Re-examination of Refrigeration Power of the LHD Cryogenic System after 18 Years of Operation

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***Abstract*—The Large Helical Device (LHD) is a heliotron-type fusion plasma experimental device having the world first fully superconducting magnetic confinement system built in 1990's. The cryogenic system of LHD executed a long-term stable operation for 18 years from 1998 to 2015, and had been proving a high availability that passed 99 %. Unfortunately, a fire accident of the cold box of the helium refrigerator occurred during the maintenance period in August, 2015, and non-metallic components in the cold box, such as multi-layer insulation films, temperature sensors and measuring instruments, etc. were burnt down. After the accident, the restoration work started from November, 2015 and it was completed at the end of July in 2016. The test operation of the helium refrigerator was done in August, 2016, and the refrigeration power was compared with that measured in the initial performance testing done in 1995. The measured equivalent refrigeration power at 4.4 K was 9.16 kW, which showed a decrease of about 2 % from 9.38 kW that was measured 21 years ago. We consider that the slight decrease in this refrigeration power is due to a possible performance deterioration by the aging of 18 years and not by the direct influence of the fire accident. The LHD restarted the operation in January, 2017, and the 19th cycle operation with deuterium plasma experiment was successfully conducted up to August. The operation history and re-operation situation of the LHD superconducting magnet and cryogenic system is reported.**

***Index Terms*—Cryogenic system, Fusion Plasma, LHD, Magnetic confinement, Operation history**

I. Introduction

The Large Helical Device (LHD) is a heliotron-type fusion plasma experimental machine which has the capability of confining current-less, high-density and high-temperature plasmas in steady-state. The steady magnetic field at the plasma center is 3 T. The LHD has a fully superconducting magnet system consisting of the helical coils, poloidal coils and superconducting bus-lines cooled by a helium refrigerator having a total equivalent cooling capacity of 9.2 kW at 4.4 K. The LHD superconducting coils are installed in the cryostat. The size of the LHD cryostat is 13.5 m in outer diameter, 8.8 m in height, and 1,500 tons in total weight. The cold mass at 4.4 K in the cryostat weights 820 tons. Three different cooling schemes are utilized; forced flow of supercritical helium for the poloidal coils, forced flow of two phase helium for the supporting structure for the large electromagnetic forces between the superconducting coils, and pool boiling of liquid helium for the helical coils. The excitation of the LHD superconducting coils has been performed with the superconducting bus-lines, whose maximum current capacity is 31.3 kA and the total length of 9 bus-lines becomes 497 m. The bus-lines are also cooled by forced flow of two phase helium. All components of the LHD superconducting and cryogenic system have been installed as shown in Fig. 1.

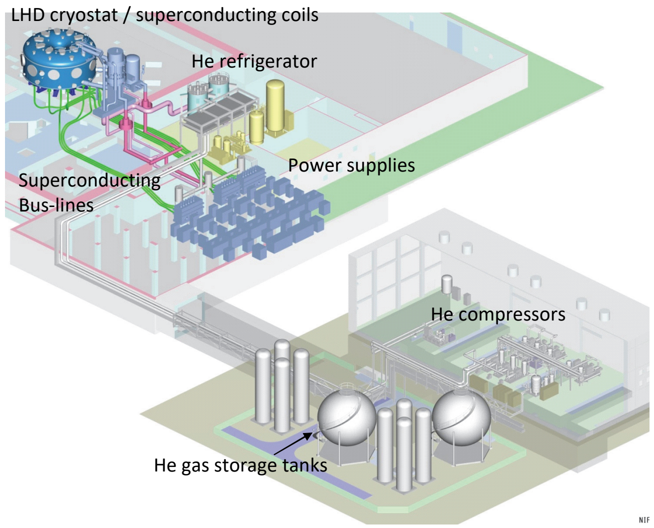

Fig. 1 Layout of LHD superconducting and cryogenic system

II. Restoration of the Helium Refrigerator

A. Fire Accident of the Helium Refrigerator

The cryogenic system of LHD executed a long-term stable operation for 18 years from 1998 to 2015, and had been prov-

