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KEKB/SUPERKEKB CRYOGENICS OPERATION

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Abstract

At KEK, the operation of the superconducting cavities was started with TRISTAN accelerator in 1988 [1], The superconducting cavities are continuously operated even after that. In this paper, the operation of the refrigerator for the superconducting cavities of KEKB/SuperKEKB is mainly introduced. In KEKB/SuperKEKB, the superconducting magnets are also used. They have their own refrigerator [2].

The refrigerator for the superconducting cavity for KEKB/SuperKEKB was constructed for the TRISTAN accelerator [3], The capacity of the refrigeration is 8.1 kW at 4.4 K [4] [5]. Since the number of superconducting cavities used in KEKB / SuperKEKB is smaller than that of TRISTAN, there is a margin for the capacity of the refrigerator. In order to operate this old refrigerator, proper maintenance is necessary, and periodic inspection and equipment updating are carried out.

CRYOGENIC SYSTEM FOR SUPERCONDUCTING CAVITIES

Large-scale Helium Refrigerator

KEKB was built in the tunnel of the TRISTAN accelerator. The TRISTAN accelerator was operated from 1986 to 1995. The superconducting acceleration cavities were installed in 1988 to increase the beam energy. The cryogenic system for superconducting cavities was also established by Hitachi, Ltd. simultaneously. In 1989 superconducting acceleration cavities were added, and cryogenic systems were also enhanced. Its design capacity was increased from 4kW to 6.5kW. Schematic diagram of the refrigerator for superconducting cavities is shown in Fig. 1. By adding expansion turbines (T4 and T5), it became possible to operate the refrigerator without liquid nitrogen. By adopting the supercritical burbine expander (T3), the capacity of refrigerator was increased. And, two compressors (C5 and C6) were added. As a result, the practical refrigeration capacity was reached to 8.1kW at 4.4K.

KEKB took over many facilities from TRISTAN. The cryogenic system for superconducting cavities is one of them. This refrigerator is still used in SuperKEKB.

Superconducting Cavity

In TRISTAN, a cryostat for superconducting acceleration cavities had two of 5cell cavities (See Fig. 2). Finally, 16 cryostats were installed. An estimation of the heat loads are shown in Table 1. The total heat load for TRISTAN cryogenic system at 4.4K is about 4 kW, which can be sufficiently cooled by the enhanced refrigerator.

KEKB accelerator operated from 1998 to 2010. In KEKB, a cryostat for superconducting acceleration cavities had a single-cell cavity (See Fig. 3). 8 cryostats were installed. The static heat load is about 30W/cryostat [6]. The RF loss is 100W/cavity. As can be seen from Table 1, the main component of the heat load is the RF loss of superconducting cavities. In KEKB, there is enough margin for refrigerating capacity, because the number of superconducting cavities is small. Since the RF loss of the cavity changes according to the acceleration voltage, The sum of the compensation heater power and the RF loss is controlled to be constant. The RF loss of the Table 1 includes the output power of the compensation heaters.

From 2007 to 2010, two superconducting crab cavities were adopted. The crab cavity have a superconducting device called coaxial coupler. To cool the coaxial coupler, a liquid helium of about 5g/s was required (See Fig. 4). As a result, the thermal load appeared to be about 100W larger than the superconducting acceleration cavity.

In SuperKEKB, the crab cavities are not used. They have been removed. The eight superconducting cavities are still in operation.

Transfer Line

A high-performance transfer line is required to supply liquid helium from the helium refrigerator installed on the ground to the underground cryostat. The cross-section of transfer line was shown in Fig. 5 The heat load is about 1W/m as shown in Table 1. In KEKB, an improved transfer line was developed, and the performance was tested. The cross-section of the improved transfer line was shown in Fig. 6. In multi-channel transfer line, the heat load was only 0.05W/m. The multi-channel transfer line was adopted to connect from refrigerator to D10 test stand as shown in Fig. 1. The single-channel transfer line was adopted to connect between the cryostats and existing multi-channel transfer line in KEKB.

