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T. Satow, S. Imagawa, N. Yanagi, K. Takahata, T. Mito,
S. Yamada, H.Chikaraishi, A. Nishimura, I. Ohtake,
Y. Nakamura, S. Satoh, O. Motojima

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Achieved capability of the superconducting magnet system for the Large Helical Device

T. Satow, S. Imagawa, N. Yanagi, K. Takahata, T. Mito, S. Yamada, H. Chikaraishi, A. Nishimura, I. Ohtake, Y. Nakamura, S. Satoh, O. Motojima

National Institute for Fusion Science, 322-6 Oroshi-cho, Toki, Gifu, 509-5292 Japan

e-mail contact of main author: satotaka@LHD.nifs.ac.jp

Abstract. The Large Helical Device (LHD) is a plasma physics experimental device with a magnetic stored energy of 960 MJ, consisting of two sc (superconducting) helical coils and six sc poloidal coils. The trial operation and the first plasma discharge of the Phase I project for LHD were finished on 31 March 1998 as initially planned. The second experimental campaign was conducted by additional heating using two NBI devices. The third campaign started in June 1999 and was finished in January 2000. Many plasma heating tests up to a plasma field of 2.90 T were carried out. Major test results on the sc magnet system for LHD are as follows: (1) The LHD cryogenic system succeeded in 13,400-hour operation and proved its high reliability. (2) A central field of 2.91 T at a radius of 3.60 m was achieved at an H-I current of 11.08 kA, an H-M current of 11.83 kA and an H-O current of 12.02 kA. (3) All six poloidal coils were excited stably. (4) Nine flexible sc bus-lines with a total length of 497 m were operated stably and safely.

1. Introduction

The Large Helical Device [1-3] is a plasma physics experimental device consisting of two sc helical coils, three pairs of sc poloidal coils, a cryogenic support structure, a torus-shaped cryostat vacuum vessel, and a helical plasma vacuum vessel. There are two operational stages for LHD, Phase I and Phase II. The key parameter in Phase I is a central helical field of 3.0 T at a radius of 3.9 m. After plasma experimental research in Phase I, the next program for Phase II is expected to begin, where the field will be enhanced up to 4.0 T.

Design and construction of LHD started in April 1990. All assembly and attachment work was completed in the middle of January 1998. The trial operation and the first plasma discharge of the Phase I project for LHD were finished on the last day of March as initially planned [3]. From that time to the middle of May, the first experimental campaign was carried out at a plasma central field of 1.5 T at a plasma major radius of 3.75 m using electron cyclotron heating (ECH). The second experimental campaign was conducted by additional heating using two neutral beam injection (NBI) devices. The third experimental campaign started in June 1999. Many plasma heating tests up to a plasma field of 2.9 T were carried out.

2. Features of the Superconducting Coils for LHD

An outside view of LHD is shown in Fig. 1 [1]. Major parameters of the helical coils and the poloidal coils for LHD in both Phase I and Phase II operation are listed in Table 1. Their coils were assembled inside and outside the cryogenic support structure as shown in Fig. 2 [2].

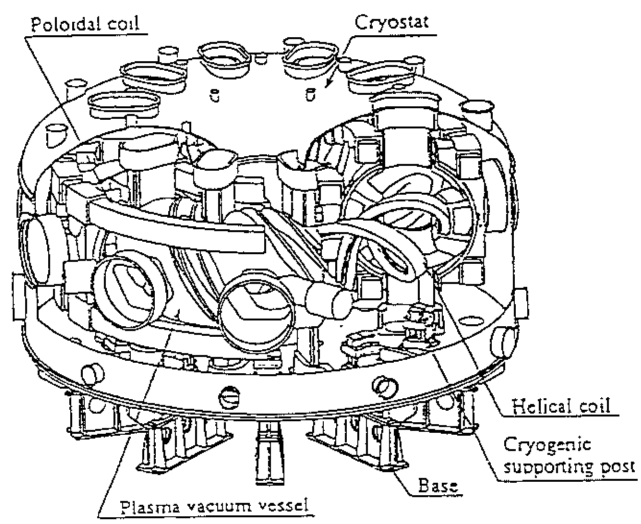

Fig. 1. Outside view of LHD

2.1 Helical Coils

Two helical coils (H1 and H2) were designed to be fully stable in pool-boiling liquid helium cooling in Phase I. Each coil is composed of three sc blocks (inner block H1-I

