability of two-phase flow, and to exclude the occurrence of the helium vapor bubble.
  - Cryostat performance is very important because heats are absorbed by the sensible heat of the liquid helium (0.5 W/g/s, ΔT=0.1 K).
- The refrigerators and sub-coolers
  - The refrigerators supply a flow of 20 g/s at 1.6 bar and the sub-coolers cool the flow to ~4.4 K along the isobaric line.
  - In the cryostat, return from 4.4 K (Point C) to 4.74 K (Point B), (13.3–11.2) J/g*20 g/s= ~40 W, available for each cryostat.

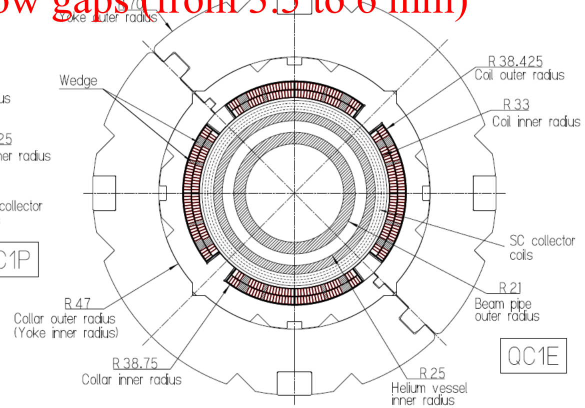


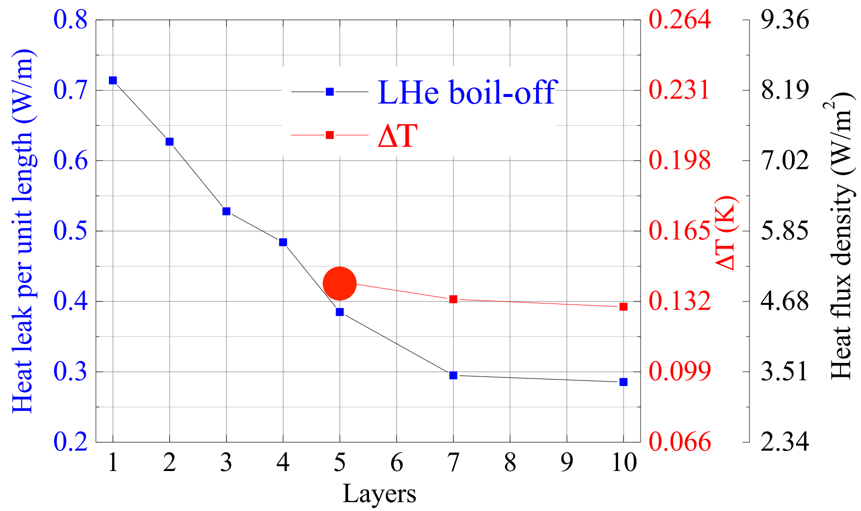
Heat leak estimations of the left cryostats

Items	Cold mass		Remarks
	Rear	Front	
Support rod (Thermal anchor: 110 K)	1.76	6.68	Ansys
Current lead pipe	-	-	Ansys
Thermal radiation from beam pipes	1.1	3.18	5 W/m^2
Thermal radiation from LN2 shields	0.3	0.9	0.5 W/m^2
Instrument signal wire	0.01	0.01	Estimation
Summary	3.17	10.77	13.94 W