Liquid Nitrogen Circulation System

The cryostat of the superconducting cavity and the transfer line have the radiation shield which called 80K shield. To cool the 80K shield, a nitrogen circulation system was adopted. A circulation system is very suitable for cooling the shield by pipe cooling. This is because cooling in a single pass can not sufficiently cool the downstream. In the case of using a circulation system, the refrigerant returns in two-phase flow, so that all passes are completely cooled. As

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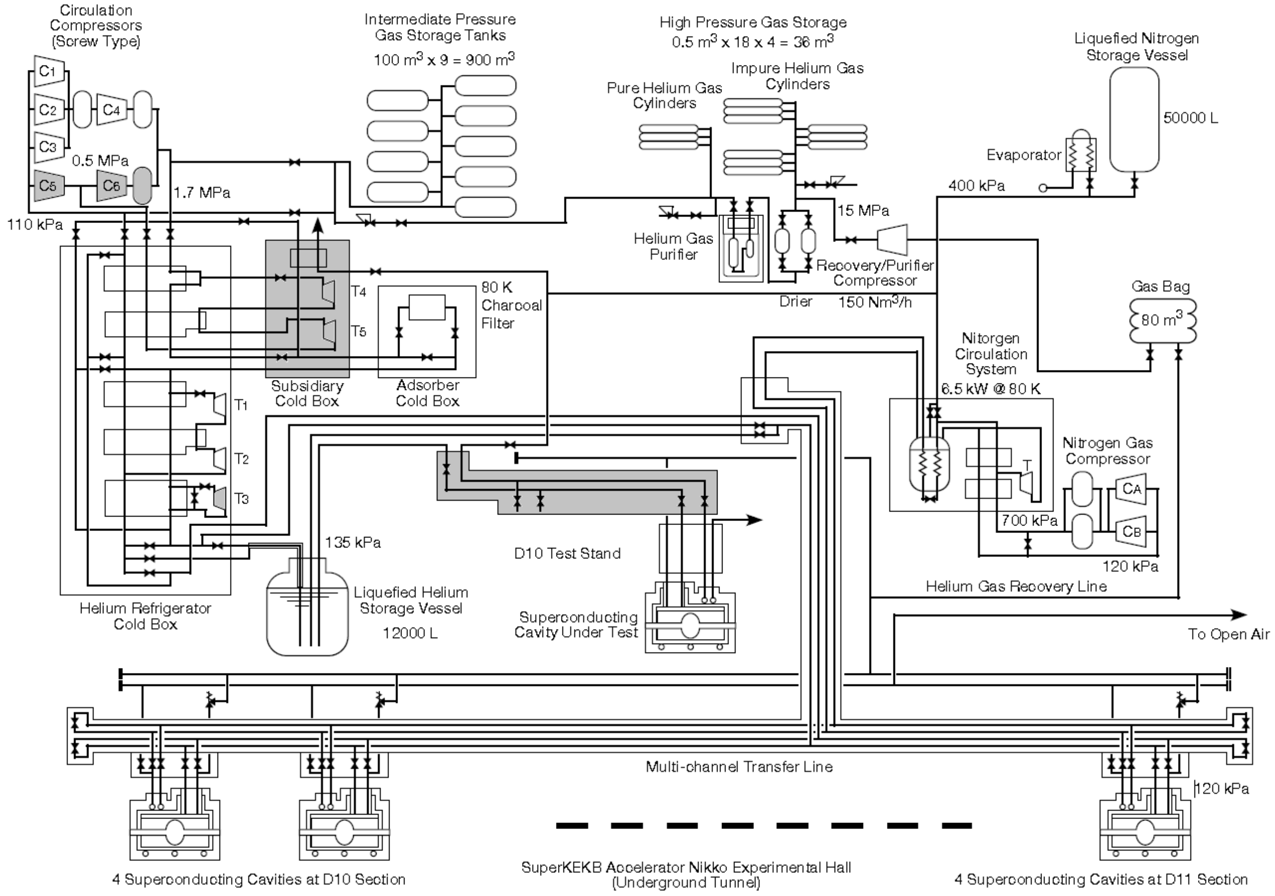

Figure 1: Flow diagram of the refrigerator for superconducting cavities. Shaded areas indicate extended parts.

Table 1: Heat loads of the TRISTAN cryogenic system at 4.4K

Compontnts		**Heat loads**
Cryostats	22.8 W/cryostat × 16	364.8 W
Transfer Lines (380m)		412.4 W
Cold Valves & Joints		147 W
RF Loss	90 W/cavity × 32	2880 W
Total Heat Loads		3804.2 W

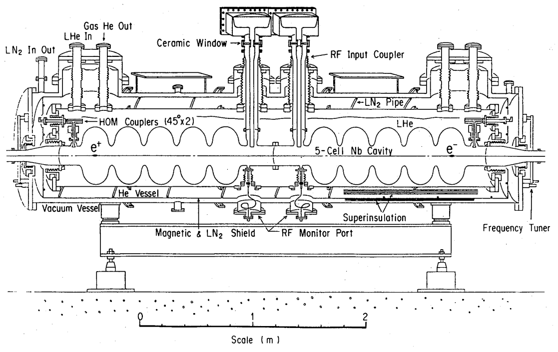

Figure 2: TRISTAN superconducting acceleration cavity cryostat.

