PROGRESS SUMMARY OF LHD ENGINEERING DESIGN AND CONSTRUCTION

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Abstract

In March 1998, the large helical device (LHD) project finally completed its 8 years construction schedule. LHD is a superconducting (SC) heliotron type device with R=3.9 m, a_p=0.6 m, and B=3 T, which has simplex and continuous large helical coils. The major mission of LHD is to demonstrate the high potential of currentless helical-toroidal plasmas, which are free from current disruption and have an intrinsic potential for steady state operation. After the intensive physics design studies in the 1980's, the necessary programs of SC engineering R&D were made and carried out, and as a result, LHD fabrication technologies were successfully developed. In this process, a significant database on fusion engineering has been established.

These achievements have been made in various areas, such as the technologies of SC conductor development, SC coil fabrication, liquid helium (LHe) and supercritical helium (SHe) cryogenics, development of low temperature structural materials and welding, operation and control, and power supply systems and related SC coil protection schemes. They are integrated, and nowadays comprise a major part of the LHD relevant fusion technology area. These issues correspond to a necessary technological data base for the next step of future reactor designs. In addition, we could increase this with successful commissioning tests just after the completion of LHD machine assembly phase, which consisted of vacuum leak test, LHe cooldown test, and coil current excitation test. We recapitulate and highlight these LHD relevant engineering developments in this paper.

To summarize our construction of LHD as an SC device, the critical design with NbTi SC material has been successfully accomplished by our R&D activities, which enables us to move into a new regime of fusion experiments.

1. INTRODUCTION

A major goal of the LHD project is to demonstrate a high potential of the Heliotron-type device by producing currentless-steady-state plasmas with a large Lawson parameter but without any hazardous plasma current disruptions. LHD is a superconducting toroidal device with a continuous helical divertor as a powerful plasma edge control tool. It has ℓ/m = 2/10 SC helical coils and three sets of SC poloidal coils, of which major radius, minor plasma radius, magnetic field strength, maximum coil currents and the stored energy are 3.9 m, 0.6 m, 4 T, 7.8 MA, 5.0 MA, -4.5 MA, -4.5 MA, and 1.6 GJ, respectively. LHD construction has been completed and currently, it is being successfully operated at 1.5 T, which is half of these nominal specification. A bird's eye view of the LHD experimental hall

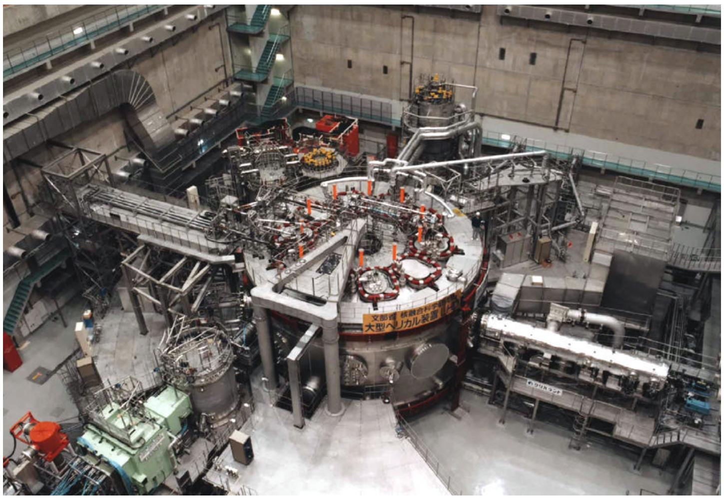

Fig. 1 Bird's eye View of LHD after Completion.

Table 1 Specifications of LHD.

Major Radius (m)	3.9
Coil Minor Radius (m)	0.975
Averaged Plasma Radius (m)	0.5~0.65
n, m	2, 10
Magnetic Field (T)	3 (4)
Helical Coil Current (MA)	5.85 (7.8)
LHe Temperature (K)	4.4 (1.8)
Poloidal Coil Current	
Inner Vertical Coil (MA)	5.0
Inner Shaping Coil (MA)	-4.5
Outer Vertical Coil (MA)	-4.5
LHe Temperature (K)	4.5
Plasma Volume (m^3)	20~30
Heating Power (MW)	40
Coil Energy (GJ)	0.9 (1.6)
Refrigeration Power (kW)	9 (~15)
Total Weight (ton)	1,500
LHe Cooled mass (ton)	850

and basic specifications of LHD are shown in Fig. 1 and Table 1 [1][2].

