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# Renewal of the control system and reliable long term operation of the LHD cryogenic system

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**Abstract**

The Large Helical Device (LHD) is a heliotron-type fusion plasma experimental machine which consists of a fully superconducting magnet system cooled by a helium refrigerator having a total equivalent cooling capacity of 9.2 kW@4.4 K. Seventeen plasma experimental campaigns have been performed successfully since 1997 with high reliability of 99%. However, sixteen years have passed from the beginning of the system operation. Improvements are being implemented to prevent serious failures and to pursue further reliability. The LHD cryogenic control system was designed and developed as an open system utilizing latest control equipment of VME controllers and UNIX workstations at the construction time. However the generation change of control equipment has been advanced. Down-sizing of control devices has been planned from VME controllers to compact PCI controllers in order to simplify the system configuration and to improve the system reliability. The new system is composed of compact PCI controller and remote I/O connected with EtherNet/IP. Making the system redundant becomes possible by doubling CPU, LAN, and remote I/O respectively. The smooth renewal of the LHD cryogenic control system and the further improvement of the cryogenic system reliability are reported.

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## 1. Reliable long term operation of the LHD cryogenic system

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. Seventeen plasma experimental campaigns have been performed successfully since the 1997 fiscal year with a high reliability of more than 99 %. The total operation time of the LHD cryogenic system has accumulated to 74,595 hour during sixteen years of operation.

### *1.1. Configuration of the LHD cryogenic system*

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 cryogenic system are installed as shown in Fig. 1. The helium refrigerator consists of two cold-boxes divided on high temperature side and low temperature side, the 20,000 liter liquid helium reservoir, the 50,000 liter liquid nitrogen reservoir, and the 50 g/s helium gas purifier. Eight oil-injected screw compressors (960 g/s, 1.9 MPa) with two redundant compressors are installed in the compressor room, which is 50 m apart from the He refrigerator room, and are connected with pipes running in the underground tunnel. Two 700 $m^3$ (2.0 MPa) spherical holders and four 100 $m^3$ (2.0 MPa) cylindrical holders are used as helium buffer tanks to stabilize inlet and outlet pressures of the helium compressors and are also used for balancing the helium inventory in the LHD cryogenic system. Four 100 $m^3$ (2.0 MPa) cylindrical holders are used as supplying tanks of impure helium gas, which must be purified by the purifier before supplying to the He buffer tanks. The total helium inventory is 40,000 $m^3$ and the average consumption of helium gas is about 5,000 $m^3$ per year. About the half of the helium gas consumption is necessary to keep the purity of helium gas during the system operation and the other is used for the leakage test during the system maintenance.

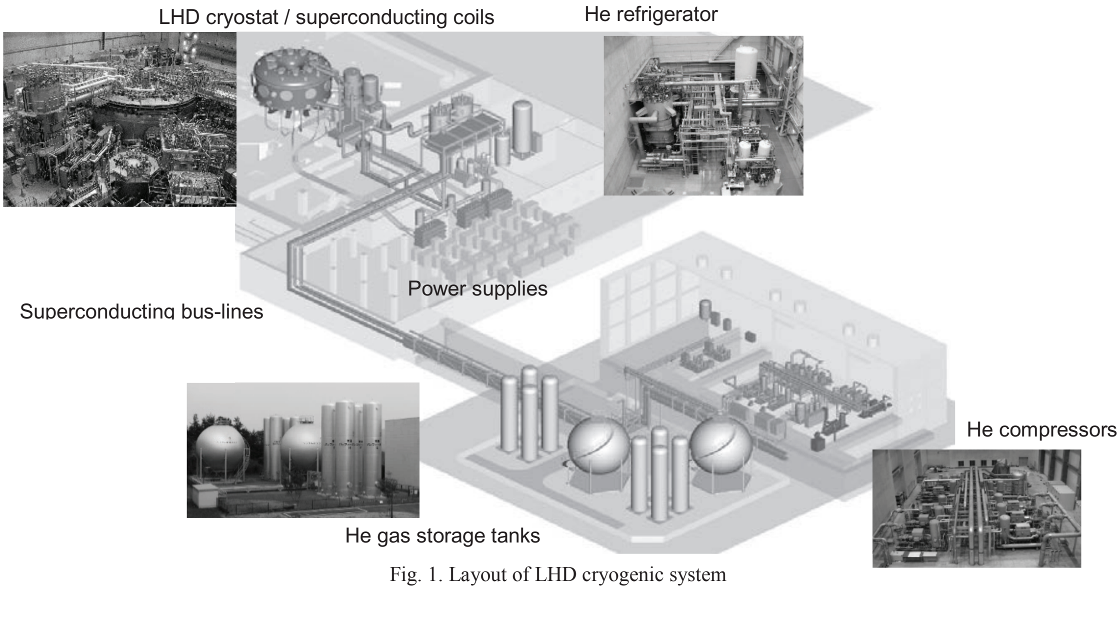


Fig. 1. Layout of LHD cryogenic system

The helium refrigerator consists of 7 expansion turbines with dynamic gas bearing and 15 heat exchangers. The 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. The total equivalent cooling capacity at 4.4 K is 9.2 kW, with the electric power consumption of 3.2 MW.