shown in Fig. 1, the circulation system for KEKB consists of a compressor, a heat exchanger and a turbine expander. It not only recycles the returned liquid nitrogen, but also liquefies a part of the returning nitrogen gas. By using sensible heat of evaporated gas, consumption of liquid nitrogen was suppressed. The heat load for TRISTAN accelerator at 80K are shown in Table 2. In TRISTAN, the daily consumption of liquid nitrogen decreased from 8000L to 1800L by using the liquid nitrogen circulation system. In KEKB, it is about 1500L. Most of the heat load at 80 K comes from the transfer line, and since this part is not updated, the consumption of liquefied nitrogen has not changed significantly.

Table 2: Heat loads of the TRISTAN cryogenic system at 80K

Compontnts		**Heat loads**
Cryostats	48.8 W/cryostat × 16	780.8 W
Transfer Lines (380m)		5569 W
Cold Valves & Joints		294 W
Total Heat Loads		6643.8 W

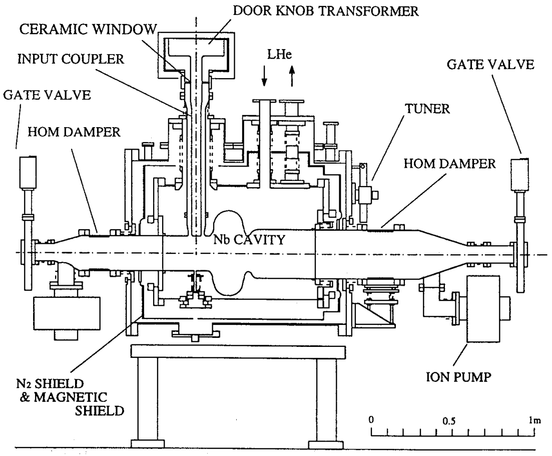

Figure 3: KEKB superconducting acceleration cavity cryostat.

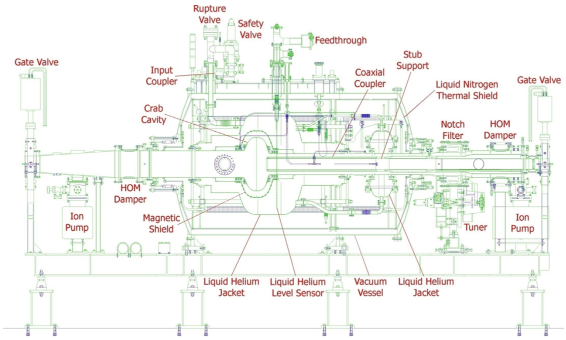

Figure 4: KEKB superconducting crab cavity cryostat.

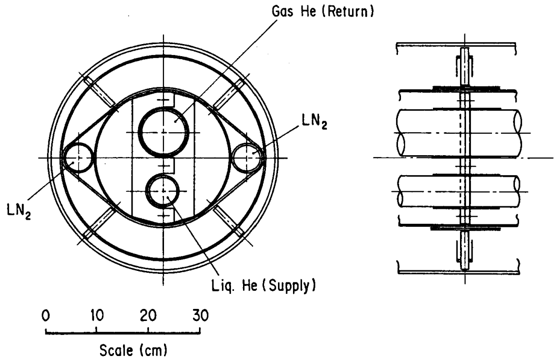

Figure 5: Cross-section of transfer lines for TRISTAN.

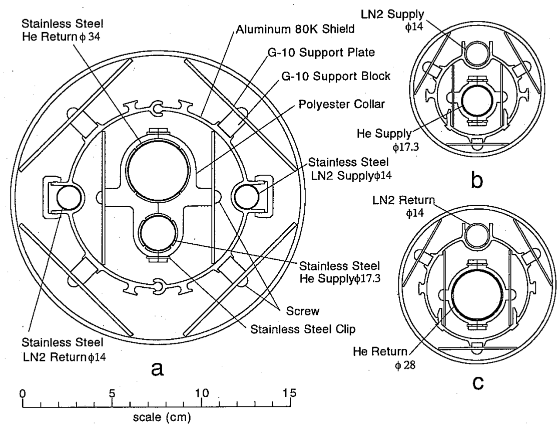

Figure 6: Cross-section of transfer lines for KEKB: a: multi-channel(main), b) single-channel for helium supply, and c) single-channel for helium return [7].