The engineering missions of LHD during its construction phase have been clearly focused upon developments of Super-Conducting (SC) coil technologies. Since physics missions lie on the understanding and development of currentless steady-state plasmas with high and improved performances near the break-even condition, developments of new SC technologies were strongly required, which assured adequate plasma capabilities, and high technical feasibility for the experiments. Major issues were the realization of two interlinked huge continuous helical coils and three sets of circular poloidal coils with a higher coil-current density and a higher required magnetic field than existed at that time in the world.

The total construction plan was carefully established to meet the above physics requirements taking into account the expected and possible engineering developments. LHD construction schedule consists of five parts, i.e., 1) conceptual design, 2) research and development (R&D), 3) engineering design, 4) construction and assembly, 5) commissioning test and 6) first plasma production. This is shown in Fig. 2.

The technical solution logically converged to the usage of NbTi [3]. Since the maximum magnetic field on the coil surface is about twice that on the plasma axis, in order to get the maximum value of 4 T here, the value on the coil surface becomes higher than critical field BC at 4.4 K. To solve this problem, subcooled or super fluid He cooling were proposed and it was decided to utilize the latter. Therefore, nowadays, LHD machine operation and experimental plan are divided into two phase. In

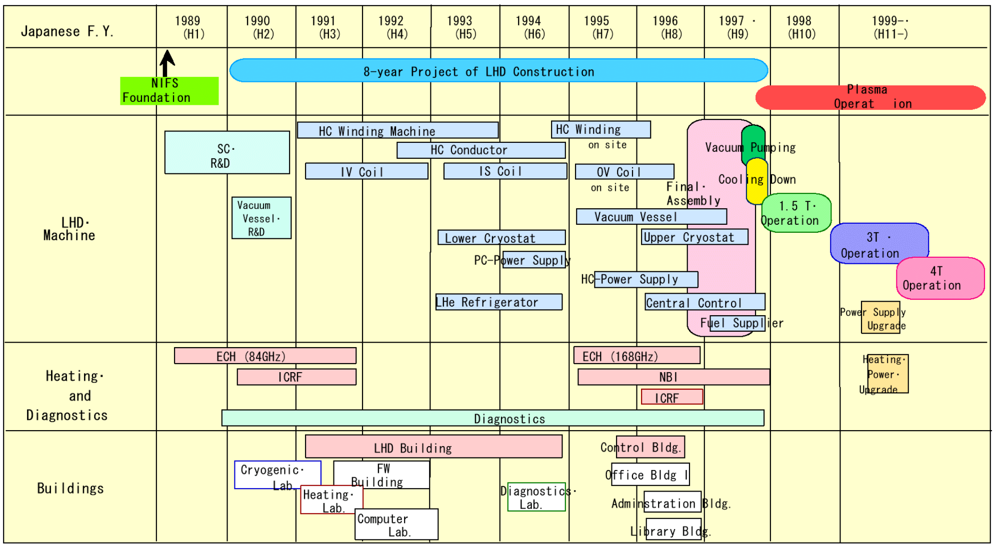

Fig. 2 Construction Schedule of LHD.

the first phase I, field strength on the axis is 3 T using normal LHe, and after that in the second phase II, completing necessary technical improvements, we will try to increase the magnetic field up to 4 T. The final specification of coils system decided is summarized in Table 2.

Table 2 List of Coil Parameters.

	Helical Coil	IV Coil	IS Coil	OV Coil
Superconductor	NbTi/Cu	←	←	←
Conductor Type	Compacted Strands	CICC	←	←
Cooling Method	Pool-Cooled	Forced Flow	←	←
Conductor Size (mm)	12.5×18.0	23.0×27.6	23.0×27.6	27.5×31.8
Major Radius (m)	3.9	1.80	2.82	5.55
Weight per Coil (tons)	120	16	25	50
Maximum Field in Coil (T)	9.2	6.5	5.4	5.0
Stored Energy (GJ)	1.6	0.16	0.22	0.61
Nominal Current (kA)	17.3	20.8	21.6	31.3
Coil Current Density (A/mm^2)	53	29.8	31.5	33.0
Magnetomotive Force (MA)	7.8	5.0	-4.5	-4.5
Hoop Force (MN)	356	262	116	263
Up-down Force (MN)	240	-60.2	95.6	72.2
Diameter of Filament (μm)	47	15	12	14
Diameter of Strand (mm)	1.74	0.76	0.76	0.89
Number of Strands	15	486	←	←