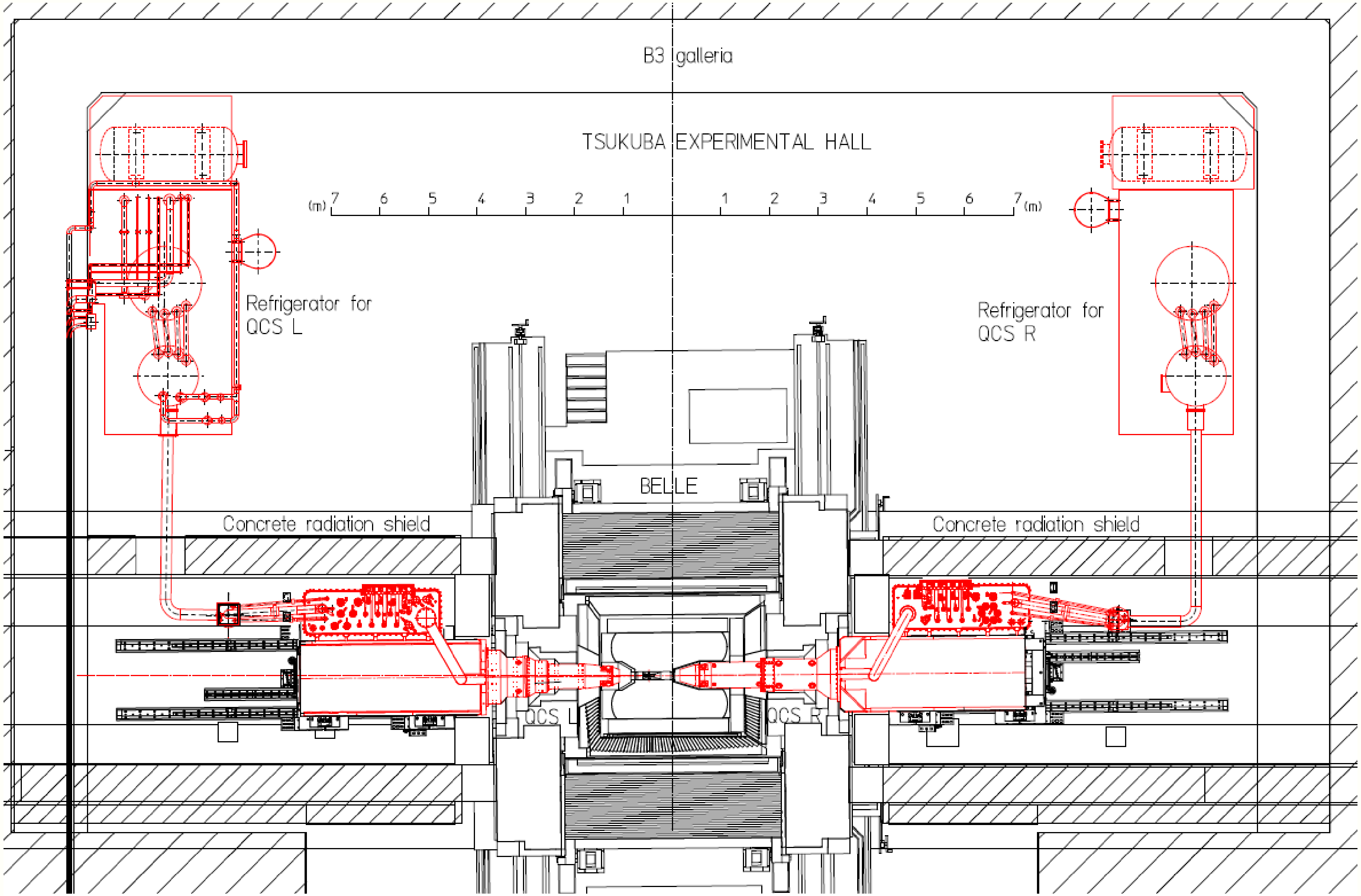
- Main heat leaks are from the support rods (~8.4 W)
- A source: thermal radiation from warm beam pipes (from ~300 K to LHe temperature)
  - Experimentally studied (total MLI layers vs. heat flux in the narrow gaps (from 3.5 to 6 mm)