Table 1. Major Parameters of the Coils for LHD

	Helical coil		IV	IS	OV coils
	Phase I	Phase II	Phase II		
Magnetomotive force (MA)/ coil	5.85	7.80	5.0	-4.5	-4.5
Maximum magnetic field (T)	6.9	9.2	6.5	5.4	5.0
Shape of coil	Helical		Circular		
Average diameter of coil (m)	7.8		3.60	5.64	11.1
Coil rated current (kA)	13.0	17.3	20.8	21.6	31.3
Overall current density (A/mm²)	40	54	30	31	33
Stored energy (MJ)/ 2 coils	960	1700	161	220	625
Type of superconductor	NbTi/Cu / Al composite		CICC with NbTi/Cu strands		
Coil cooling method	LHe pool	HeIIp	SHe forced flow		

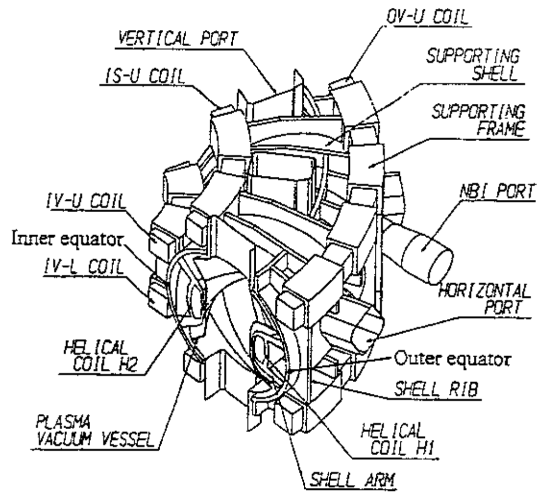

Fig. 2. Configuration of Coils and Support Structure for LHD

or H2-I, middle block H1-M or H2-M, and outer block H1-O or H2-O) as shown in Fig. 3 [4]. The superconductor is a 12.5 mm thick by 18 mm wide composite of NbTi/Cu monoliths and Al stabilizers. Short sample critical currents and recovery currents of all 38 conductors used for the windings were measured in liquid helium at 4.4 K [5]. All conductors were confirmed to have critical currents of 21 to 23 kA and recovery currents of 13 to 17 kA at 6.9 T.

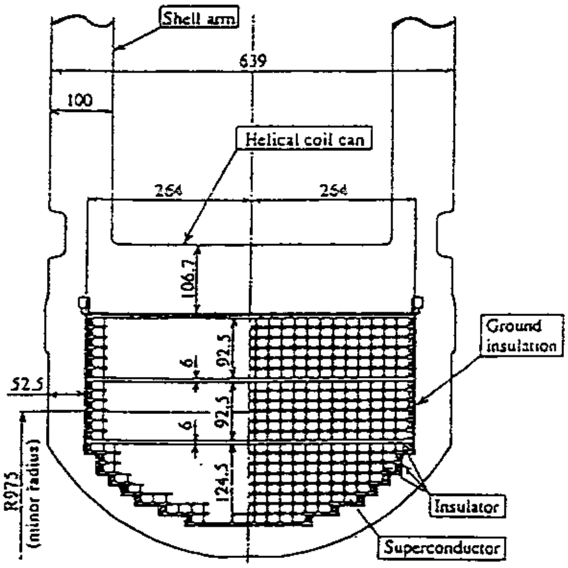

Fig. 3. Cross-section of a Helical Coil

2.2 Poloidal Coils

There are three pairs of poloidal coils, namely, inner vertical (IV-L and IV-U) coils, inner shaping (IS-L and IS-U) coils, and outer vertical (OV-L and OV-U) coils. The poloidal coils were designed and fabricated in accordance with the specifications of Phase II. They are operated in steady state modes in Phase I but in slow pulsed modes in Phase II. For example, the maximum field changing rate in the IV coil winding is only 2.2 T / 5 s in Phase II operation.

The configuration of the poloidal coils is shown in Fig. 4. Each coil is circular, stacked with eight double-pancakes wound from cable-in-conduit conductors (CICCs). Both CICCs for the IV coils and the IS coils have the same conduit dimension of 23.0 mm by 27.6 mm, and that for the OV coils is 27.5 mm by 31.8 mm. Each CICC consists of 486 NbTi/Cu strands. Simple NbTi/Cu monolithic conductors were chosen to increase stability as sc strands. Their Cu/SC ratio and critical current / operational current ratio (I_C / I_{OP}) were designed on the basis of a practical design criterion. The ratio I_C / I_{OP} for the strands is about three at 4.5 K. A group of NbTi filaments is placed as close to the center of the strand as possible in fabrication. No insulation