2. ISSUES AND BASIC SCHEME OF SC R&D

The intensive R&D program was carried out immediately after NIFS was founded in 1989. The items of major R&D issues are summarized in Table 3. The R&D items clearly show the progress of SC technology which consist of component development and system integration. The results of R&D primarily comprise this paper and it is possible to say that the obtained data base would assist the further progress of SC technology as an important academic contribution. In this R&D process, major achievements are the development of a fully stabilized conductor for the helical coil, a new CIC conductor for the poloidal coil, and winding and assembling techniques. We could certify our novel technologies by several R&D coil tests and a completed coil commissioning test. The R&D test facilities at NIFS, 200 ℓ/hr LHe liquefier, 500 ton LHe temperature mechanical testing machine, 9 T test magnet adequately meet the demands of these R&D programs [2][4].

Here, in Fig. 3, we summarize initial design criteria, practical engineering schemes and achievements for these helical and poloidal coils which originated during the design and construction period. The mechanical accuracy required for these coils is very high, which necessitates engineering innovations for toroidal magnetic fusion devices. This importance was first pointed out and realized in

Table 3 R&D Items for SC Coil.

1. Conductor Developments
   NbTi, High Stability Margin, High Current Density, Reduced AC Loss, Large Mechanical Rigidity
2. Small Coil Tests
   Kyoto-SC, Toki-WT, Toki-MC, Toki-PF, Toki-HC, Toki-TF
3. Coil Fabrication
   Development of Winding Machine, Method to Improve Rigidity of Coil Package
4. Coil Assembling Technique
5. Method of Electrical Insulation
6. Development of Low Temperature Structural Materials and Method of Welding
7. Lhe Refrigeration and Cryogenics
8. Bus Line
9. Coil Power Supply and Coil Protection
10. Real Coil Test
    EXSIV-IV Coil Test
11. Sample Tests and Assessment
12. System Integration
13. Method of Quality control
14. Etc.

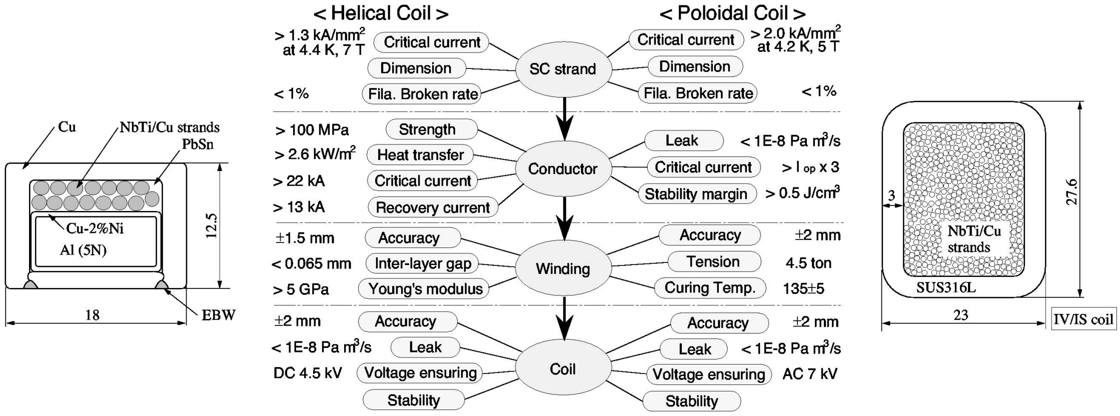

Fig. 3 Quality Control Scheme of LHD SC Coil.

the Heliotron E project [5]. The typical required value in LHD is ±2 mm for m/n = 1/1 deformation. There are two major reasons for this requirement in both physics and SC coil technology. One is the allotted error field level of $B_{error}/B_0 = 10^{-4}$, which corresponds to the coil deformation of ±2 mm and produces an 3~4 cm island averaged in the LHD vacuum magnetic surface structure. This is thought to be the allowable maximum and also the reasonable amount to realize the unperturbed field configuration for the advanced and precise physics confinement experiment. Another important reason arose from the requirement to actualize the rigidity of the helical coil package. Since the helical coil adopted pool-boiling-type SC conductor, the inter-layer gap accuracy between conductors and insulators is required to be less than 0.065 mm. This is the condition to get a higher Young's modulus of the coil package to withstand huge magnetic force of 40,000 ton in total [6]. Otherwise the helical coil would suffer SC quench phenomena by a small displacement between conductors and the resultant friction heat.

