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Achievement of High Availability in Long-term Operation and Upgrading Plan of the LHD Superconducting System

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Abstract. The Large Helical Device (LHD) that has been demonstrating high performance of heliotron plasma is the world's largest superconducting system. Availability higher than 98% has been achieved in a long-term continuous operation both in the cryogenic system and in the power supply system. It will be owing not only to the robustness of the systems but also to efforts of maintenance and operation. One big problem is shortage of cryogenic stability of a pair of pool-cooled helical coils. Composite conductors had been developed to attain the sufficient stability at high current density. However, it was revealed that a normal-zone could propagate below the cold-end recovery current by additional heat generation due to the slow current diffusion into a thick pure aluminum stabilizer. Besides, a novel detection system with pick-up coils along the helical coils revealed that normal-zones were initiated near the bottom of the coil where the field is not the highest. Therefore, the cooling condition around the innermost layers, the high field area, will be deteriorated at the bottom of the coil by bubbles gathered by buoyancy. In order to raise the operating currents, methods for improving the cryogenic stability have been examined, and stability tests have been carried out with a model coil and small coil samples. The coil temperature is planned to be lowered from 4.4 K to 3.5 K, and the operating current is expected to be increased from 11.0 kA to 12.0 kA that corresponds to 3.0 T at the major radius of 3.6 m.

1. Introduction

The Large Helical Device (LHD) is the largest stellarator, which is utilized for the research of fusion plasma near a reactor region [1]. Superconducting magnets are adopted in order to demonstrate steady-state operation, which is essential to magnetic fusion reactors. The magnet system consists of a pair of pool-cooled helical coils, three pairs of poloidal coils made of cable-in-conduit conductors, and nine superconducting bus-lines, as shown in Fig. 1. The major and minor radii of the helical coil are 3.9 m and 0.975 m, respectively. The LHD is the world's largest superconducting system under operation, whose stored energy is 0.9 GJ at the central toroidal field of 3 T. The LHD program is intended in plasma physics research and technology development to prepare for future power reactors.

The first cool-down of the LHD was successfully carried out in the spring of 1998, and first plasma was ignited on March 31, just as scheduled [1]. Since then, nine cycles of plasma experimental campaigns have been performed in eight years, and the plasma parameters have been extended year by year. Availability higher than 98% has been achieved in a long-term continuous operation both in the cryogenic system and in the power supply system. It shows not only the robustness of the system design but also proper efforts of maintenance and operation. We have resolved many kinds of problems, such as initial malfunction of devices, impurity control of helium gas, failure of electrical devices, and so on. A left big problem is shortage of the cryogenic stability of the helical coils [2]. A wide propagation of a normal-zone was observed in the helical coil on the way of the first trial to the design value of 3 T, and the quench detection system acted correctly. In spite of repeated excitations for the coil training, propagation of a normal-zone have been observed several times at almost the same currents even by the slower charging rate. While the causes have been clarified, methods for improving the cryogenic stability have been examined. According to the stability tests with a model coil, we decided to lower the coil temperature from 4.4 K to 3.5 K by utilizing surplus power of the refrigerator. This paper will summarize the achievement of eight years' operation of the superconducting system and the upgrading program.

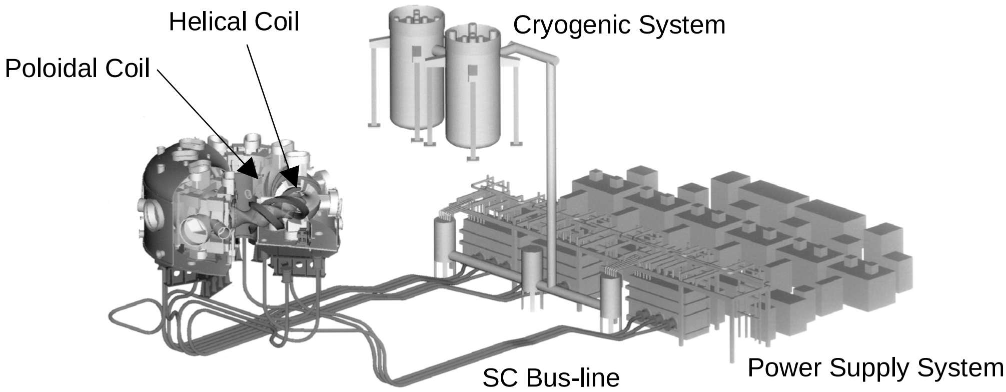

FIG. 1 Superconducting system of LHD.

