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Commissioning of the SuperKEKB final focusing superconducting magnet cryogenic systems

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Abstract. The 55 SuperKEKB final focusing superconducting magnets are assembled into two cryostats, located at the left side and the right side of the accelerator interaction point, respectively. The two cryostats are cooled by sub-cooled liquid helium at 0.16 MPa with two independent refrigerators of about 250 W cooling capacity. From August 2016, the two cryostats were installed into the accelerator beam line and were connected with their own sub-coolers and refrigerators. As cryogenic systems, commissioning was carried out to cool down the cryostats, to excite superconducting magnets, and to test system interlock protections against some emergencies. This paper introduces the cryostats and cryogenic systems, and the commissioning processes. The cryostat heat loads were measured and the results are presented in this paper.

1. Introduction

The SuperKEKB accelerator is seeking a luminosity of $8 \times 10^{35} \text{ cm}^{-2}\text{s}^{-1}$, 40 times higher than that achieved at its predecessor, KEKB, in order to search for new physics beyond the Standard Model on the luminosity frontier [1]. The luminosity increase will be achieved with the “nano-beam scheme”, in which the electron and positron beams are squeezed to a size of about 50 nm at the interaction point (IP) by the final focusing superconducting (SC) magnet system (QCS) at the interaction region (IR) [2].

The QCS system was designed with quadrupole magnet doublets to form an independent focusing pair for each beam. It consists of 8 main SC quadrupole magnets, 4 compensation SC solenoid magnets, and 43 SC correction magnets [3]. The 55 magnets are assembled in two cryostats, which are inserted into the Belle II detector, from the left side (the QCS-L cryostat, according to the view from the center of the accelerator main rings to the IP) and the right side (the QCS-R cryostat), respectively.

The QCS-L cryostats were installed into the accelerator beam line in August 2016. The fabrications of the cryogenic multi-channel transfer lines and warm pipes for flows from current leads, and the connections of instrumentation and control signal wires, were completed by the end of October. As a cryogenic system, the QCS-L cryostat was firstly cooled down with its sub-cooler and refrigerator and the system was commissioned by the end of 2016.

The QCS-R cryostat was delivered to the accelerator beam line in February 2017. After roll-in of the Belle II detector in April, the two cryostats were inserted into the Belle II detector. From May 2017, the two cryogenic systems were cooled down to prepare for excitation tests of SC magnets under the operation conditions, and magnetic field measurements. This paper introduces the commissioning processes. The cryostat heat loads were measured and the results are presented in this paper.



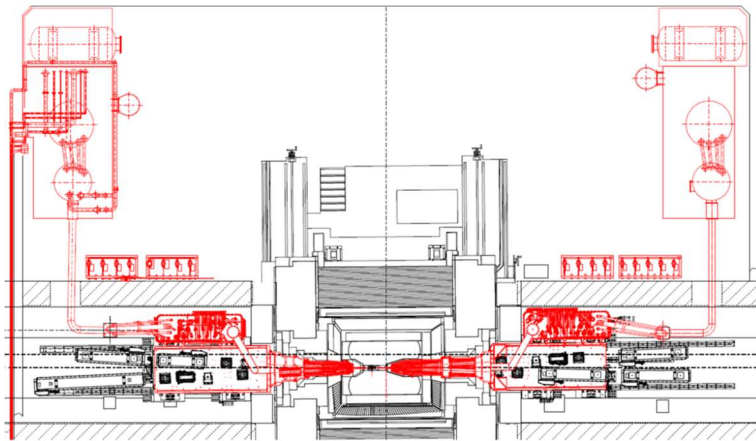


Figure 1. Layout of the QCS cryostats and their cryogenic systems, with the Belle II detector in the SuperKEKB interaction region.

2. The QCS cryostats and their cryogenic systems

The QCS-L and QCS-R cryostats have the same configuration and consist of a magnet cryostat, a service cryostat, a cryogenic pipe connecting the magnet cryostat and the service cryostat, and a support table. The cryostat is dedicated to being cooled with a sub-cooled LHe flow of 20 g/s at the pressure of 0.16 MPa, which is produced by a refrigerator and a sub-cooler. The layout of the QCS cryostats and their cryogenic systems in the SuperKEKB IR is shown in Figure 1.