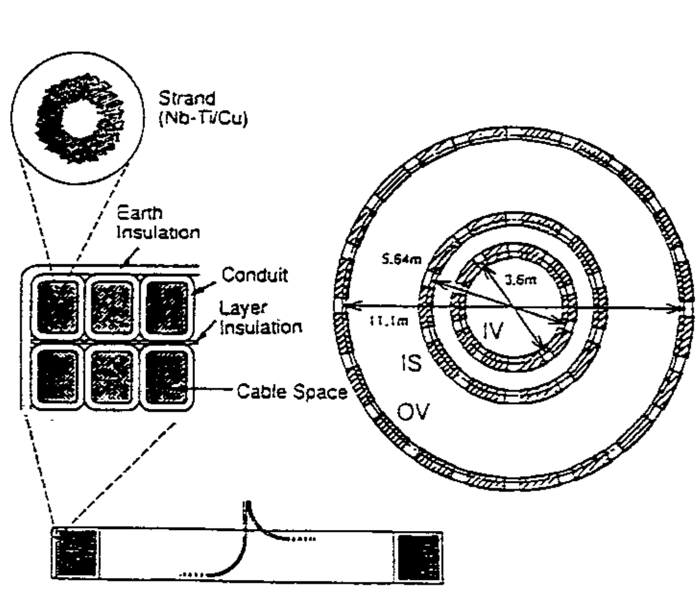

Fig. 4. Configuration of the Poloidal Coils

is used on the strand surface, so that the normal current flowing in one strand on quenching can easily transfer to neighboring strands.

3. Operational Process of LHD

3.1 Trial Operation and First Experimental Campaign

Evacuation of the cryostat and the plasma vacuum vessel started on 20 January 1998. After helium leak tests the cool-down of the coils, structure and 80 K radiation shields were carried out from 23 February using helium gas cooled by liquid nitrogen on the condition that the difference between inlet and outlet gas temperatures is no more than 50 K [6]. All radiation shields were cooled by helium gas during steady state as well as the cool-down process. All eight coils and nine bus-lines became superconducting on 17 and 18 March, respectively. The measured residual resistance ratio (RRR) at 293 K and about 10 K of the stabilizer of the conductor for the helical coils was about 1,000, that for the poloidal coils was about 200, and that for the bus-lines was about 2,300. Liquid helium was stored in the helical coil windings and in the torus-shaped buffer tank on 22 March. The cool-down time of LHD was 28 days.

The corresponding blocks of the two helical coils are connected in series at the warm terminals of the current lead cryostat for six bus-lines, and three electrical circuits (H-I, H-M, and H-O) were formed. The IV-L coil and the IV-U coil were connected in series in the LHD cryostat. The same connections were utilized for the IS coils and the OV coils. Three circuits for the helical coils were energized to 6.5 kA, which generated a central helical field of 1.5 T, by using three independent power supplies on the trial operation on 27 March. At the same time the IV coils were excited to 7.5 kA. The IS coils and the OV coils were excited to 7.9 kA and 9.0 kA, respectively in the opposite way as the helical coils. The charging time was 15 minutes.

The first plasma of LHD was ignited at 1.5 T at a radius of 3.75 m by using ECH on 31 March 1998 as initially planned. This standard #1-o mode is the most popular in plasma experiments (see Table 2.). From that time to the middle of May, the first experimental campaign was carried out. It was successfully finished on 15 June through 23-day warm-up of LHD.

3.2 Second Experimental Campaign

The second cool-down of the LHD coils and structure started on 18 August 1998, and all coils became superconducting on 5 September. The cool-down time of LHD was reduced to 23 days. After one month plasma experiments at 1.5 T by additional heating using two NBI devices, the excitation test for higher field generation was carried out on 21 October. The main events in the excitation tests in the second and third experimental campaigns are listed in Table 2. The six coil circuits were stably excited to 2.70 T in #1-o mode. When the coil currents became constant at 2.75 T, however, the inside coil lead and the inner block (H1-I) of one helical coil caused two-stage successive normal propagation at 11.45 kA. When the coils were discharged with a time constant of 20 s, a voltage of 770 V was applied between both terminals of each helical coil block. As the result of inspections such as voltage decay form and coil inductance, the insulation of the helical coils was shown to be normal. In the last excitation test of 18 December the helical coils were stably excited to the same current of 11.45 kA in the sc state.

3.3 Third Experimental Campaign

The third cool-down of the LHD coils and structure started on 10 June 1999. Some excitation tests were conducted as shown in Table 2. Many plasma discharge tests are carried out up to the maximum plasma field of 2.90 T in #1-d (3.5 m) inward shift mode. Excellent plasma results were achieved, including a plasma startup by NBI and an electron temperature of 4.4 keV. A central field of 2.91 T at a radius of 3.60 m was achieved at an H-I current of 11.08 kA, an H-M current of 11.83 kA and an H-O current of 12.02 kA. All six poloidal coils were excited perfectly stably. The maximum currents of the IV, IS and OV coils in excitation tests were 15.6, 15.3 and 19.0 kA, respectively. The coils were excited 394 times, and the total number of plasma shots was 17,311 in the third campaign which was finished on 21 January 2000.