2. Development of Superconducting Systems of LHD

2.1. Superconducting Magnets

Major requirements for the superconducting magnets in LHD are high dimensional accuracy and stable operation. In addition, a fairly high current density of 40 A/mm^2 is required for the helical coils. Major specifications of the magnets are listed in Table 1. To obtain a high accuracy in the helical shape, we selected pool-cooled medium size conductors for the helical coils. To attain the high current density, a pure aluminum stabilizer was adopted. Various types of conductors with different internal structures were evaluated [3]. The final conductor dimension is 12.5 mm × 18.0 mm, as shown in Fig. 2. The nominal current is 13.0 kA at 4.4 K for 3 T at 3.9 m of the major radius. The aluminum stabilizer was cladded by Cu-2%Ni to reduce magnetoresistance caused by the Hall current while maintaining smooth current transfer from superconducting strands. The specifications of the conductors are listed in Table 2. The helical coil was designed to be cryostable using the measured recovery currents with short samples. However, it was revealed that a normal-zone could propagate at around 11 kA that is significantly less than the cold-end recovery current. The main cause is additional heat generation due to the slow current diffusion into the thick pure aluminum stabilizer [4]. Pickup coils along the helical coils revealed that the recovered normal-zones propagated to one side. The asymmetry of the propagation will be caused by electromagnetic interaction [5, 6]. The helical coil is divided into three blocks, which are I, M, and O-blocks, to change the minor radius of current center and to reduce the voltage during current shut-off. An average current of 11.67 kA was attained by the current grading method, in which the current of the innermost block was decreased and those of the other two blocks were increased. The attained values are shown in brackets in Table 1.

Cable-in-conduit conductors are used for the poloidal coils because of their high strength and rigidity against electromagnetic force. The conductors were designed for the 4 T operation in preparation for the upgrade. The strand surface is uncoated to maintain current redistribution and heat transfer to coolant. A high stability margin of bare strands in DC operation was confirmed with a mock-up coil [7]. The poloidal coils were double-pancake coils, and the accuracy of the coils were attained within ±0.5 mm by using high accurate bobbins and by centering the pancakes during the stacking process [8]. The poloidal coils have demonstrated expected performances and stable operation of cable-in-conduit conductors.

The superconducting flexible bus-line was developed for the current feeding system [9]. The bus-line consists of a pair of aluminum-stabilized superconducting cables and five coaxial corrugated stainless-steel tubes. Liquid helium cools the cables in the center tube and returns through the next outer tube. The aluminum-stabilized compacted strand cable was also developed to achieve a full cryogenic stability for 32 kA. Performance was confirmed with a 20 m full-scale mock-up. The flexible bus-lines were useful for shortening the construction schedule. Also, They have been demonstrating the stable operation of superconducting cables.

TABLE I: MAJOR PARAMETERS OF SUPERCONDUCTING COILS.

Items	Helical coil	IV coil	IS coil	OV coil
Major Radius (m)	3.90	1.80	2.82	5.55
Weight per coil (ton)	120	16	25	45
Magnetic stored energy (GJ)	0.92 [0.74]	0.16	0.22	0.61
Coil current density (A/mm^2)	40 [35.9]	29.8 [22.3]	31.5 [23.6]	33.0[21.7]
Magnetomotive force per coil (MA)	5.85 [5.25]	5.0 [3.74]	-4.5 [3.38]	-4.5 [3.12]
Conductor length (km)	36	2.7	3.7	5.0
Cooling method	Pool-cooled	Forced flow	Forced flow	Forced flow
Coil temperature (K)	4.4	4.5–4.8	4.5–4.8	4.5–4.8

(note) Attained values are shown in brackets.

TABLE II: SPECIFICATIONS OF SUPERCONDUCTING CONDUCTOR FOR LHD.