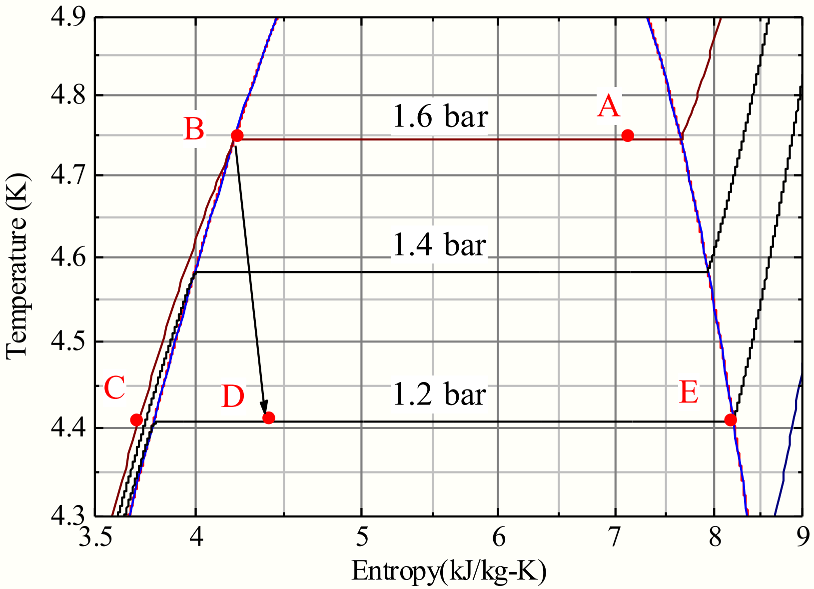


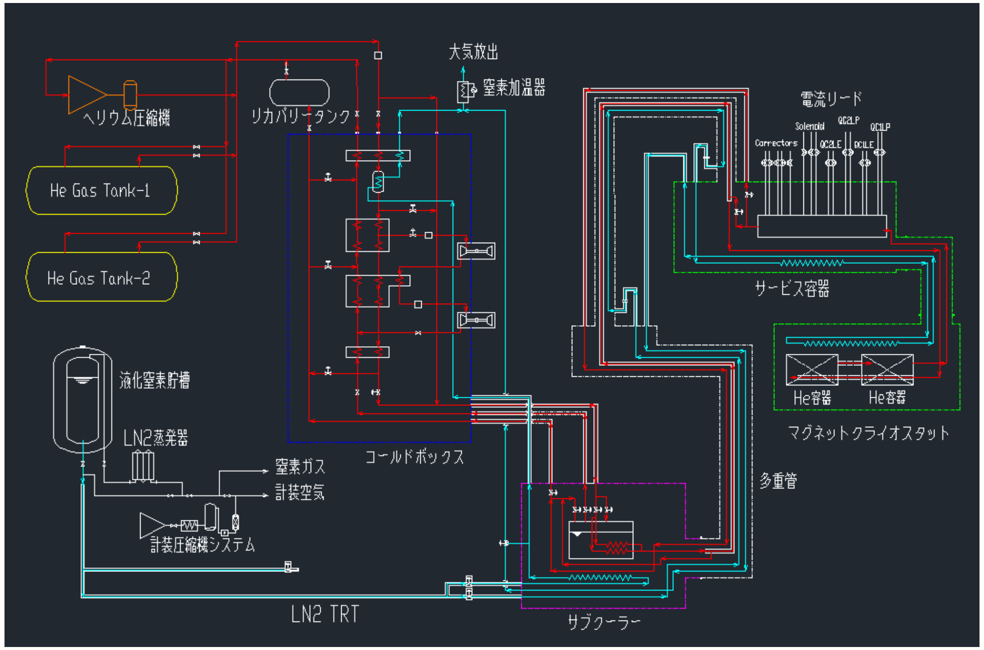


Cryogenic systems for the cryostats



Cold box and sub-cooler for each cryostat

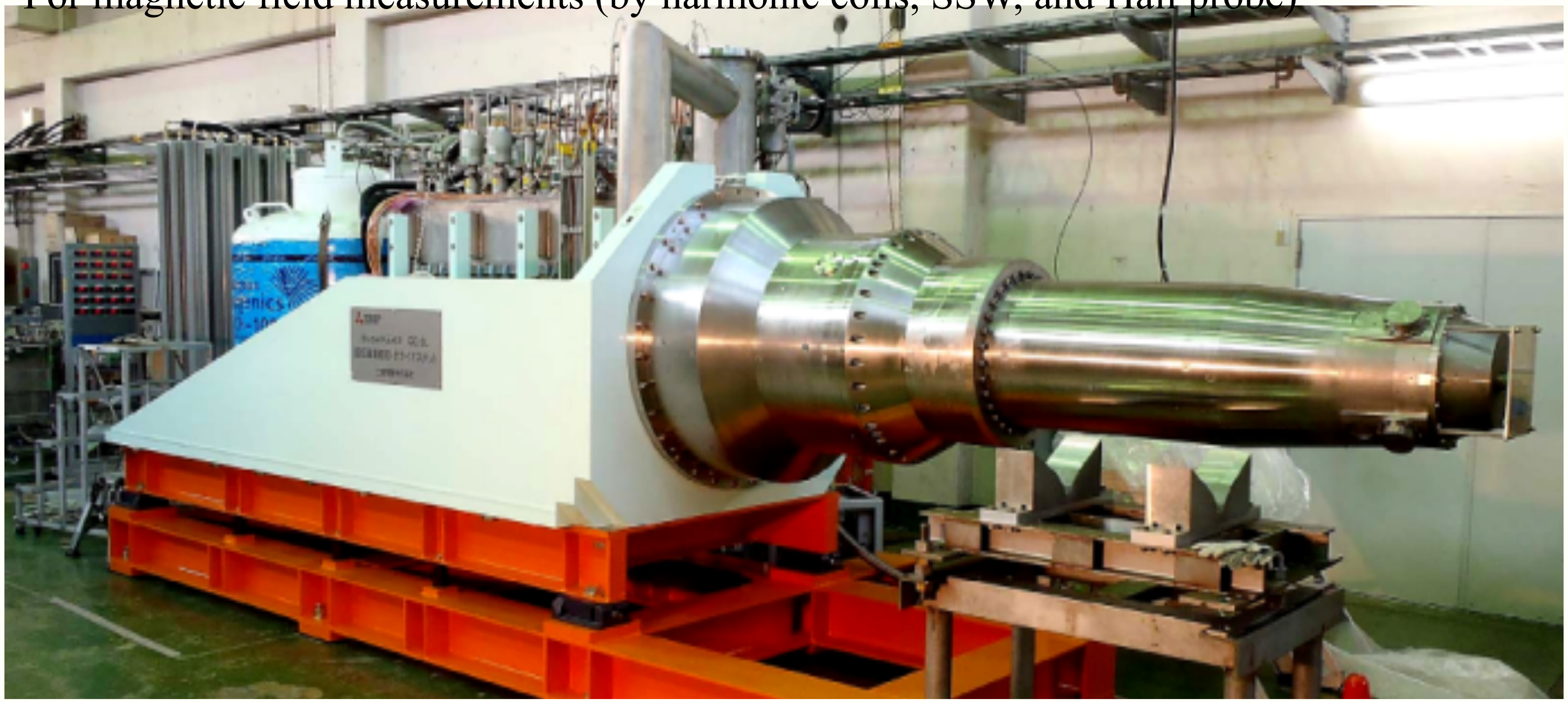




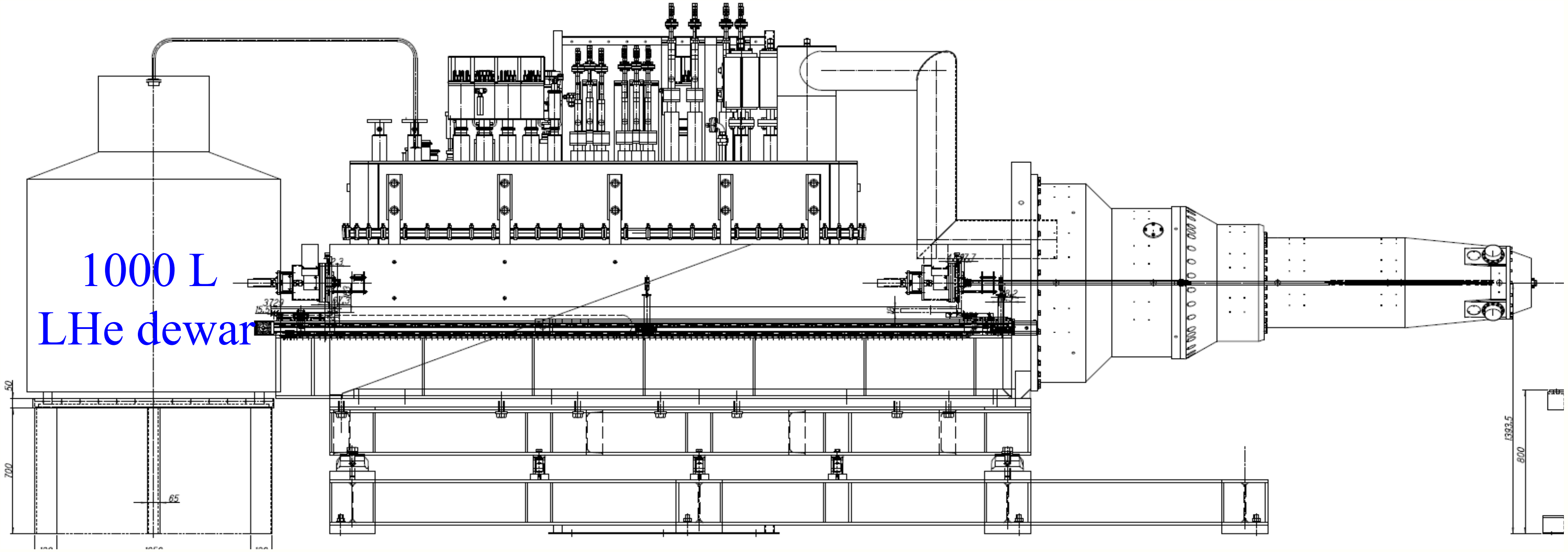
- To maintain SC magnets in the single phase LHe cooling
  - A: outlet from Coldbox: 1.6 bar (20 g/s, ~4.74 K, saturated LHe, two phase)
  - A->B->C: in the sub-cooler and multi-channel transfer lines
  - C->B: single liquid phase in the service cryostat and cryostat, a part to current leads