As for the poloidal coils, which use CIC conductors, this gap problem does not occur. However, the required accuracy is in the same range due to the need to suppress the low mode error field. In this coil, we tried to increase a stability margin more than 500 mJ/cm^3 [7]. Resultantly, the high stability margin more than 1,000 mJ/cm^3 was confirmed by the R&D coil test and numerical analyses.

In Fig.3, other key parameters are summarized for both helical and poloidal coils. During the R&D phase, these issues were intensively investigated and settled by real and practical engineering based achievements. The cross-sections and basic specifications of conductors are shown in this figure. It is possible to see clearly the different characteristics among specifications of both coils. A reasonable amount of optimization design has been conducted during this process.

3. HELICAL COIL DEVELOPMENT

In this section, we highlight the technology used to manufacture NbTi pool-boiling type helical coils. Many types of superconductors with different internal structures were proposed and examined with short sample tests [8]. The final conductor size is 12.5 mm × 18.0 mm, and the nominal current is 13.0 kA (4.4 K/Phase I), and 17.3 kA (1.8 K/Phase II). Total length necessary reaches to 36 km. It took one year and a half to complete the on-site winding by working night and day. Pure aluminum (to within 5 digits) is the main stabilizer. The conductor size has been optimized not only for mechanical flexibility to facilitate the on-site winding process but also for cryogenic stability due to the optimization of the surface/volume ratio. Fifteen NbTi superconducting strands are twisted and formed into a Rutherford-type flat cable. Instead of conventional OFCu, Cu-2%Ni (thickness: 0.4 mm, resistivity:~2.5×10^{-8} Ωm) was selected for the clad material around the aluminum to insulate the Hall current [9] while maintaining the smooth current transfer from the superconducting strands to the aluminum. Another important development of this conductor is the adoption of electron beam welding to the half-hard copper sheath, which dramatically enhances the mechanical toughness of the conductor not only against the compressional stress of up to 100 MPa during excitation but also against plastic deformation during the three dimensional winding process. The conductor surface is oxidized to improve the heat transfer to the liquid helium.

These results are summarized in Fig. 4, which illustrates that we could succeed to reach a critical design and fabrication using the SC material of NbTi. In this figure, the ideal numbers targetted in the design and R&D are expressed by a circle of 100 % for individual technological elements, which are the expected maximum for NbTi composite conductor. Of importance is that practically achieved values during our R&D and construction are plotted and these show the progress of each item. A typical example is the critical field of NbTi which is shown at the top of this figure. Other items are current density, heat flux exchange rate, stress level and so on. The values obtained in the LHD R&D and construction have almost reached the critical and specified values of NbTi characteristics. Due to our effort to develop a critical design, the current density of the helical coil package is increased up to 53 A/mm^2 with the feasible pressure level of 100 MPa and with a high mechanical accuracy of ±2 mm. In addition, this helical coil conductor satisfies the SC fully-stable condition.

These are the basic parameters which decide the machine capability, which are also obvious ones to assess the achievements of LHD helical coil assembling technique. In this figure, existing vales of previous machines data points are shown for references. In other words, LHD has extended the possible operation regime by almost a factor of two and successfully completed the critical design.

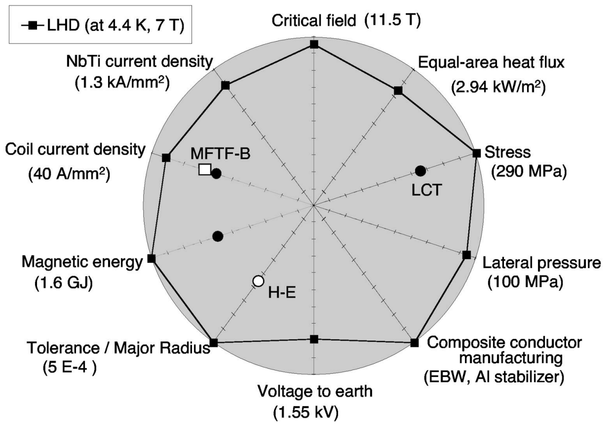

Fig. 4 Summary of SC Technology Developed for Helical Coil. (NbTi Composite Conductor)

4. RESULT OF SC COIL FABRICATION TECHNOLOGY

The main body of the LHD consists of an SC coil system (helical and poloidal coils), supporting structures for the magnetic force, a vacuum chamber, an outer cryostat, and a base. The total weight is about 1,500 ton, in which the LHe cooled mass is 850 ton. The required capability for the helium refrigerator is 2,700 ℓ/hr at 4.4K. With this large refrigerator, it takes approximately two weeks to cool down the system .