2.1. The magnet cryostats

For each cryostat, the magnet cryostat accommodates SC magnets (QCS-L: 25/QCS-R: 30) with two LHe vessels. The front LHe vessels are closer to IP than the rear vessels. The rear vessels have one quadrupole magnet (QC2E) and their correction coils. For the QCS-R side, two compensation solenoid magnets (ESR2 and ESR3) are also assembled in the rear vessel, as shown in Figure 2. The rest of magnets are installed in the front vessels. The LHe vessels integrate magnets, iron yokes, mechanical supports, and radiation shields (heavy metal, Tungsten) and the total cold masses are 1522 kg for the QCS-L cryostat and 3139 kg for the QCS-R cryostat, as listed in Table 1.

Each LHe vessel is suspended by 8 support rods of titanium alloy (Ti-6Al-4V) from vacuum vessels. Rods are thermally anchored and connected to liquid nitrogen (LN_2) pipes to intercept heat conductions. Design temperatures of thermal anchor are about 120 K for heat load estimations, which are listed in Table 1 for each LHe vessel.

The LHe vessel outsides are surrounded by LN_2 thermal shields and are applied with multi-layer insulation (MLI) with a heat flux of 1.0 W/m^2 for heat load estimations. The inner cylinders of LHe vessel accommodate beam pipes with narrow gaps of about 3.5 to 6 mm. Beam pipes are kept at room temperatures by circulating water and LN_2 shields are not equipped because of the limited gap spaces. The cylinder inner surfaces are coated with aluminum vapor deposition and 5 layers of MLI are applied to reduce heat radiation from warm beam pipes to LHe vessel cylinders. The configuration of heat transfer was studied in details [4] and a heat flux of 5 W/m^2 was used for heat load estimations.

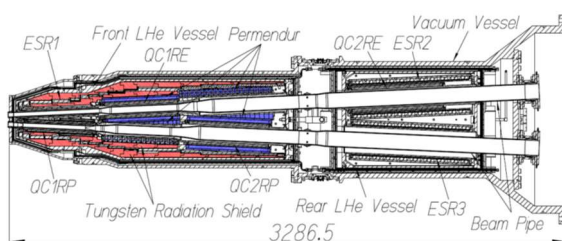


Figure 2. Cross section of the magnet cryostat of the QCS-R cryostat.

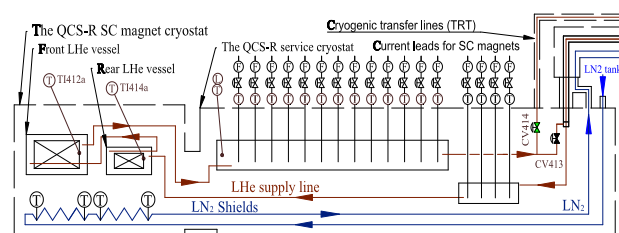


Figure 3. Cooling scheme of the magnet cryostat and the service cryostat of the QCS-R cryostat.

Table 1. Heat load distributions of the QCS cryostats.

Items	Unit	QCS-L cryostat				QCS-R cryostat			
		Supply	Rear	Front	Return	Supply	Rear	Front	Return
Flow lines or vessels									
Cold mass at LHe	kg	-	342	1180	-	-	1063	2076	-
Support rods or pipes	Design	W	1.63	2.01	7.71	9.86	2.72	2.15	3.61
	Calc.	W	2.91	2.87	10.98	16.2	3.4	2.45	4.63
Thermal radiations	W	0.55	1.69	4.93	1.39	0.71	4.59	5.47	1.39
Instrumentation wires	W	0.75	0.87	0	3.05	0.75	0.87	0	2.67
Cryogenic pipes	W	2	-	-	2	2	-	-	2
Sub-total	Design	W	4.93	17.21	18.30	6.18	16.69	17.81	
	Calc.	W	6.21	21.34	24.64	6.89	18.01	20.25	
LHe consumption	L/h	5.98	-	-	22.12	6.84	-	-	22.12
of current leads	g/s	0.21	-	-	0.77	0.24	-	-	0.77
Total (+TRT, 16 W) Des./Calc.		56.44/68.19 W+28.1 L _{LHe} /h				56.67/61.11 W+28.96 L _{LHe} /h			

2.2. The service cryostats and cooling scheme

The service cryostats are equipped to function as interfaces to access power cables from current sources and cryogenic transfer lines from sub-cooler and refrigerator, and host ports of instrument wires.