  - B->D: J-T valve in the service cryostat.
  - D->E: in the multi-channel transfer lines and subcooler, return to coldbox at E point

Cold tests of the QCS-L cryostat

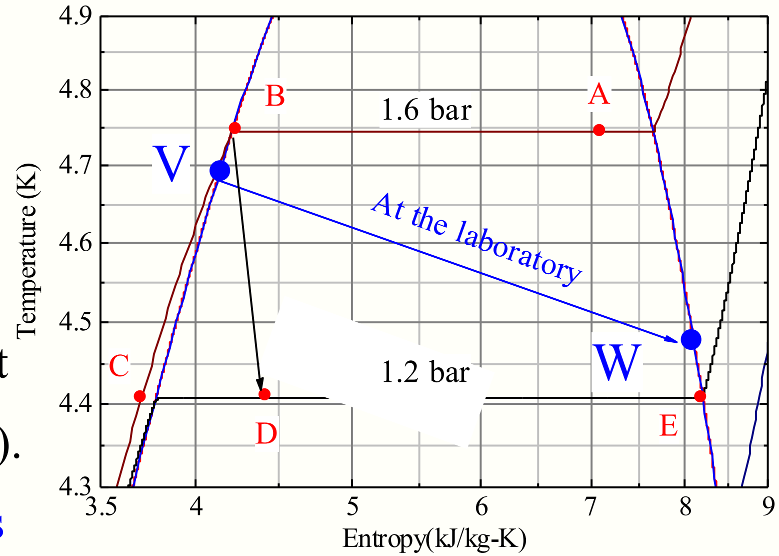
- Cooling the SC magnets down to ~4.5 K in the experimental laboratory (Feb.~Jul.)
  - To see the temperature profile in the SC magnet cryostat
  - To measure heat leaks of the cryostat
  - To excite all the SC magnets in the independent or combined modes (main quadrupole+corr.+ESL)
  - For magnetic field measurements (by harmonic coils, SSW, and Hall probe)