The executed design tasks of the LHD have typically made a large contribution to the fusion mechanics. The mass of the supporting structure for the LHD superconducting magnet system is more than 400 ton, which sustains the total magnetic force of 40,000 ton. Due to the requirements for the high rigidity and compactness of this supporting structure, the coil system is directly welded to a thick and heavy SUS316 cylinder, the so-called supporting shell. The thickness and minor radius are 100 mm and 1.8 m, respectively . Since the one-turn electrical break is not necessary, unlike the tokamak-type device, such supporting configuration is applicable for the LHD. Helical and poloidal coils are mechanically and electrically linked tightly with each other. Therefore, the coil assembling design and fabrication process were required to be well balanced in many engineering issues and situations.

The helical coil conductor was finally wound into the helical-coil-can which was again welded to the supporting shell with the shell-arm. In this process, a special winding machine with 13 axis

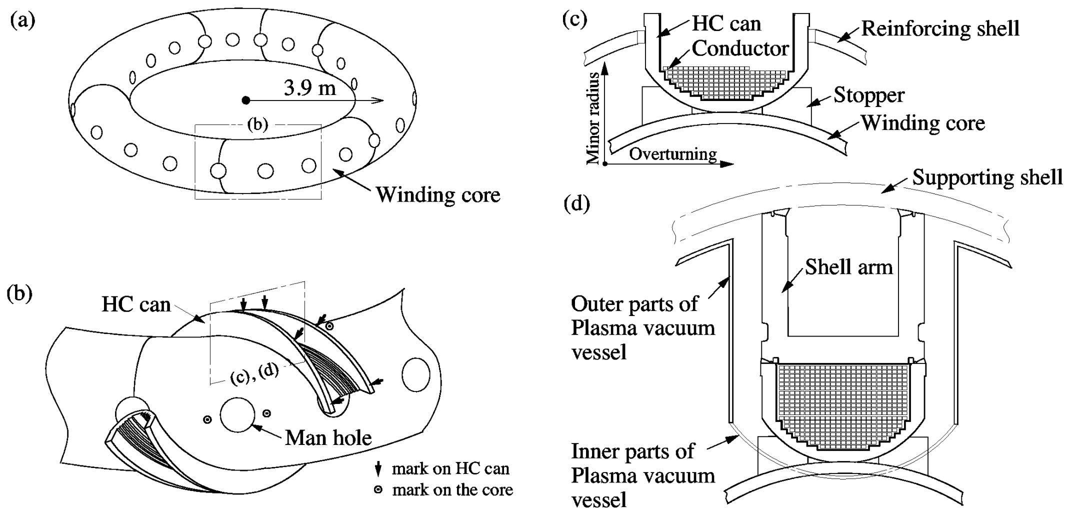

Fig. 5 Manufacturing Process of Helical Coil Package.

computer control was developed and utilized . The method to support the poloidal coils was also carefully decided. All the poloidal coils were stiffly fastened to the supporting shell in all directions. By stiffly fastening the poloidal coils to the shell, their displacement becomes small and symmetric, which is quite important to guarantee the presence of good magnetic surfaces. The process to manufacture the helical coil package is illustrated in Fig. 5.

The mechanical accuracy of each coil is summarized in Table 4. From this table, it is clear that a slight accumulation of error occurred but finally stayed at a very accurate level. This was demonstrated by the electron beam mapping measurement with fluorescent mesh screen at 0.25 T, which is shown in Fig. 6. The left figure shows the calculated vacuum magnetic surfaces and the right figure indicates the observed magnetic surfaces. The coincidence of both figures is remarkable and this demonstrates the high accuracy and successful fabrications of the helical coils and the poloidal coils.

Table 4 Accuracy of Coils of LHD.