As each magnet is equipped with an individual current source and in total, 110 current leads are needed to energize the QCS magnets [5]. Current leads are installed in two service cryostats (51 leads for QCS-L and 59 leads for QCS-R) to span the temperature interval from room temperature (~ 300 K) to LHe temperature. For the main quadrupole magnets (design currents: 1.0, 1.25, 1.35, 1.8 and 2.0 kA, respectively) and compensation magnets (ESL and ESR1: 450 A), current leads are the conventional vapor cooled type. For correction coils (~ 60 A), a compact HTS unit to integrate 8 leads was developed and can be installed with only one port [6]. The current leads for the QCS magnets have the optimum designs and a LHe consumption of about 1.5 L_{LHe}/hour/kA. Their thermal and electrical performance was qualified in cryogenic environment, prior to installation. For each cryostat, current leads consume a LHe liquefaction of about 29 L_{LHe}/h.

Current leads are installed in service cryostats with 16/17 ports for QCS-L/QCS-R along supply or return lines, as shown in Figure 3. The port connection pipes between vacuum vessels and LHe pipes are thermally anchored to LN₂ shields of service cryostats. In Table 1, the design heat loads with thermal anchor temperatures of 120 K of ports are listed and 11.5/12.5 W for QCS-L/QCS-R. Another head load is introduced by instrumentation wires and are about 4.5 W for both sides, which are calculated with a simple thermal conduction model.

For each cryostat, two LHe vessels have a total heat load of about 40 W and are cooled with one sub-cooled LHe flow of about 20 g/s. The sub-cooled LHe flow can prevent heat transfer instability of the two-phase (vapor and liquid) flow and can absorb about 40 W heat by the LHe sensible heat with a temperature increase of about 0.3 K (~ 2.0 W/g/s: 4.45 K \sim 4.76 K).

At the outlet points of the cryostats, LHe flow (~ 0.16 MPa) is expanded by a J-T valve (CV413, in Figure 3) into the two-phase state (~ 0.123 MPa). The cryogenic transfer lines (TRT) between sub-cooler and service cryostat are designed with a coaxial structure of tubes and supply LHe from sub-cooler goes through inner tubes while two-phase LHe returns in annular region in outer tubes [7]. The return two-phase LHe prevents heat loads of cryogenic transfer line from invading supply single-phase LHe and also helps to further cool supply single-phase LHe from subcooler. This scheme is efficient to guarantee sub-cooled state of supply LHe. LHe in return flows is boiled off by heats through heat exchangers or from heater immersed in sub-cooler LHe. The heater power consumes the abundant capacity or margin of refrigeration to keep the refrigerator normal operation.

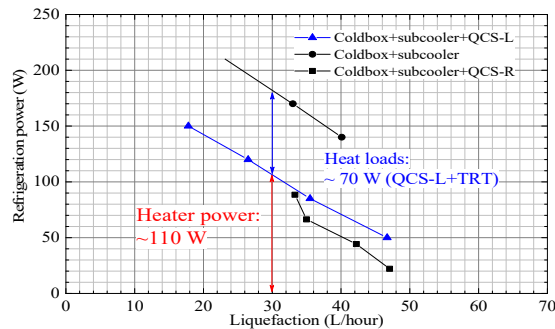


Figure 4. Measured capacities with and without the QCS-L cryostats.

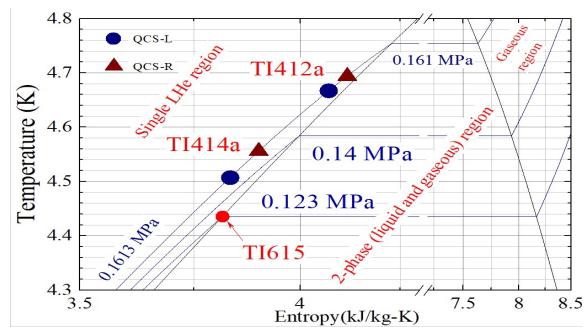


Figure 5. Cooling processes of the QCS-L/R cryostats in the helium T-S diagram.

3. Cooling down of the QCS cryostats

The QCS-L refrigerator had served for the TRISTAN [8] and KEKB [9] projects at KEK and was set up to cool the QCS-L cryostat for SuperKEKB. Its refrigeration and liquefaction capacities were tested without connecting the QCS-L cryostat, as marked with the circled black line in the refrigerator load map (Figure 4). After connecting and cooling the QCS-L cryostat, the heater powers were reduced by about 70 W (from 180 W to 110 W, with a liquefaction of 30 L/h), which was considered to be the total heat load of the cryogenic transfer lines (TRT) and the QCS-L cryostat. The measured temperatures of rod and pipe thermal anchors were about 150 K for QCS-L (140 K for QCS-R), which were higher than design of 120 K and caused a calculated heat load increase of 12 W, listed in Table 1. The total heat loads (Calc.) are about 68.2 W, which agrees with the measured result of 70 W.