### *1.2. Operation history and analyses of the system trouble*

The construction of LHD was completed by the end of 1997 and seventeen plasma experimental campaigns have been performed successfully up to the 2013 fiscal year. Typical operation of LHD is once per year except for the first and the second cycles. Before the cool-down of the system, the purification is operated for about ten days to remove impurities in the circulating helium gas. Then the system is cooled down over four weeks. The steady state operation, that continuously keeps the LHD system in superconducting state, continues for about 3 months, and the fusion plasma confinement experiments are executed. After the end of plasma experiments, the system is warmed up to the room temperature for maintenance.

The operational history of the LHD cryogenic system is summarized in Fig. 2. The total operation time of the system until the end of the seventeenth cycle in the 2013 fiscal year was 74,595 hour, and the steady state operation hours for keeping the system in the superconducting state have reached 48,031 hour.

Fig. 3 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 has achieved a high average availability of 99%.

$$Availability = \frac{MTBF}{MTBF + MTTR} \tag{1}$$

At the fourteenth cycle operation, the thrust bearings of the screw compressors broke down after the start of the operation. It required 228.4 hour for the repair, and as a result, the availability of the fourteenth cycle has considerably decreased. It was judged that the cause for the thrust bearing failure depended on metal powders in the compressor lubricating oil that were accumulated during the operations of more than one year. The metal powders have been accumulated because the compressor lubricating oil had not been changed in order to prevent the contamination of cryogenic system with impurities such as water in the oil. The bearings and the lubricating oil of the compressors have been exchanged for the repair. After the fourteenth cycle operation, in addition to the chemical composition management of the lubricating oil, the amount of metal powders in the oil have been also checked during the maintenance period.

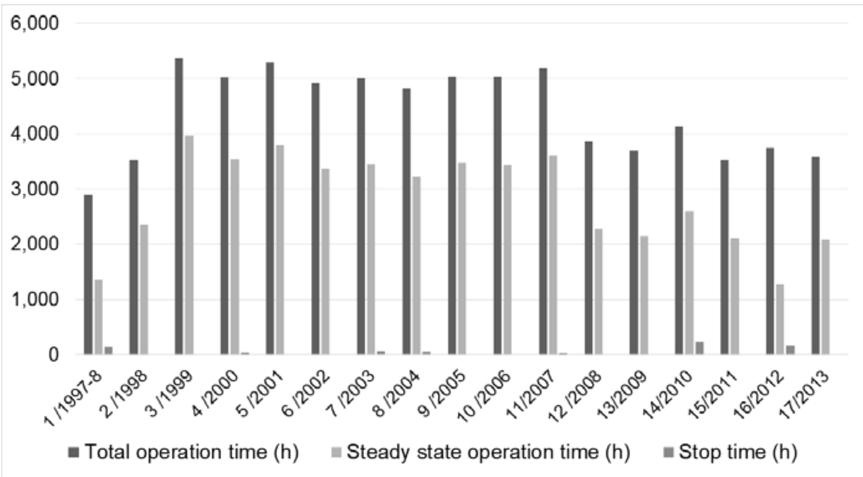


Fig. 2. Operation history of LHD cryogenic system.

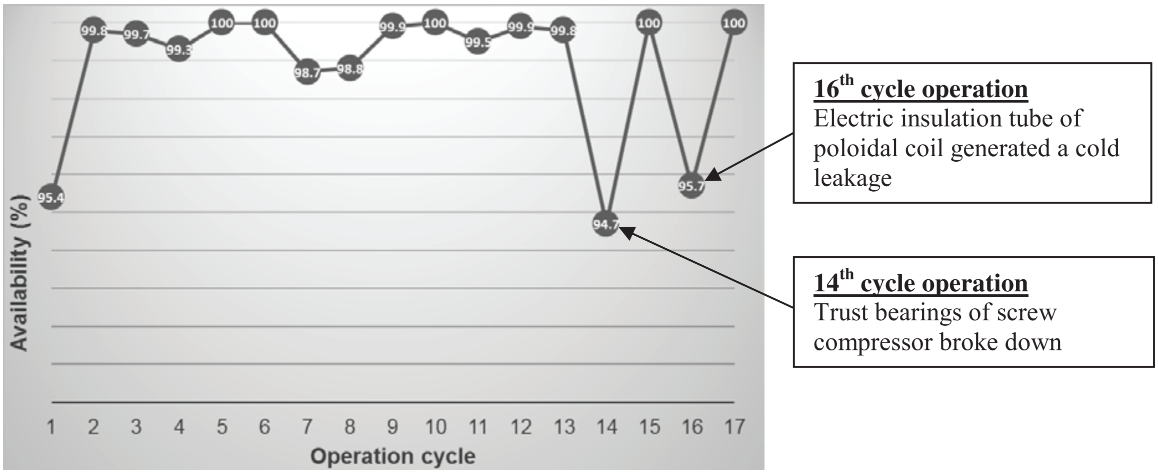


Fig. 3. Availability of LHD cryogenic system.