Setting-up to cool the SC magnet cryostat

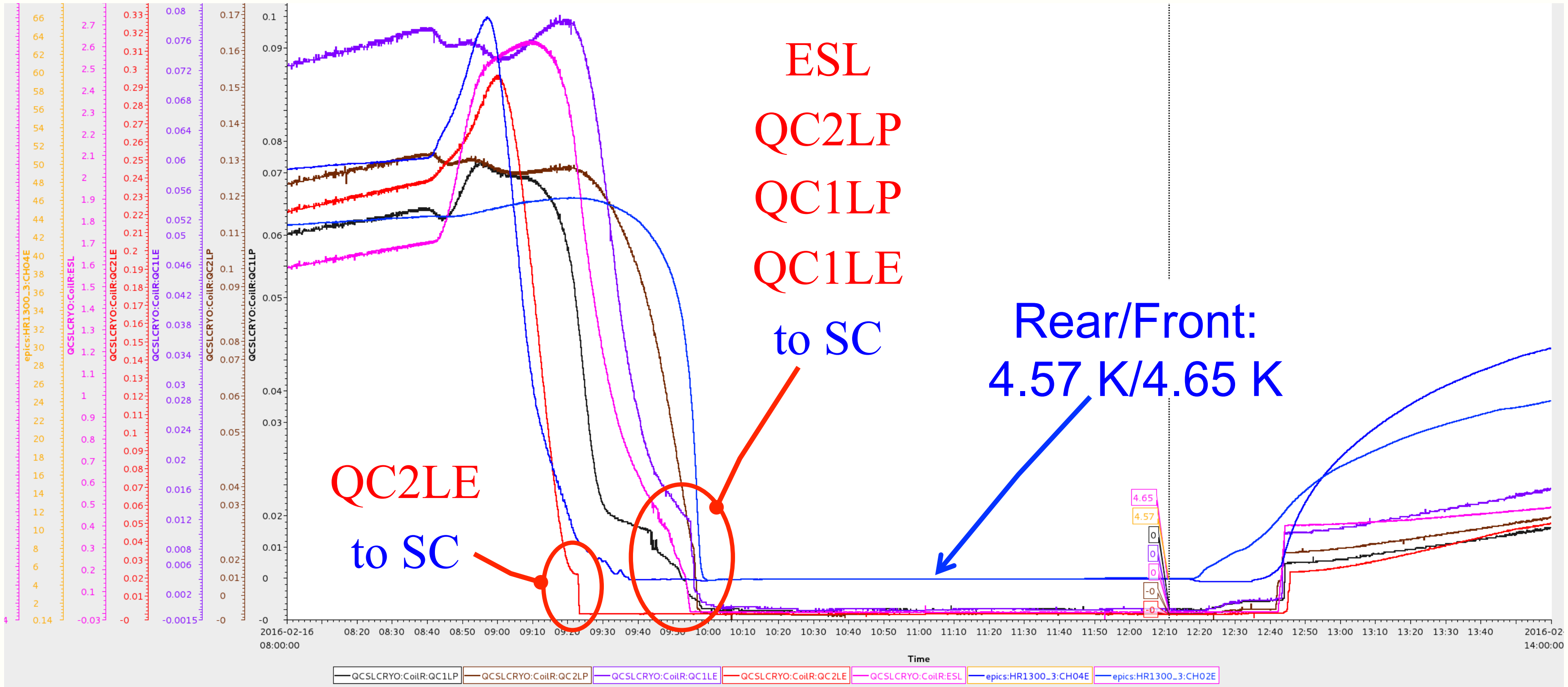


- Saturated LHe (two phase-vapor and liquid) instant of the single phase LHe
  - LHe was transferred into the service cryostat from the pressurized LHe dewar (1000 L, 1.4~1.6 bar). Helium gas vents through current leads or return line from the cryostat (~1.2 bar).
  - Not higher temperatures in the cooling process



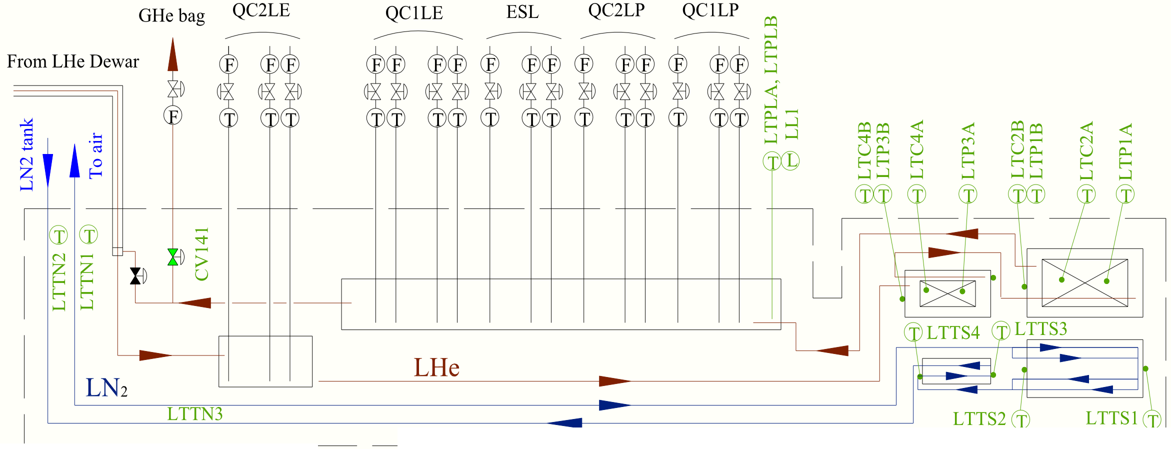
Cold tests of the QCS-L cryostat in the experimental laboratory

- The cryostat was pre-cooled with LN_2 and was cooled with LHe on Feb. 12 2016 (Fri.)
  - With LN_2 cooling the LN_2 shields (~ 40 L/hour) and use 1000 LHe a day.
- A small current (0.05~0.5 A) to monitor the evolutions of the coils' resistances with temp..
  - To see the SC state of the magnets with the temperatures (on Feb. 16, 2016, Tue.)
- Vacuum level of the cryostat: 10^{-5} (~50 K, in the morning) ~ 10^{-6} Pa (at LHe temperature)