<Errors of Fabrication of Helical Coils(3σ)>				
	Bobbin (HC can)	Winding	Welding to Shell	Total
Minor radius (mm)	±1.43	±1.07	<±1.0	<±2.1
Overturning (mm)	±1.50	<±0.75	<±1.0	<±2.0
Ave. Major radius (mm)	-0.6	-0.3	-0.6	-1.5
<Errors of Fabrication & Installation of Poloidal Coils>				
	Each Pancake	Coil (ave.)	Installation into shell	Total
Major radius (mm)	<±2.0	<±0.33	<±1.0	<±1.4
Height (mm)	—	<±0.5	<±1.0	<±1.5

5. COMMISSIONING TEST

Immediately after the completion of the LHD assembling process at the end of 1997, the carefully programed commissioning test started. This process consists of 1) vacuum evacuation test for plasma vacuum chamber and cryostat, 2) coil cool down test and 3) coil current excitation test. These were performed successfully with really limited time allowance. We report on this referring to the actual calender dates.

Evacuation of the cryostat and the plasma vacuum vessel was started on 20 January 1998. After intensive and successful helium leak tests, the first cooldown process of LHD has started on 23 February, using a large-scale helium refrigerator/liquefier which possesses a cooling capacity of 5.65 kW at 4.4 K, 20.6 kW from 40 K to 80 K and 650 ℓ/hr liquefaction, respectively [9]. One of the most challenging issues for the LHD refrigerator/liquefier system is that it was made possible to execute a simultaneous control of four different major cooling paths; 1) liquid helium for the helical coils and

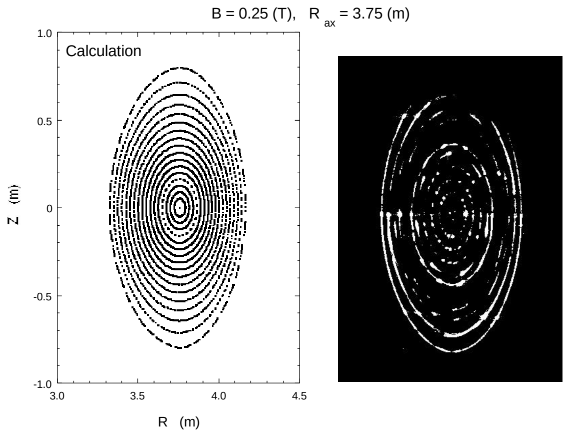

Fig. 6 Electron Beam Mapping Experiment.
***Left**: Calculated Vacuum Magnetic Surfaces,*
***Right**: Observed Points on fluorescent Screen,*

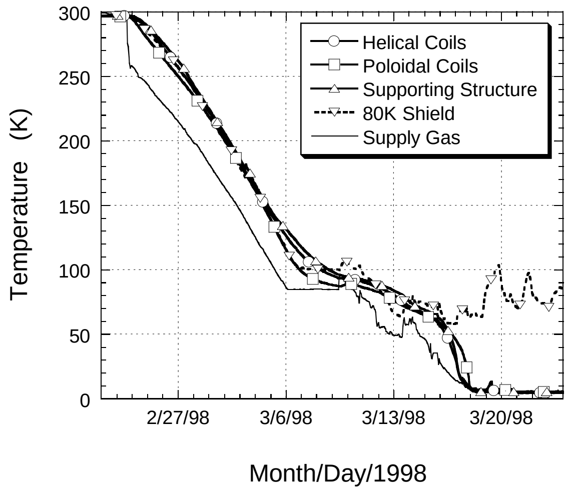

Fig. 7 First Cooldown Curves of LHD Coils.

the current leads, 2) forced-flow supercritical helium for the poloidal coils with CIC conductors, 3) forced-flow two-phase helium for the supporting structure and the superconducting bus-lines, 4) forced-flow gas helium of 40 - 80 K for the radiation shields. To prevent the thermal stress by the large temperature difference, the cooling process is carried out with a condition restricting the temperature difference of coolant between inlet and outlet to be below 50 K.

Helical and poloidal coils, and nine bus-lines became superconducting on 17 and 18 March, respectively. The measured residual resistance ratio (RRR) of the helical coils was about 1000, that of the poloidal coils was about 200, and that of the bus-lines was about 2300. Liquid helium was stored in the helical coil windings and in the torus-shaped buffer tank on 22 March. The total cooldown time of LHD for this first run was 28 days. This process is illustrated in Fig. 7.