Items	Helical coil	Bus-line	IV coil	IS coil	OV coil
Superconductor	NbTi	NbTi	NbTi	NbTi	NbTi
Maximum magnetic field (T)	6.9	< 1.0	6.5	5.4	5.0
Nominal current (kA)	13.0	32	20.8	21.6	31.3
Diameter of strands (mm)	1.74	2.91	0.76	0.76	0.89
Number of strands	15	9	$3^4 \times 6 = 486$	486	486
Cu ratio in strand	0.9	1.0	2.7	3.4	4.2
Diameter of filament (mm)	47	30	15	12	14
Number of filaments	726	4891	690	864	750

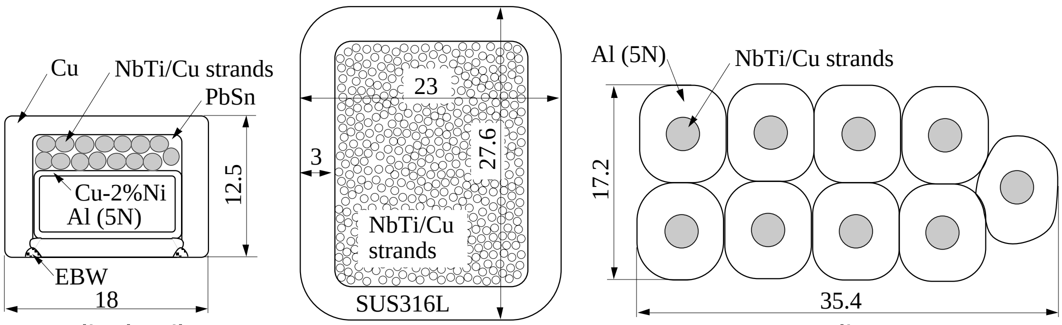

FIG. 2 Cross-section of conductors for the helical coils, the poloidal coils, and the bus-lines.

2.2. Cryogenic System

The cryogenic system for the LHD consists of the helium refrigerator/liquefier [10], a main cryostat, current-leads cryostat, superconducting bus-lines, and two valve-boxes for the helical coils and poloidal coils, as shown in Fig. 3. Reliable long-term operation capabilities are necessary for the cryogenic system because a warm-up of the total system will be done only once or twice a year. In order to realize high reliability and flexibility, a new control system was developed by using standard hardware, such as PCs and VME (Virtual Machine Environment) boards. The software tool packages were developed based on standard operating software that provides us more flexible and easy construction of a control program. These software tool packages have functions of setting a system configuration, easy making graphic control panels, programming sequences, and flow loop control.

Three different cooling schemes are utilized for each cooling objects; a pool-cooling for the helical coils, a forced flow of supercritical helium for the poloidal coils, a forced flow of two-phase helium for the supporting structures and the bus-lines. This system has cooling capacities of 5.65 kW at 4.4 K, 650 liter/hr liquefaction and 20.6 kW at 80 K. Measured and estimated heat loads at steady operation are about 1.9 kW at 4.4 K, 450 liter/hr, and 12 kW at 80 K. In order to prevent a temperature rise in all parallel cooling paths of two-phase helium, a sufficient mass flow is supplied for the supporting structures and the bus-lines, and the returned liquid is evaporated by electric heaters in their outlet tanks. The heating powers at steady operation are approximately 0.4 and 1.1 kW, respectively. Therefore, superfluous refrigerating capacity is more than 2 kW at 4.4 K.

2.3. Power Supply System

The power line system consists of six power supplies and nine sets of current-leads and superconducting bus-lines, as shown in Fig. 4. These power supplies contains thyristor rectifiers, DC filters, quick dump circuits, and quench protection circuits [11]. Because of large mutual coupling factors between the three blocks of the helical coil, each block current is easy to transfer to the other. The self and mutual inductances were measured and adjusted precisely for the accurate current control. The other major feature is the long time constant of the secondary circuit made of the supporting structures of the order of 1 s. We have efficiently dealt with the secondary circuit in the case of rapid control. Each power supply has an own local unit to control the current and voltage. In order to ensure non-interactive control, the necessary voltages are calculated by the central control unit from the measured currents by using the inductance matrix.