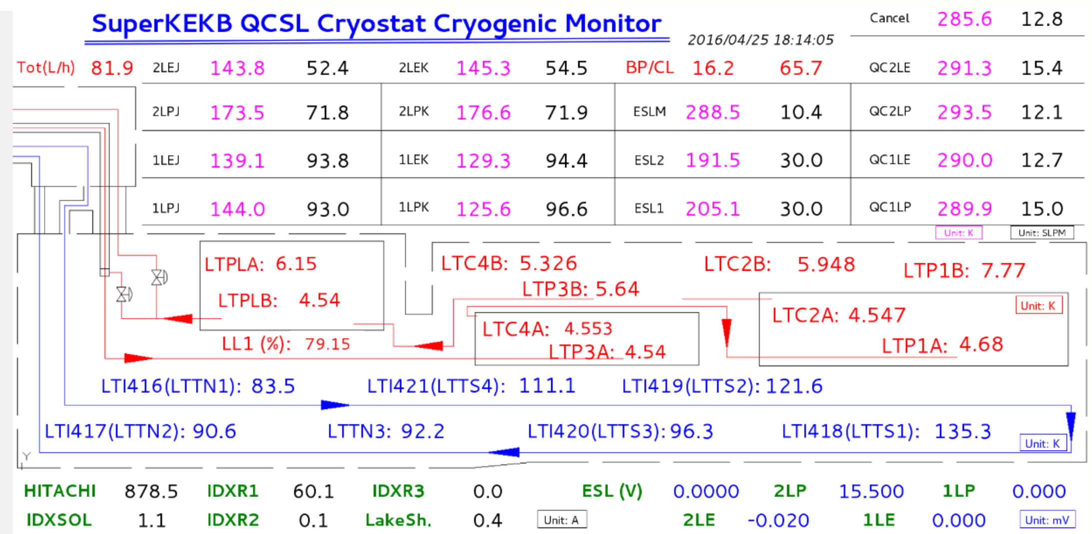
Cold tests of the QCS-L cryostat in the experimental laboratory

- Cryogenic ready (Once an hour to check and have a log of the main parameters)
  - LHe level: LL1
  - Flows of current leads
  - Flows of by-pass line
  - Temperatures at LHe
  - LN_2 shield temperatures



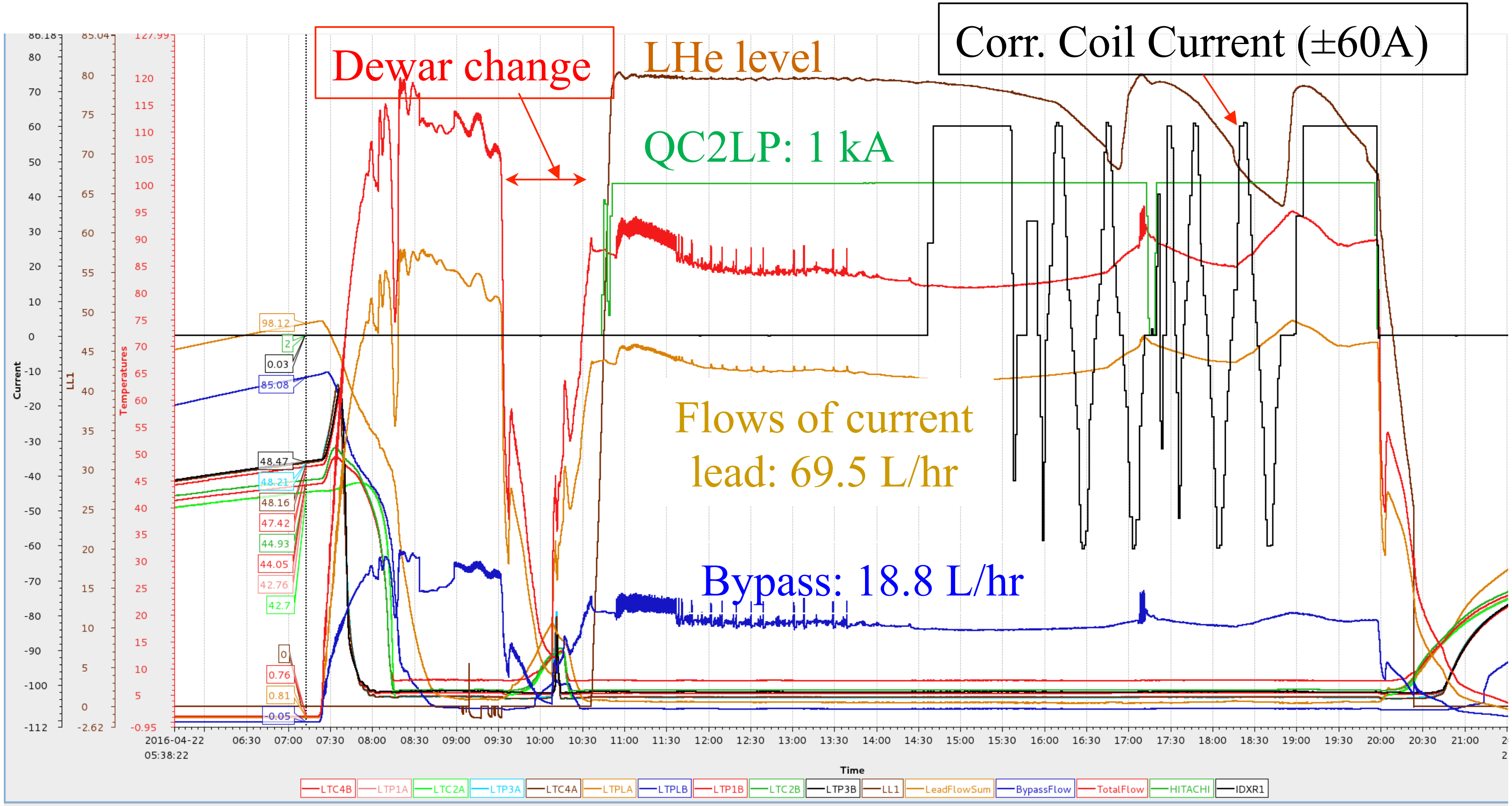
- Flow meter interlock with current sources