At the sixteenth cycle operation, the electric insulation tube of the poloidal coil (IS-L coil) generated a cold leakage. The poloidal coils are the forced flow coils of SHe using the cable in conduit conductor. In order to separate between the electric current circuit in serious connection and the SHe flow in parallel connection, electrical insulation tubes are installed at each end of the double pancake coils. The electrical insulation tubes bond metallic conduit to the glass fiber reinforced plastic tube with the adhesive. During the cool down of sixteenth cycle operation, a cold leakage occurred form the bonded part of the insulation tube caused by the aging of the adhesive. In the sixteenth operation, the system was warmed up to repair the insulation tube with a cold leak. After the completion of the sixteenth cycle operation, all insulation tubes (120 places) in the six poloidal coils have been replaced during the maintenance period.

The degradation by the aging of the superconducting coil will become more important in the future. The establishment of diagnostics that prevents the failure beforehand detecting the aging of the superconducting coil is a pressing necessity.

The failure number during the sixteen years of operation that caused the cryogenic system to go down, the down time, and MTTR according to the failure causes are summarized in Table 1. 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 twenty seven times failures causing the cryogenic system to stop. However, the total of the down time was only 742.2 hour.

Table 1. Failure analyses of the cryogenic system during sixteen years of operation.

| Cause of failures | Number of failures | Total down time (h) | MTTR (h) |
|---|---|---|---|
| Cryogenic control system | 11 | 287.4 | 26.1 |
| Compressors | 5 | 268.2 | 53.6 |
| Superconducting coils | 1 | 169.0 | 169.0 |
| Loss of electric power | 5 | 10.0 | 2.0 |
| Utility (cooling water) | 4 | 7.5 | 1.9 |
| Miss operation | 1 | 0.1 | 0.1 |
| Total | 27 | 742.2 | 27.5 |

The LHD cryogenic system has achieved high reliability of 99% and there has been no serious failure that terminates the stable operation. By the result, the LHD keeps offering the stable fusion plasma experiment environment to the fusion scientists and engineers for sixteen years.

## 2. Renewal of the LHD cryogenic system

### *2.1. Addition of redundant compressors*

Two kinds of redundant compressors were added to back up the system when one of eight compressors breaks down. The compressor system of the LHD helium refrigerator consists of A-system of inlet pressure 0.1013 MPa and B-system of inlet pressure 0.203 MPa. The outlet pressure is 1.935 MPa in both A- and B-systems. The A-system is composed of four low pressure compressors and two high pressure compressors. B-system is composed of a low pressure compressor and a high pressure compressor. The eight compressors were not made redundant, and when one broke down, the operation of the cryogenic system could not be continued. Since there is a long time to repair when the failure occurs with the compressor, the availability of the system is remarkably decreased.

Two redundant compressors (R-system) both for the low pressure unit and for the high unit were added to improve the system reliability further. The redundant compressors have the possibility to switch by valves to back up the compressors in low pressure or high pressure and A-system or B-system. In addition, it is possible to replace the operating condition by adjusting the load of the capacity control valve according to the compressor backed up. The redundant compressors were installed in 2012 and have been tested as a back-up condition during the seventeenth cycle operation in 2013.

### *2.2. Renewal of the LHD cryogenic control system*

The LHD cryogenic control system was designed and developed as an open system utilizing latest control equipment of VME controllers and UNIX workstations at the construction time of LHD. However the generation change of control equipment has advanced in sixteen years. Down-sizing of control devices has been done from VME controllers to compact PCI controllers in order to simplify the system configuration and to improve the system reliability.

Fig. 4 shows the previous cryogenic control system with VME controllers. The system consisted of 12 VME controllers for the He refrigerator, the helical coils, the poloidal coils, the superconducting bus-lines and the integrated controller unifying the total system operation. Each VME controller was duplicated for redundancy; one was in active state and the other in standby. The number of control signals was the analogue input AI:1045, the analogue output AO:216, the digital input DI:896, the digital output DO: 768. It became too complicated system because of distributed, redundant system with automated fault diagnosis. The advantage of open system was lost. New VME products have not been developed now because of the down-sizing of control devices. As a result, the system reliability depends on the products of a specific manufacture.