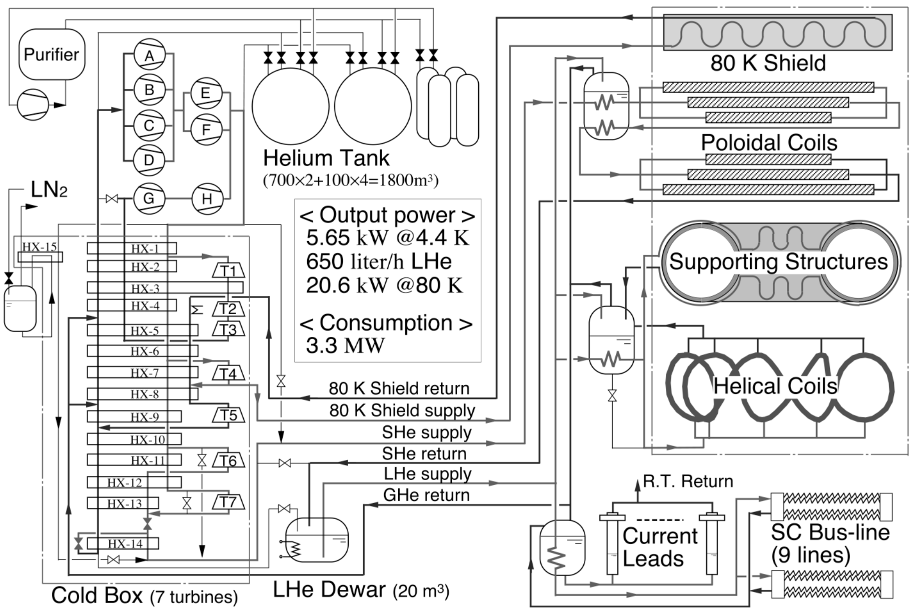

FIG. 3 Flow diagram of LHD cryogenic system.

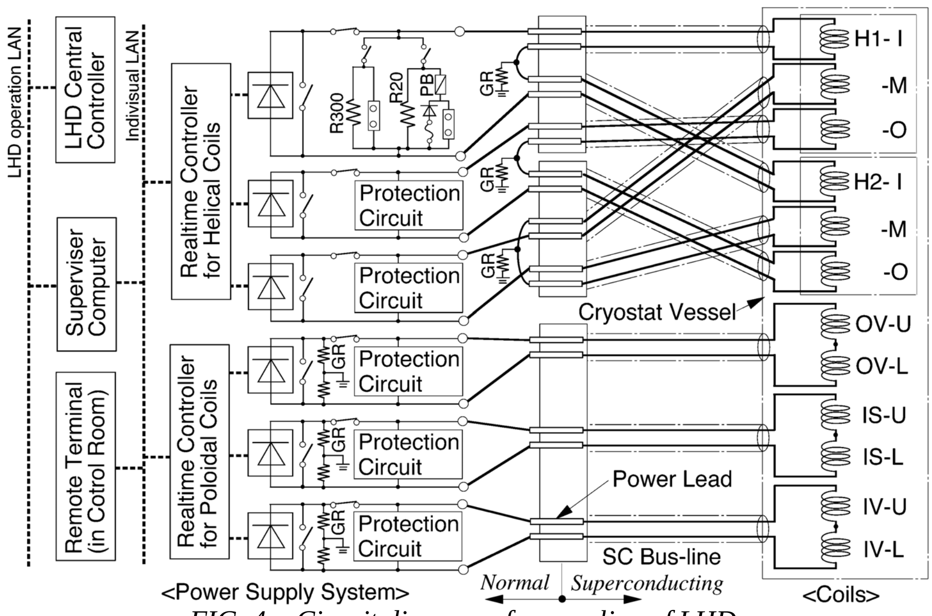

FIG. 4 Circuit diagram of power line of LHD.