Unit: K, SLPM (Standard liter per minute), L/hr)



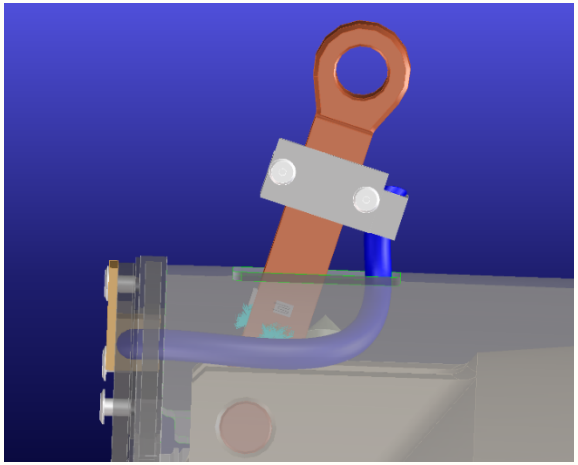
A typical one-day for magnetic field measurement

- Cool down from ~45 K and keep more than 10 hours (consuming >1000 L LHe a day)
  - About 2 hours cooling down and have the LL1 of about 80%, and then energize the SC magnets
  - The SC magnets were sufficiently cooled and no quench happened due to the cooling conditions.



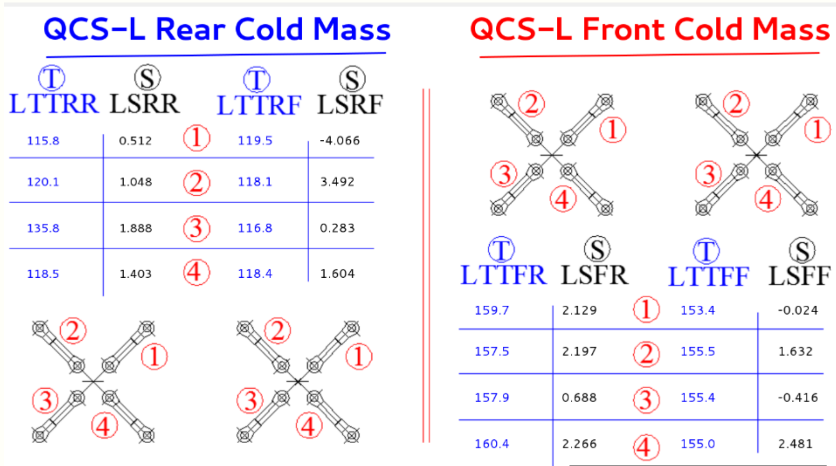
Some issues – Higher temperatures of LN2 level

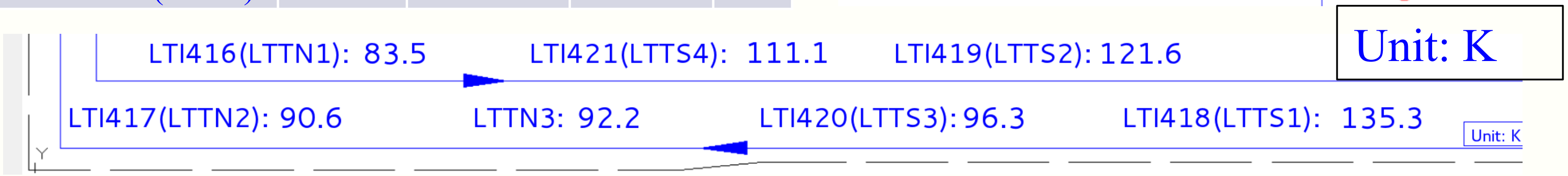
- Higher temperatures of LN_2 shields (110 K to 130 K)
  - Because of the temporary setting-up in the experimental laboratory (counter usage of the inlet and outlet of the LN_2 shields to fit the port types) (needs more analysis)
  - For the next step, use the design set-up.



- High temperatures of thermal anchors of support rods
  - 110 K to 155 K (design about 90~100 K), increase the heat leak to LHe level
  - Because of the higher LN2 shield temperatures
  - Because of the thermal anchor cross-sections

Item	Rear	Front		Total
Dimensions (mm)	120*7.5	133.5*13.5	83.5*13.5	W
Heat leaks (120/155K)	0.9/1.1	4.2	7.2	13.4
Heat leaks (110 K)	1.76	2.44	4.24	8.44