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ing a high availability that passed 99 %. Unfortunately, a fire

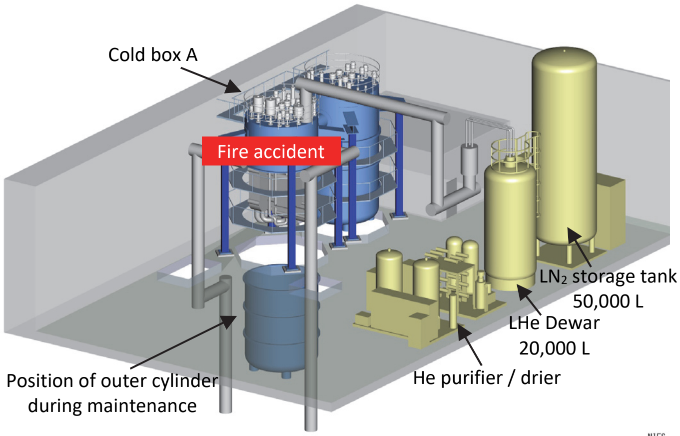

Fig. 2. Equipment layout in the H refrigeration room.

accident of the cold box of the helium refrigerator occurred during the maintenance period in August, 2015. Fig. 2 shows the equipment layout in the helium refrigerator room. The helium refrigerator consists of two cold-boxes divided on high temperature side (cold box B) and low temperature side (cold

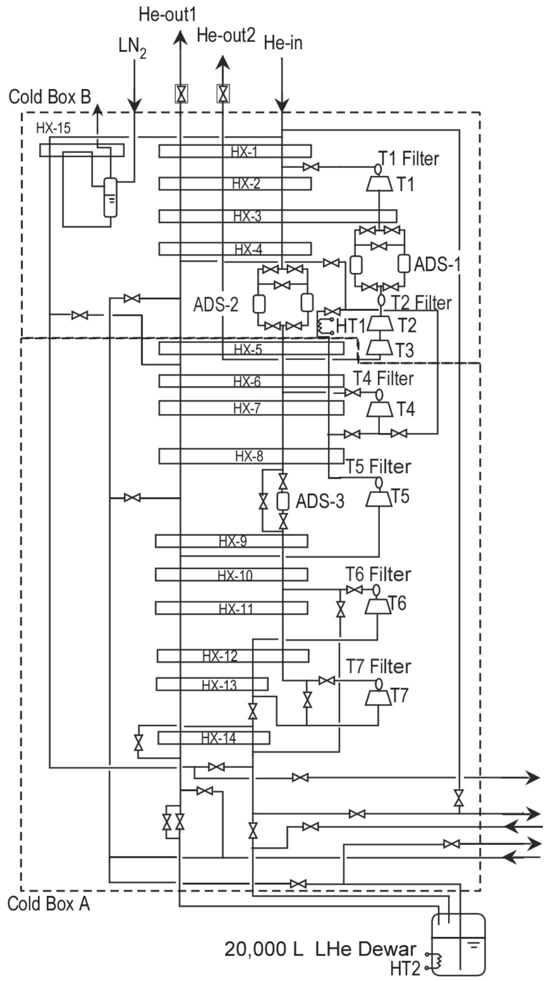

Fig. 3. Configuration in the cold box A and B of the He refrigerator.

box A), the 20,000 liter liquid helium Dewar, the 50,000 liter liquid nitrogen storage tank, and the 50 g/s helium gas purifier / drier. Both cold boxes are covered with the outer cylinder in operation, and is kept in the state of vacuum. In the 18th cycle operation, the differential pressure rise was observed at the turbine inlet filters caused by accumulated contamination during the long-term operation. Then the turbine filters and the internal absorbers (ADS-1) have been exchanged at the maintenance period after the 18th cycle operation. The cold box A in Fig.2 shows the outer cylinder taken down during maintenance and the cold box B shows the situation in operation. The fire accident occurred during the welding operation in the cold box A where a new filter was connected to exchange the fourth turbine inlet filter. Non-metallic components in the cold box A and B, such as multi-layer insulation films, temperature sensors and measuring instruments, etc. were burnt down. Fig. 3 shows configuration in the cold box A and the cold box B. The helium refrigerator consists of 7 expansion turbines (T1 - T7) with dynamic gas bearing and 15 heat exchangers (HX-1 - HX-15). The nominal cooling capacities are 5.65 kW at 4.4 K, 20.6 kW from 40 K to 80 K and 650 L/h liquefaction for the current leads, simultaneously.