3. Operation and Maintenance of LHD Superconducting System

Many types of remodeling, such as a double-loop control, additional helium tanks, impurity control, and premeditated replacement of instruments, have been carried out in the cryogenic system to attain high availability. Major modifications are shown in Table 3. Also, equipment adjustment and improvement of operativeness have been carried out in the power supply system, the main cryostat, and the valve-boxes. LHD technical meetings have been useful for this maintenance. The person in charge of each system has reported a trouble and its countermeasure at the meetings, and its was discussed and improved. Furthermore, the shared information is valuable for improving the other systems.

As the results of efforts of maintenance and operation, high availability has been achieved as shown in Table 4. The stop time and the causes are listed in Tables 5-7 for the compressors, the cryogenic turbines, and the power supply, respectively. In the first and second cycles, main causes of the system stop were initial malfunctions of devices and defects in the architecture of interlock. After that, the main causes have been the failures and malfunctions of electrical devices, such as relays and VME boards. The failures by superannuation are not remarkable yet. Forecast of faults and preventive maintenance are important to maintain the high availability. Concerning the performance of the superconducting magnets, specific excitation tests have been carried out after each cool-down, and any degradation is not observed.

TABLE III: MAJOR MODIFICATION OF THE CRYOGENIC SYSTEM.

Year	Modification of the cryogenic system
1999-2000	Increase of helium gas tank, **Double loop control,** Measures for voltage drop of compressor
2001	Improvement of oil separator, Reinforcement of turbine filter**, High-speed network**
2002	**Replacement to general purpose PC control**
2003	Increase of recovery compressor, Improvement of turbine control valve
2004	Recovery compressor powered by a private generator, Improvement of purifier
2006	Main compressors powered by a new private generator

TABLE IV: AVAILABILITY OF LHD CRYOGENIC SYSTEM AND POWER SUPPLY SYSTEM.

Cycle	Run time (Availability) of the cryogenic system		Run time (Availability) of Power supply system
	Main compressors	Main turbines	
1	2,860 h (95.4%)	1,936 h (99.7%)	692 h (92.4%)
2	3,179 h (99.8%)	2,771 h (99.7%)	442 h (94.4%)
3	5,002 h (99.8%)	4,252 h (99.0%)	708 h (98.3%)
4	5,017 h (99.3%)	3,862 h (99.7%)	632 h (100%)
5	5,292 h (99.9%)	4,097 h (99.8%)	631 h (97.5%)
6	4,920 h (100.0%)	3,768 h (100%)	460 h (98.2%)
7	5,061 h (98.7%)	3,760 h (99.8%)	548 h (99.2%)
8	4,815 h (98.9%)	3,547 h (100%)	578 h (99.3%)
9	5,035 h (100.0%)	3,783 h (99.8%)	669 h (100%)
Total	41,181 h (99.2%)	31,776 h (99.7%)	5,360 h (97.7%)

TABLE V: STOP TIME OF COMPRESSORS OF THE CRYOGENIC SYSTEM.

Cycle	Stop time	Causes (time [h])
1	138 h	VME board (19), Warm-up heater of HC-valve-box (119)
2	4.8 h	Power failure (4.8)
3	12.4 h	Cooling water leak (4.7), VME board (6.5), Power failure (1.2)
4	37.2 h	Failure of delay relay (14.3), Oil pressure switch (13.2), VME board (3.4), Oil leak from a joint (6.3)
5	3.5 h	Power failure (3.5)
6	0.1 h	Compressor trip by over-pressure caused by defective operation (0.1)
7	64.5 h	Oil pressure switch (5.4+4.4), VME board (50.6+4.1)
8	54.1 h	Failure of VME boards (54.1)
9	2.4 h	Failure of a check valve in a water-cooling system (2.4)

TABLE VI: STOP TIME OF TURBINES OF THE CRYOGENIC SYSTEM.

Cycle	Stop time	Causes (time [h])
1	6.8 h	VME board (6.8)
2	7.5 h	Power failure (7.5)
3	45.1 h	VME board (10.3), Rotation meter (11.2), Power failure (6.1), Failure of an oil pump motor of a compressor (17.5)
4	10.8 h	Brake valve (10.8)
5	7.3 h	Power failure (5.5), Brake valve (1.8)
6	0	
7	7.3 h	VME board (0.7), Oil pressure switch (6.6)
8	0	
9	6.9 h	Failure of a check valve in a water-cooling system (6.9)

TABLE VII: STOP TIME OF THE POWER SUPPLY SYSTEM AND THE CAUSES.