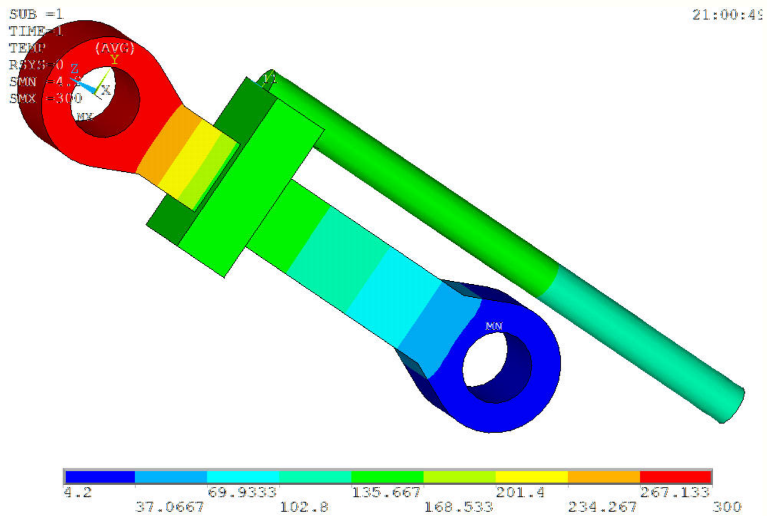


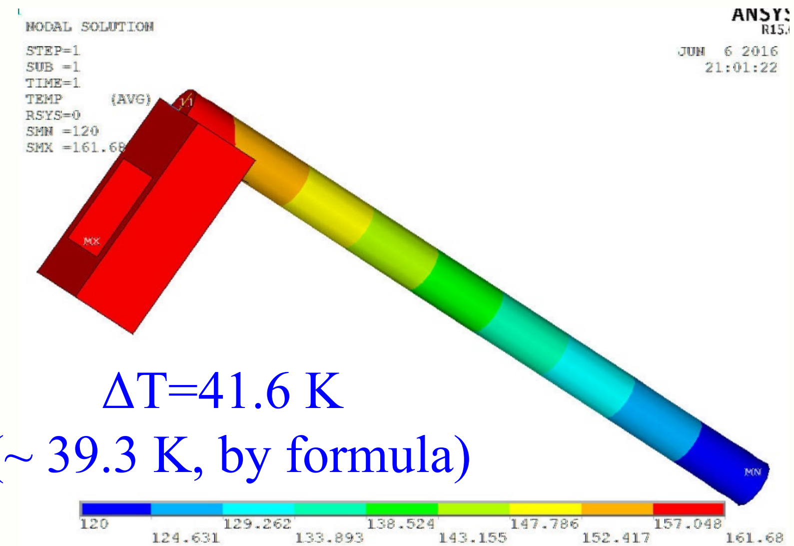


Some issues – Higher temperatures of LN2 level

- High temperatures of thermal anchors of support rods
  - The cross-section areas are not sufficient to intercept heat leaks from room temperatures.
  - For the QCS-R cryostat, we will confirm the thermal anchor design (cross-section areas and contact surfaces between the copper braids and LN2 shields)

Item	Rear	Front		Total
Dimensions (mm)	120*7.5	133.5*13.5	83.5*13.5	Design
Thermal anchor	Φ7	2.5*25	Φ7	Design
ΔT (K)	23	45.6	41.6	Cal.





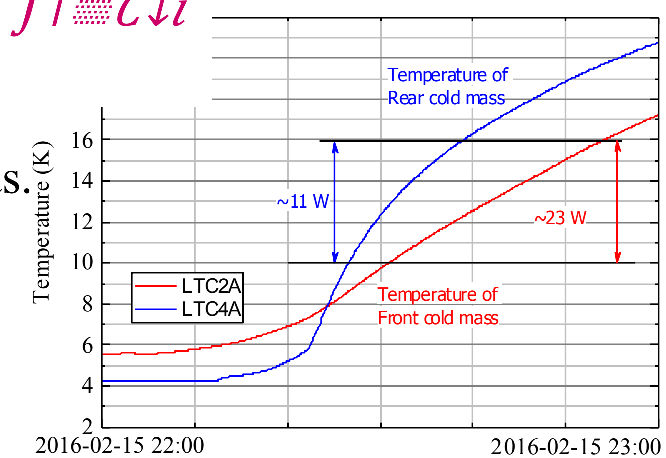
ΔT=41.6 K
(~ 39.3 K, by formula)

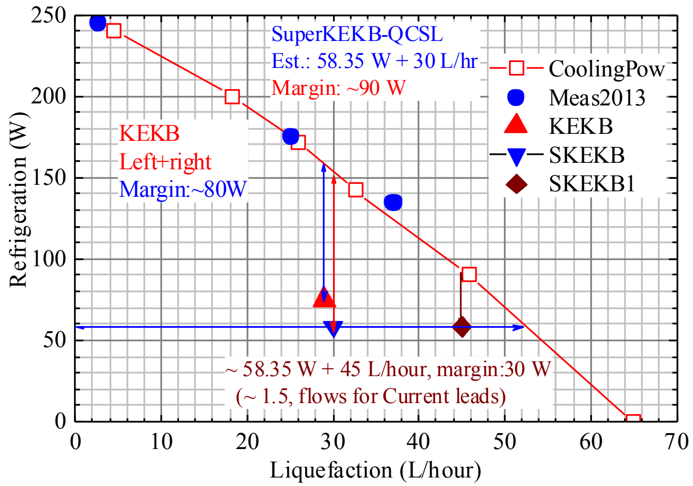
Summary of the QCS-L cryostat cold test

Items	Cold mass		Remarks
	Rear	Front	
Total heat leaks at the cryostat side	11.5	23.6	35.1 W (Measured)
Total heat leaks at the service cryostat (calculated)			13.25
Multi-Channel transfer line between sub-cooler and the service cryostat			<10 W

$$Q=\sum m_i \int C_i \, dT \, /time$$

- Heat leak meas. with temp. increase from 10 to 16 K





- Estimated working point of the refrigerator (for the left side)
- Summary: The left cryostat has successfully been cooled down at the KEK lab and the field measurements have been performed. The heat leaks are higher than expected and still affordable for the refrigerator. More analysis is needed for the next stage.