The QCS-R refrigerator was saved for about 20 years after the TRISTAN project. In May 2017, we had a very hard schedule cool the QCS-R cryostat and also met some troubles, such as a mis-connection of the turbine inlet flow meter and a stagnation at 20 K. Figure 6 shows temperature decreases, LHe emergencies and accumulations in the service cryostat and sub-cooler, for the first time to reach cryogenic ready state (defined with a LHe level in sub-cooler: >50 %). It took about 65 hours and was longer than cooling down (~48 hours) of the QCS-L cryogenic system. The magnet resistances were monitored, which had the same trends with decreasing of LHe vessel temperatures as shown in Figure 7. The magnet superconducting transitions occurred at about 10 K of cryostat temperatures, which demonstrates adequate cooling inside LHe vessels. The control program of cryogenic systems [10] were tested and qualified, to automatically response troubles with SC magnets, compressors, and turbines.

4. Heat load measurements with LHe flow temperatures

Cooling of the QCS cryostats is considered to be an isobaric process at 0.16 MPa. Heat loads are absorbed by the sensible heat of LHe flow with temperature increases. The temperature sensors are set up in-flow at the flow inlets of rear LHe vessels (TI414a) and outlets of front vessels (TI412a), which are the calibrated CernoxTM type with high accuracies (~80 Ω /K) around 4.5 K.

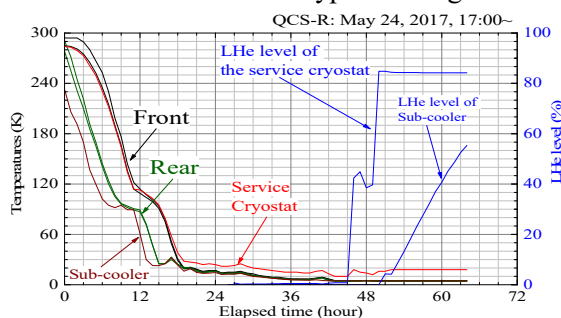


Figure 6. Cooling-down and LHe accumulation curves of the QCS-R cryostat.

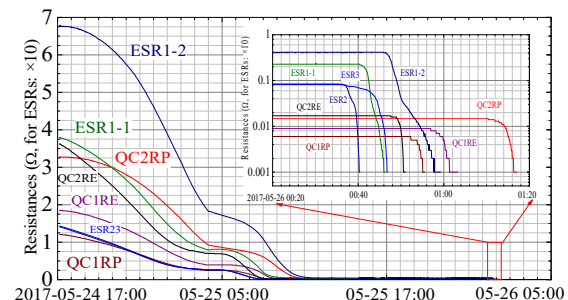


Figure 7. Monitored resistance evolution of the QCS-R SC magnet coils.

Table 2. Measured heat loads of the QCS-L/R cryostats.

	flow rates	TI412a	TI414a	Δh	Rear&Front
	g/s	K	K	J/g	W
QCS-L	22.6	4.506	4.668	~ 1.10	24.8
QCS-R	17.4	4.556	4.692	1.0	17.4

The measured temperatures (TI414a and TI412a) of the QCS LHe vessels are marked in the helium temperature-entropy (T-S) diagram (Figure 5) and are lower than the saturated temperature (~ 4.75 K) of the cryostat pressures of 0.16 MPa, which demonstrates all the QCS magnets are cooled by sub-cooled LHe. The heat loads were calculated with enthalpy differences determined by temperatures and pressures of LHe, and LHe flow rates measured from cryogenic systems, as listed in Table 2. The results agree well with the calculated heat loads (anchor temperatures: 150 K) in Table 1. The QCS-L has a larger heat load in LHe vessels, which are due to the larger cross sections of its support rods.

5. Conclusion

The QCS-L and QCS-R cryostats were installed in the accelerator IR and connected with their own refrigerators and sub-coolers. The cryogenic systems were commissioned and their performances were qualified for the accelerator Phase II commissioning, with cooling margins of about 100 W. There were also some issues, such as a stagnation at 20 K during cooling down and a leaking valve. We did tuning, trials and maintenance works to solve the issues before the accelerator Phase II commissioning, which will be presented in the future.

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