Cycle	Stop time	Causes (time [h])
1	57 h	DCCT failure (48), Voltage drop (2×2), LAN (2+1), PC error (2)
2	26 h	Voltage drop (2×4), LAN (2×2), Relay (2×3), Controller (2×3), Defective operation (2+2)
3	12 h	VME memory (2), LAN (2), DCCT (2×2), Over current (2), Cooling water (2)
4	0	
5	16 h	Over current (2×2), Voltage sensor (2×4), Relay (2), VME memory (2)
6	8.5 h	VME transceiver failure (4.5), VME memory (2×2)
7	4.6 h	VME memory (4.3), Defective operation (0.3)
8	4.0 h	VME memory (2), Defective operation (2)
9	0	

4. Upgrading Plan of Helical Coils

4.1. Methods to improve cryogenic stability

In steady operation, the helical coils are cooled by saturated helium from the reservoir through a pre-cooler in the valve-box. The flow rate for the helical coil is controlled to keep the liquid level in a buffer tank in the main cryostat, and the average flow is about 5 g/s. A novel detection system with pick-up coils along the helical coils revealed that normal-zones were initiated near the bottom of the coil where the field is not the highest. Therefore, the cooling condition around the innermost layers in the high field is considered to be deteriorated at the bottom of the coil by bubbles gathered by buoyancy.

Upgrading methods were studied for the cooling system of the helical coils with utilizing the superfluous capacity that is more than 2 kW at 4.4 K at steady operation [12]. It is known that the cryogenic stability is improved at the lower temperatures by being subcooled or by being evacuated. The former was selected because of the higher withstanding voltage of the coil and the lower possibility of air mixing. A set of cold compressors was selected to reduce the size of the additional cryostat, and the modification of the cooling flow was determined as the dashed line in Fig. 5. In order to lower the coil temperatures against steady heat inputs, a sufficient amount of subcooled helium must be supplied continuously. Since the return is only a gaseous line, electric heaters at the coil outlets are needed to evaporate the liquid helium. Design values of the mass flow and the inlet temperature were determined to be 50 g/s and 3.1 K, respectively, in order to adopt a set of cold compressors with rating practice within the surplus capacity of the helium refrigerator. The expected average temperature of the helical coil is 3.5 K under the steady heat input of 100 W. The increment of heat load is estimated to be 1.6 kW at 4.4 K that consists of 280 W at the subcooling heat exchanger, 360 W by the cold compressors, and 1 kW of evaporating power at the outlets of the coil.

4.2.Effect of being subcooled

In order to estimate the effect, the cryogenic stability in saturated and subcooled helium was examined with the model coil and the small coil samples. These coils were made of the same composite conductor as the helical coil. The model coil was wound by layer winding of 24 turns and 12 layers. The highest magnetic field of 6.9 T at 13 kA, the same as the helical coil, occurs at the middle turn of the innermost layer, which is the testing region for the cryogenic stability. The wetting surface fraction of the conductor and the cooling flow of the model coil were designed to simulate the helical coil [13]. Normal-zones were initiated by the tape heater inserted between the conductor and the spacer. In subcooled helium the increment of the minimum current for a normal-zone propagating, $I_{(mp)}$, is almost proportional to the degree of subcooling, and it is increased from 11.2 kA at the saturated temperature of 4.4 K to 11.7 kA at 3.5 K. This improvement is considered to be caused by the slightly higher heat flux in the convection and nucleate boiling region at the lower temperature. In saturated helium the $I_{(mp)}$ varies from 10.7 kA to 11.2 kA, and the cryogenic stability is divided into two groups. The well-cooled condition was attained by being subcooled once, and it continued even after the coil quench. The wetting area at the narrow space between the conductors and the spacers may have been improved.