After the accident, the restoration work started from November, 2015 and it was completed at the end of July in 2016. The recovery items are listed below.

- Cleaning of building and installation equipment in the helium refrigerator room
- Cleaning inside the cold box
- Cold box function recovery work
    - ･ Check and cleaning of inner surface of piping in the cold box
    - ･ Connection of piping for turbine inlet filters and ADS-1
    - ･ Check of the control valves / manual valves
    - ･ Helium leakage test
    - ･ Check of integrity of piping / heat exchangers
    - ･ Inspection of piping construction part (The completion test on the High Pressure Gas Safety Act retooling application was included)
    - ･ Exchange of 86 temperature sensors (include dual redundant sensors and sensors for interlock) in the cold box
    - ･ Repair of power wiring for heaters and external wiring for sensors
    - ･ Installation of multi-layer insulation films
    - ･ Vacuum substitution with helium gas of piping system
    - ･ Helium gas purification in the cold box
    - ･ Overhaul of ADS-1 exit valve
    - ･ Installation of seven turbines

B. *Test Operation of the Helium Refrigerator*

It aimed to confirm restoration from the fire accident, the test operation of the helium refrigerator was done in August, 2016. The confirmation of the control characteristic according to the exchange of the temperature sensors and the performance characteristic such as the control valves were confirmed at the same time. The test operation was done by the following schedules.

August 1; Preliminary work before the test operation

・Backup and modification of automatic control program for individual operation of the helium refrigerator
・Separation of the helium refrigerator with the LHD superconducting system
・Checking valve opening and closing positions
・Installation of power meters for power supplies of heaters

August 2; Start of the test operation

・Startup of helium compressors
・Purification of helium gas in the helium refrigerator, checking gas purity, dew point

August 3; Start of the precooling stage

・Startup of the turbines No. 1 - 5

August 4; Start of the refrigeration stage

・Startup of the turbines No. 6 – 7

August 5; Measurement of the refrigeration power

・The heater power that corresponds to the refrigeration load was imputed on 4 K and 80 K, and the helium liquefaction capacity was measured by the liquid helium level meter in the 20,000 L LHe Dewar.
・Confirmation of measurement accuracy of the exchanged thermometers in the cold box

August 6 - 7; Warm-up operation

August 8; End of the test operation

・Stop of the helium compressors and end treatment for the shutdown

In usual operation of LHD, one month is needed for the cool-down and one month also needed for the warm-up for the LHD superconducting system, however, the refrigeration power was able to be confirmed by one week operation of the helium refrigerator without the LHD superconducting system.

C. *Re-examination of the measured refrigeration power*

The measured refrigeration power was compared with that measured in the initial performance testing done in June, 1995 as listed in Table I. The refrigerating power at 4.4 K was measured as an input power to the heater (HT2) in the liquid helium Dewar. The helium liquefaction ability at 4.4 K was measured from the rate of increase of the liquid helium level sensor in the liquid helium Dewar. The refrigerating power at 80 K was measured as a heater input power (HT1) set up between the T4 outlet and the T5 inlet. This heater HT1 was controlled so that the temperature of the helium gas at the heater outlet became 80 K by LTIC2023 controller. An equivalent refrigeration power was summarized the above-mentioned three abilities and was converted into the refrigeration power at 4.4 K. The measured equivalent refrigeration power at 4.4 K in 2016 was 9.16 kW, which showed a decrease of about 2 % from 9.38 kW that was measured in 1995. We consider that the slight decrease in this refrigeration power is due to a possible performance deterioration by the aging of 18 years operation such as the dirt of the heat exchangers and not by the direct influence of the fire accident. In the calculation result of the computer simulation, it can explain the decrease in the refrigeration power by assuming that the heat transfer length of the heat exchangers of EX1 to EX4 decreased from 100 % to 87 % by the adhesion such as oil to the heat exchanger surface.