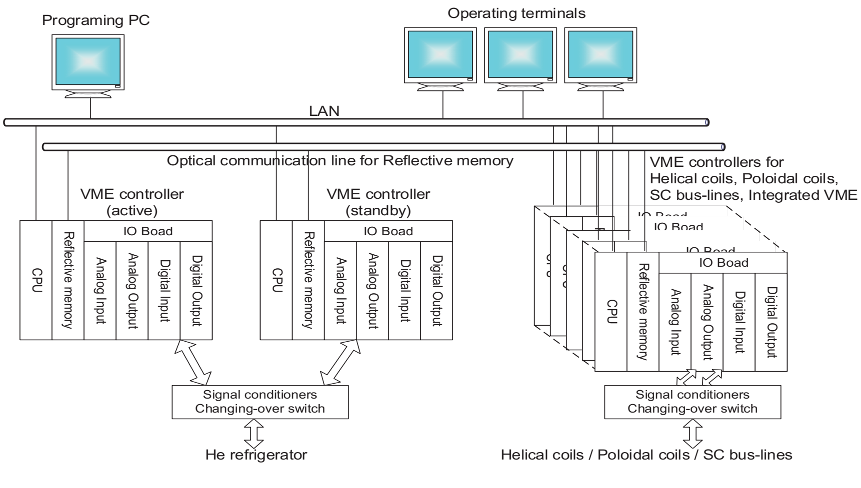


Fig. 4. Previous cryogenic control system with VME controllers.

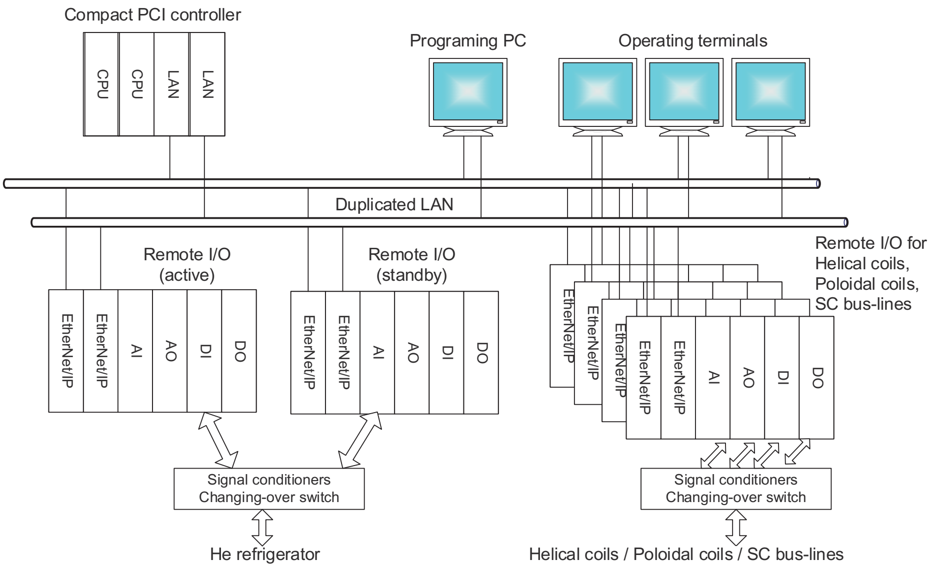


Fig. 5. Renewed LHD cryogenic control system.

For example, the reflective memory, which is necessary for the data sharing between the redundant VME controllers, is limited to a product of a specific manufacture.

Down-sizing of control devices has been done from VME controller to compact PCI controller. Fig. 5 shows the updated new cryogenic control system. The system is composed of compact PCI controller and remote I/O connected with LAN using the industrial communication protocol of EtherNet/IP. Making the system redundant corresponds to doubling CPU, LAN, and remote I/O respectively. The hardware size of the new compact PCI controllers with the remote I/O is reduced about 1/10 of the previous VME controllers with the signal conditioners. Software has interchangeability with the previous VME system. The constructed various automated programs during the operation periods of the cryogenic system can be succeeded to the new control system easily.

The development of the new control system was executed in the 2011 fiscal year, the field test have been done in 2012 and a complete shift to the new control system was completed in 2013. The system is aiming to increase availability by facilitating diagnosing the system failure. The smooth renewal of the LHD cryogenic control system and the further improvement of the cryogenic system reliability have been achieved. When the control system faults, it is necessary to re-start-up the system, it took 30 minutes for the previous VME system but it take only 3 minutes in the new CPCI system. As for this, it is very effective to cutback the mean time to repair of the control system.

## 3. Summary

Highly reliable operations of the LHD cryogenic system have been achieved during sixteen years since 1997. Total operation time is 74,595 hour with a high availability of 99%. The development of a new control system was executed in 2011, and the field tests have been done in 2012. Finally, smooth renewal of the cryogenic control system was completed successfully in 2013.

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