In the LHD helical coils, it was evaluated from balance voltages of the coils that most of the normal zones were induced at the last turn in the third layer. Figure 6 shows the load lines and the minimum currents for propagation of the model coil and the helical coil. From the comparison of the propagation velocities, the present cryogenic stability of the LHD helical coil is considered to be worse than or equivalent to the model coil before being subcooled. According to the test results of the model coil and comparison of the difference of the magnetic field, the operating current is expected to be increased to 12.0 kA by lowering the coil temperature to 3.5 K.

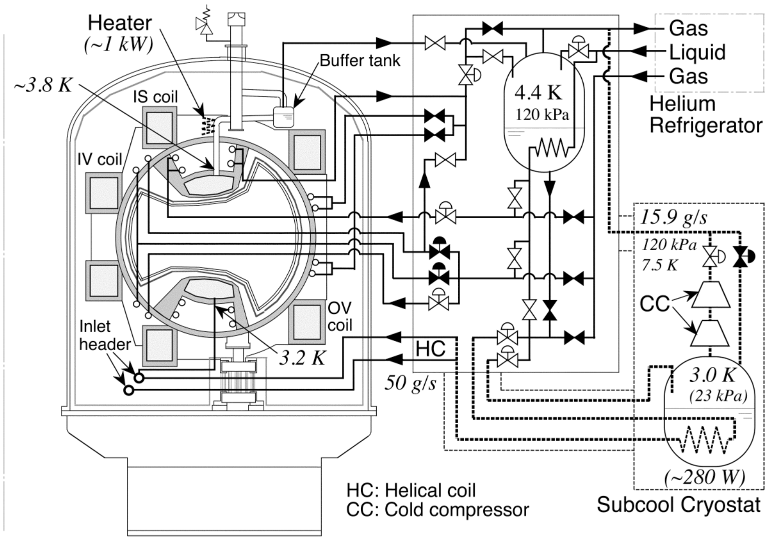

FIG.5 Flow diagram of the helical coil and supports. The added lines are drawn with dashed lines.

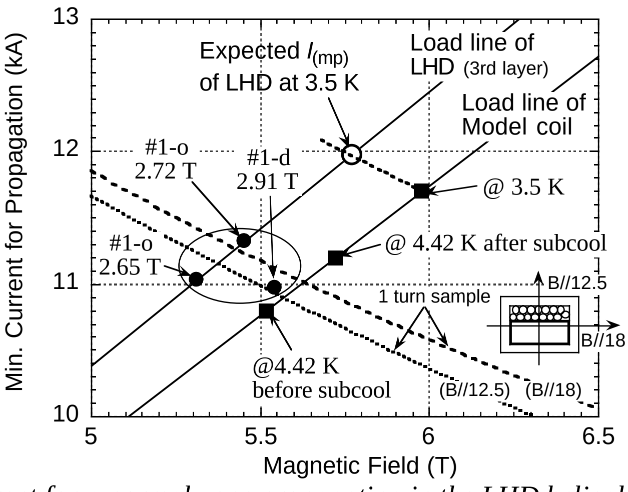

FIG. 6 Minimum current for a normal-zone propagating in the LHD helical coil and the model coil.

5. Summary

The LHD, the world's largest superconducting system, has been demonstrating a stable operation. Total run time of the cryogenic system has exceeded 40,000 hours since the first cool-down in 1998. Owing not only to the robustness of the system but also to efforts of maintenance and operation, availability higher than 98% has been achieved both in the cryogenic system and in the power supply system. Although the cryogenic stability of the pool-cooled helical coils is not sufficient due to slow current diffusion into a thick pure aluminum stabilizer, a stable operation has been performed at 2.7 T about 90% of the nominal current. No degradation is observed in the performance of the superconducting magnets. In order to raise the operating currents, methods for improving the cryogenic stability have been examined. Moreover, the dynamic cryogenic stability of the composite conductor was clarified with a model coil and small coil samples. The helical coil temperature is planned to be lowered from 4.4 K to 3.5 K, and the operating current is expected to be increased from 11.0 kA to 12.0 kA that corresponds to 3.0 T at the major radius of 3.6 m. These experiences of maintenance and operation should be useful for next large superconducting systems. Also, the research of upgrading the helical coil should be valuable to improve the performance of superconducting magnets.

Acknowledgments
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