At 34 measuring points of the exchanged temperature sensors, difference of the measurement that became a problem was not observed. More stable operation of the control valves can be achieved by improving software and hardware comparing to the beginning operation in 1995. The LHD cryogenic system stays in a minimum aging by executing an appropriate maintenance, and keeping the sufficient performance though it has been experienced operation of 18 years. It was able to be confirmed that the 19 cycle operation of LHD was possible aiming at beginning of the deuterium experiment.

TABLE I COMPARISON OF MEASURED REFRIGERATION POWER

Refrigeration power	Measurement on August 5, 2016	Measurement on June 17, 1995
4.4 K refrigeration power (Measured by heater input in LHe Dewar)	5.67 kW	5.67 kW
4.4 K liquefaction ability (Measured by He level sensor in LHe Dewar)	606 L/h	704 L/h
80 K refrigeration power (Measured by heater input of LTIC2023)	23.35 kW	20.7 kW
4.4 k equivalent refrigeration power	9.19 kW	9.38 kW

III. 19TH CYCLE OPERATION OF LHD

A. *19th cycle operation of the LHD cryogenic system*

Fig. 4 shows the 19th cycle operation of the LHD cryogenic system. The compressors of the LHD cryogenic system started on December 21, 2016. The purification operation to lower the impurity contamination in the helium cryogenic system lower than 1 ppm, placing the stop period of year end and new year, 338 hours in total was executed. Afterwards, the cool down was done spending 622 hours so that temperature gradient in the superconducting system might become less than 50 K. The steady state operation that kept a superconducting state of LHD was executed for 4,296 hours of from February 6th to August 4, 2017.

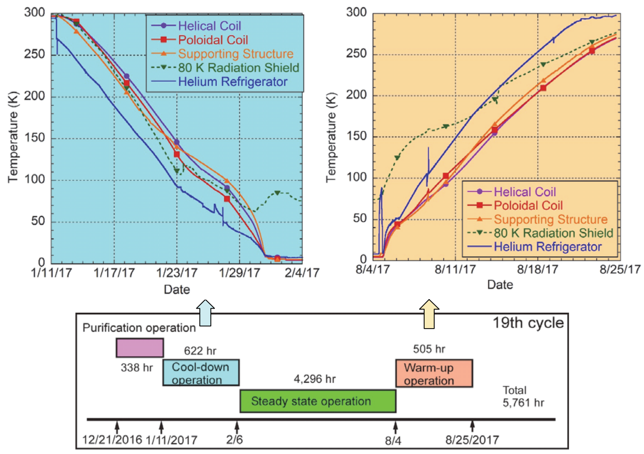

Fig. 4. 19th cycle operation of the LHD cryogenic system.

The deuterium experiment that changed the gas that generated the plasma from the hydrogen into the deuterium began on March 7, 2017. Then 120 million degrees of the ion temperature in the plasma were achieved. This temperature was one of the most important plasma conditions, and established the prospect to the helical-type fusion reactor.

The failure to the stop of the helium compressors did not occur for the period of the steady state operation. However, the failure occurred to the brake valve of turbine 2, and nine hours were required to exchange the actuators. Because turbines 1, 2, 3 had been stopped for the repair work, the refrigeration power was limited during the repair work. As a result, excitation of the superconducting system and the plasma experiment became discontinuance, and needed three days for the restoration. The warm-up operation of the superconducting system began on August 4. The malfunction that the vibration grows was observed to one of the compressors after the warm-up. It returned to the normal operation by the compressor stop time of only 30 minutes by switching to the redundant compressor. The 19th cycle operation completed successfully on August 25, the total operating time became 5,761 hours which is the longest one in the operating history of LHD.