Control System

When the cryogenic system was constructed, a distributed process control system Hitachi EX-1000 was adopted. It contained 5 Multi-controllers(MLC). The MLC has digital and analog input / output, and it can execute data monitoring, loop control and sequence control. The control period was 1 second. Data logging system is also implemented in the control system. This system is connected to the accelerator control system through the gateway unit and can exchange information necessary for operation. The control system has been updated twice, now EX-8000 is working. A schematic diagram of the control system is shown in Fig. 7.

Currently processed signals are 800 analog inputs, 168 analog outputs, 608 digital inputs and 352 digital outputs. 63 PID loop is working. Currently there are six MLCs, an MLC can handle 768 analog inputs and outputs and 512 digital inputs and outputs. There is sufficient margin for the number of signals that can be handled, and it is possible to respond to the addition of facilities.

Operation Status

In practical operation, it is necessary to cool down the equipment from room temperature. Since the deformation of the equipment due to the temperature difference during cooling down causes misalignment and vacuum leakage, it is required to slowly and uniformly cooling down. In KEKB/SuperKEKB, the cooling rate is required to be 2.5˜3K/h. The state of the most recent cooling is shown in the Fig. 8. The cavity was cooled from room temperature to about 40 K at a constant rate. In this example, the cooling rate was targeted at 2.5 K/h. In the initial stage of cooling, the superconducting cavity is cooled by using a helium gas

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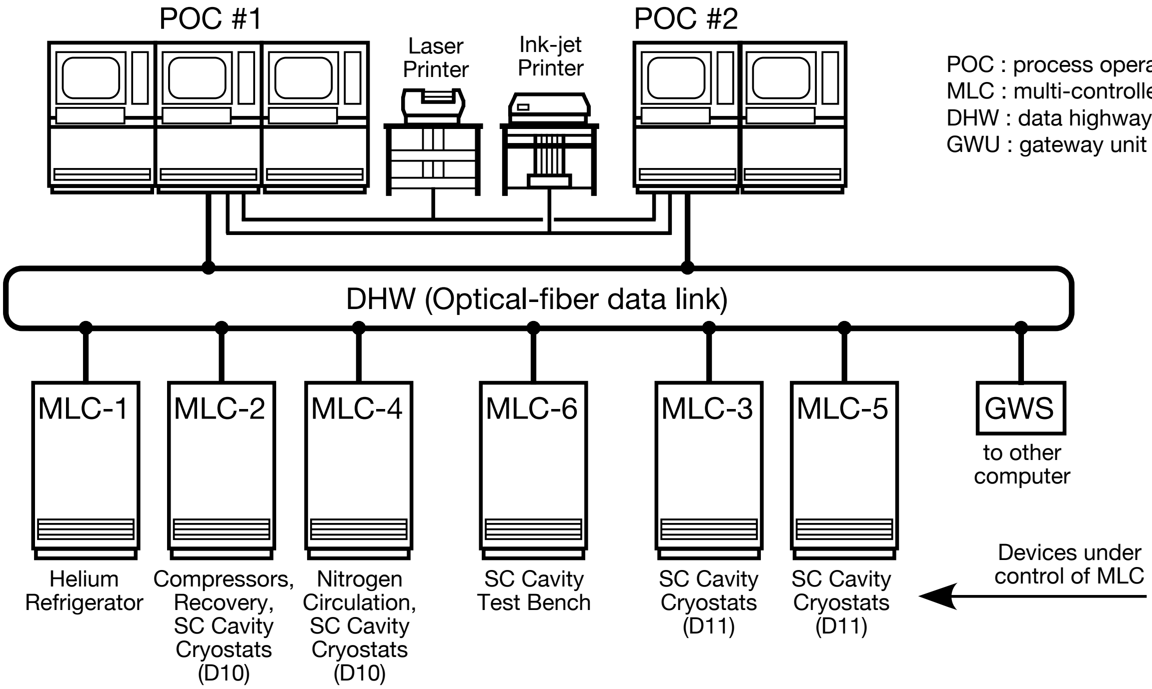

Figure 7: Schematic diagram of the control system for the large-scale helium refrigerator.

cooled by liquid nitrogen in a heat exchanger in the refrigerator. When the cavity temperature reached about 150 K, the expansion turbines (T1 and T2) were started to reduce the temperature of the helium gas to be supplied. The temperature of the supplied helium gas changes, but the cooling rate is controlled through the flow rate of the helium gas. When the cavity temperature reaches about 40 K, liquid helium is supplied from Dewar. After reaching the liquid helium temperature, the helium level in the cryostat is controlled. The refrigerator starts the liquefaction operation and supplies the liquid helium to the dewar.