Three blocks of the helical coil packages were energized to 6.5 kA by using three independent power supplies in the excitation test on the trial operation on 27 March. At the same time IV, IS and OV coils were excited to 7.58 kA, -7.97 kA and -9.09 kA, respectively. These sets of coil currents corresponds to 1.5 T on the plasma axis, which is half a nominal value of specifications of Phase I. The charging rate is 0.1 T/min and the necessary time is 15 min. All coils generated a combined stored energy of 230 MJ without a quench. Their maximum currents are plotted in Fig. 8 and 9.

The measured minimum critical currents of the conductors and the load line of the helical coils at 4.4 K are shown in Fig. 8. The rated currents of the helical coils are 13.0 kA and 17.3 kA in Phase I and Phase II, respectively. The broken line represents critical currents estimated at 1.8 K.

The first plasma was produced on 31 March 1998.

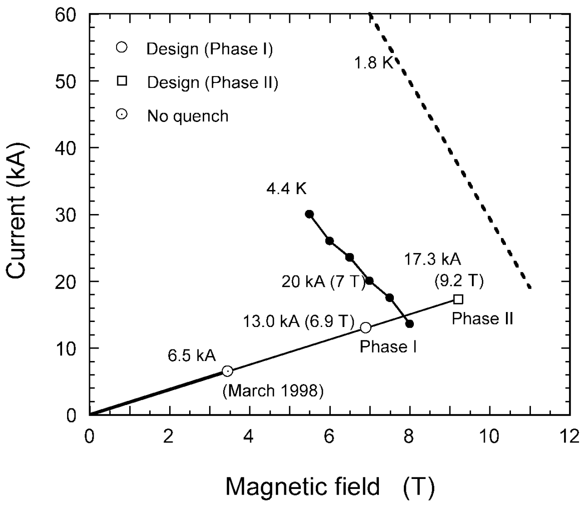

Fig. 8 Performances of Helical Coils for LHD.

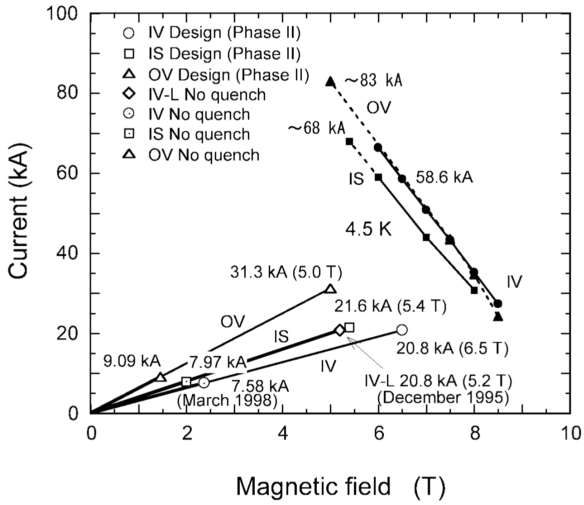

Fig. 9 Performances of Poloidal Coils for LHD.

6. SUMMARY

The construction of LHD has been successfully completed with various SC engineering results highlighted in this paper. The plasma experiments have shown a rapid build up and steady progress. The advantage of an SC machine is becoming clear with several practical physics data sets .

LHD project has developed technologies necessary to SC and related area. These are again summarized below, which make significant contributions to a wide range of fusion technologies.

1) SC coil fabrication technique, mechanical design, stress analysis, conductor development, insulation design,
2) refrigeration system design and development
3) SC bus line development
4) power supply with high reliability, fault probability of less than 10^{-6}, coil quench protection scenario
5) control system development
6) vacuum technology for a plasma chamber (210 m^3) and a huge cryostat (580 m^3)
7) high heat flux component and water cooling technique for a helical divertor
8) machine integration technique

In these processes, R&D took a very important role and contributed to produce various and necessary technical data base. It is possible to say that in order to provide reasonable and consistent engineering innovations, enough amount of the construction cost should be spent on R&D. In the case of LHD, it is around 15 % of the total construction cost.

Starting with the commissioning tests, the engineering data base was increased and grew owing to the series of practical operations. They consist of 1) evacuation test of the cryostat and plasma vacuum chamber, 2) initial cooling down test to liquid helium temperature, 3) coil current excitation test, 4) initial plasma production experiment, and 5) accumulation of operation data.

In conclusion, the broad engineering data base obtained during the LHD R&D and construction has explored a new regime of fusion engineering and mechanics, which is representative of current helical systems, but will provide many possible applications to future fusion research on toroidal magnetic fusion.

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