B. *Operation history and availability of LHD*

The operational history of the LHD cryogenic system is summarized in Fig. 5. The total operation time of the system until the end of the 19th cycle was 84,073 hours. The steady state operation time for keeping the system in the superconducting state was 54,653 hours, the purification, cool-down and warm-up time was 29,420 hours, and the stop time to have stopped the compressors by some failures was 742.7 hours.

Fig. 6 shows the availability of each operation cycle. Here, the availability is calculated by Equation (1) using the mean time between failures (*MTBF*) and the mean time to repair (*MTTR*). After the early failure period of the start of operation, the LHD cryogenic system have achieved a high average availability of 99.1 %.

$$Availability = MTBF/(MTBF+MTBR) \quad (1)$$

The failure number during the twenty years of operation

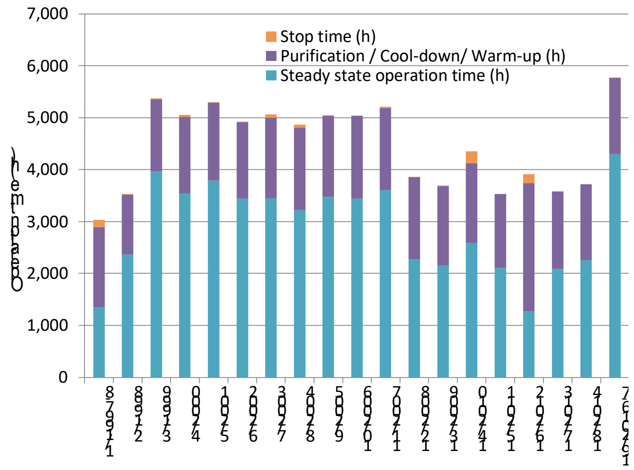

Fig. 5. Operation history of the LHD cryogenic system.

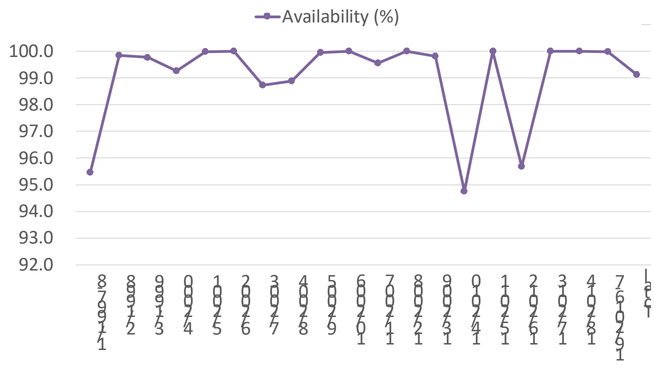

Fig. 6. Availability of the LHD cryogenic system.

TABLE II FAILURE ANALYSES OF THE LHD CRYOGENIC SYSTEM

Cause of failure	Number of failures	Total stop time (h)	MTTR (h)
Control system	11	287.4	26.1
Compressors	6	268.7	44.8
Superconducting coils	1	169.0	169.0
Loss of electric power	5	10.0	2.0
Utility	4	7.5	1.9
Miss operation	1	0.1	0.1
Total	28	742.7	26.5

that caused the cryogenic system to go down, the down time, and MTTR according to the failure causes are summarized in Table II. It was shown that the failures of the control system with a lot of number and the failures of the compressor with long MTTR have the majority of the failure causes for the cryogenic system. There were 28 times failures causing the cryogenic system to stop. However, the total of the down time was only 742.7 hours.

IV. CONCLUSION

LHD restarted operation in January, 2017, and the 19th cycle operation with deuterium plasma experiment was successfully conducted up to August, 2017. After the fire accident, the restoration work started from November, 2015 and completed at the end of July in 2016 and the cooling power was reexamined by the test operation in August, 2016. The LHD cryogenic system stays in a minimum aging by executing an appropriate maintenance, and keeping the sufficient performance though it has been experienced operation of 20 years. Highly reliable operations of the LHD cryogenic system have been achieved with availability of 99.1 %. Total operation time became 84,073 hours from 1997 to 2017.

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