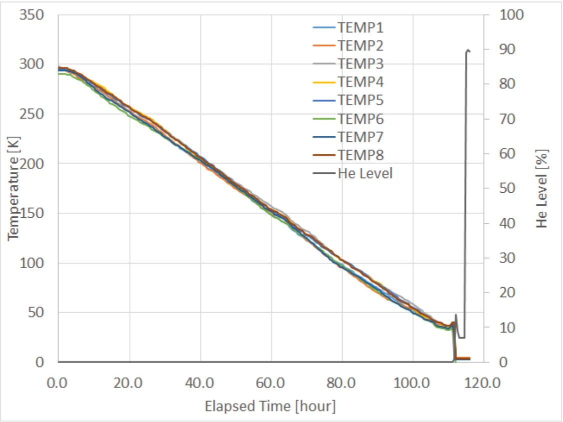

Figure 8: Cool down curves of the SuperKEKB superconducting cavities.

In the steady state, the liquid level in the superconducting cavity cryostat is controlled to be constant. In TRISTAN, the RF loss of superconducting cavity increased from about 30W at beam injection to about 120W at the top energy operation in about two minutes. There was a concern that the state of the refrigerator would not be stabilized due to rapid changes in the temperature and flow rate of the evaporated gas returned to the refrigerator. As already mentioned, this variation was canceled by the compensation heater. In KEKB/SuperKEKB, RF loss is stable, however compensation heaters are still in use.

Maintenance and Updating

In Japan, refrigerators are classified as high-pressure gas equipment. A high-pressure gas equipment should be operated according to the high pressure gas safety act. The maintenance work required for the refrigerator for KEKB/SuperKEKB superconducting cavity is as shown in the Table 3. Maintenance cycle depends on refrigerator specifications.

Electronic devices require periodic maintenance. When the refrigerator was constructed, the control system was EX-1000. It was updated to EX-7000 in 2002 and EX-8000 in 2012. Electronic circuits such as signal converters periodically measure their characteristics and update them as necessary. Inspection and updating are also carried out for actuators for valves and sensors in the same way.

Trouble

The helium refrigerator was operated in the TRISTAN accelerator for seven years from 1988 to 1995, and the operation time was 38000 hours. The cause of the trouble that caused the refrigerator to stop operating during this period was the initial failure such as oil leakage from the mechanical seal of the compressor and mistakes in the set values of

Table 3: Maintenance cycle of high pressure gas equipment

Items	Maintenance cycle
Whole system	1 year
Compressor	2 year
Pressure gauge	2 year
Thermometer	2 year
Cold Evaporator	3 year
others	1 year
	Cycle of the open inspection
Recovery Compressor	10 years or 3000 hours* of operation
Circulating Compressor	10 years or 30000 hours* of operation
others	Exemption**

*:Operating time for maintenance is recommended by the manufacturer.
**:Dry Helium : There is no worry of thinning or deterioration.

the equipment. Examples of the time required for trouble restoration are 2 hours for restoration from power failure due to lightning strike and 66 hours for stop due to compressor oil temperature abnormality [8].

The KEKB accelerator was operated for 12 years from 1999 to 2010, and the operation time was about 62000 hours. The cause of abnormal stop that occurred during KEKB operation is shown in the Fig. 9. Initially there were many stops due to expansion turbo tripping, interlock due to superconducting cavities, power outage, but there were also malfunction due to aging of electronic equipment at the end of operation.

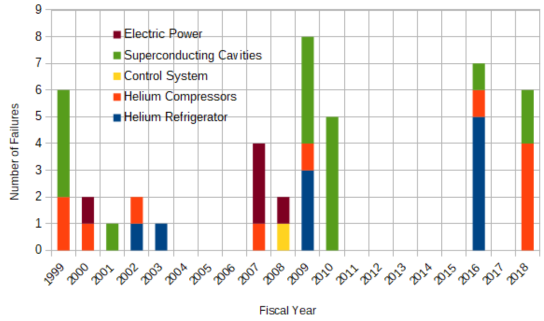

Figure 9: Fatal failures of the helium refrigerator during KEKB/SuperKEKB operation (1999-2018).

The SuperKEKB accelerator operation was carried out in 2016 (Phase1) and in 2018(Phase2). The total operation time is 7700 hours. While the accelerator was upgraded, there was hardly any operation of the refrigerator, but regular inspections were carried out.

HELIUM REFRIGERATOR FOR QCS MAGNETS

In KEKB, Superconducting magnets group were adopted as a final focusing system (QCS). The QCS consists of two superconducting quadrupole magnets, two superconducting solenoids and six superconducting correction coils. In TRISTAN, four QCS systems were adopted, and four helium refrigerators were operated. To cool QCS for KEKB, one refrigerator was diverted [2]. A schematic diagram of the refrigeration system for QCS is shown in the Fig. 10. The capacity of refrigerator is 250 W at 4.4 K. The heat load and the amount of liquid helium used for current lead cooling of this system were 75W and 29L/h, respectively, with a margin of 81 W. The QCS magnets were on both sides of the collision point and the subcooled liquid helium (4.4K, 0.157MPa) was supplied 10g/s respectively.

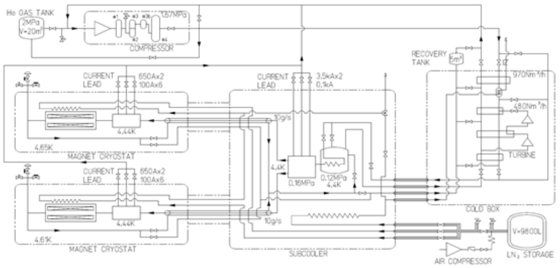

Figure 10: Flow diagram of the QCS cryogenic system.

It takes 1.5 days to cool this system from room temperature and 2 days to warm it up. EX-8000 is adopted as a control system like a refrigerator for a superconducting cavity. The control system of QCS was placed in the control room about 1 km away from the magnet. In the control room there is also a control system for the refrigerator for the superconducting cavities. The total operation time at KEKB was 74123 hours.

The QCS for SuperKEKB was newly developed. Since the new QCS required a larger refrigeration capacity than before, another one of the refrigerators used in TRISTAN was used. Cryostats were placed on both sides of the collision point, and a refrigerator was connected one by one.

HELIUM REFRIGERATOR FOR BELLE-II MAGNET

In KEKB, particles generated by beam collision were measured by a detector called Belle. To carry out the particle analysis, magnetic field was applied in the Belle. To make the magnetic field, a superconducting solenoid was adopted [2]. This superconducting solenoid is a huge one with an inner diameter of 1.8 m and a length of 3.91 m. A helium refrigerator which was used in TRISTAN was diverted to cool the Belle solenoid. A schematic diagram of the refrigeration system for QCS is shown in the Fig. 11.

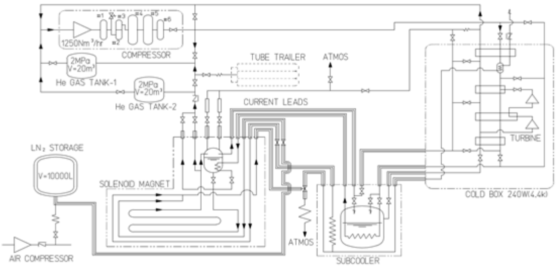

Figure 11: Flow diagram of the Belle solenoid cryogenic system.

The capacity of refrigerator is 250 W at 4.4 K. The heat load and the amount of liquid helium used for current lead cooling of this system were 84W and 26L/h, respectively, with a margin of 102W. Subcooled liquid helium of 10 g / s is supplied through a pipe that is thermally contact with the solenoid, and the magnet is cooled by conduction. The supplied liquid helium becomes a two-phase flow at the pipe exit. It takes 6˜7 days to cool this system from room temperature and 4 days to warm it up. Total operating time at KEKB is 75985 hours and will continue to be used in SuperKEKB.

SUMMARY

In SuperKEKB, refrigerators manufactured for TRISTAN are used. These refrigerators have been operated for a long time by undergoing periodic maintenance. Since superconducting cavities of SuperKEKB are fewer than TRISTAN, the refrigerator for superconducting cavities has sufficient capacity. Hardware development has also been done. The developed a high-performance transfer line and adopted it partly.

In KEKB, superconducting magnets are adopted for QCS and Belle-II. Two of the four refrigerators that had cooled the QCS of TRISTAN were used and cooled QCS and Belle solenoid, respectively.

In SuperKEKB, QCS has been enhanced, so three refrigerators were adopted to cool QCS-L, QCS-R and Belle-II solenoid, respectively.

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