Table 2. Main Events in the Excitation Tests

Date	Mode	Radius of plasma axis	Field	Coil current (kA) HC	IV	IS	OV	Remarks
Second experimental campaign in 1998								
Oct. 21	#1-o	3.75 m	2.75 T	11.45	9.35	-4.59	-17.9	Sweep rate 0.1T/min.
								H1-I normal propagation at current keeping.
								Current interruption at a time constant of 20 s.
Dec. 16	#1-b	3.75 m	2.70 T	11.25	13.2	-13.7	-15.7	Sweep rate 0.01T/min. at high field region.
								#1-b horizontal elongation mode. Stress measurement
	#1-c	3.90 m	2.50 T	10.41	6.48	-5.44	-15.7	#1-c outward shift mode. Stress measurement.
Dec. 18	#1-o	3.75 m	2.75 T	11.45	9.35	-4.59	-17.9	Sweep rate 0.01T/min. HCs keep superconducting.
Third experimental campaign in 1999								
July 7	#1-b	3.75 m	1.50 T	6.25	7.34	-7.63	-8.74	Current interruption test at a time constant of 30 s.
July 21	#1-o	3.75 m	2.72 T	11.33	9.25	-4.54	-17.7	Sweep rate 0.01T/min. at high field.
								H1-I normalcy and recovery at current holding.
Aug. 5	—	—	—	0.05	15.6	-0.05	-2.5	For AC loss measurement in the IV coils.
Aug. 6	#1-d	3.60 m	2.85 T	11.40	11.6	-3.11	-18.6	Sweep rate 0.005 T/min. at high field.
								HCs keep superconducting.
Sep. 9	#1-d	3.50 m	2.90 T	11.27	13.6	-1.77	-19.0	A new mode for plasma discharge test.
Sep. 22	#1-d	3.70 m	2.50 T	10.27	9.02	-3.72	-16.3	Another new mode for plasma discharge test.
Nov. 30	#1-d	3.60 m	2.91 T	grading	11.6	-3.29	-18.9	Current grading excitation of HC blocks:
								H-I 11.08 kA, H-M 11.83 kA, H-O 12.02 kA.
Dec. 17	—	—	—	0.05	0.05	15.3	-5.1	For AC loss measurement in the IS coils.

4. Major Results on the Superconducting Magnet System for LHD

Major results on the sc magnet system for LHD are summarized as follows: (1) The cryogenic system for LHD has a capability of 5.6 kW and 650 *l* /h at 4.4 K, and 20 kW at 80 K. The cryogenic system succeeded in 13,400-hour operation in all three campaigns, and proved its high reliability. (2) The helical coils were stably excited to 11.45 kA in the sc state in spite of one occurrence of normal propagation. In the third campaign a central field of 2.91 T at a radius of 3.60 m was achieved by using a helical coil block current grading method such as an H-I current of 11.08 kA, an H-M current of 11.83 kA and an H-O current of 12.02 kA. (3) The insulation of the helical coils was experimentally shown to be normal. (4) All six poloidal coils were excited perfectly stably. (5) No resistive voltages were observed in all conductor joints for the helical coils and the poloidal coils. (6) The stresses at an inner equator and an outer equator on the support structure (see Fig. 2) were measured. Analytical values by a finite element method agreed very well with measured ones. (7) Ten cryogenic supporting posts were utilized to support the coils and structure of about 850 tons in total as shown in Fig. 1. As long-term test results the plate-spring-type post made of 316 stainless steel plates and CFRP plates was appropriate for large-scale sc magnets. (8) The total heat loads in the steady state condition were 1.94 kW + 434 *l* /h (1.5 T) at 4.4 K and 12.1 kW at 80 K, which were the same as the final design values [6]. (9) Nine flexible sc bus-lines with a total length of 497 m arranged in the basement of the LHD main building were operated stably and safely. (10) Six units of the thyristor power supplies were successfully controlled under the tight coupling of six inductive coil circuits.

5. Discusions about the Coils for LHD

5.1 Helical Coils

The phenomenon observed in the helical coils on 21 July 1999 may be explained as follows. As soon as the coil current was held at 11.33 kA, a resistive voltage occurred and disappeared in the inner block of one helical coil. It is thought as a mechanism of this phenomenon that small current flows in the stabilizer of the helical coil conductor with asymmetrical superconductor-stabilizer arrangement [5] during charging, and then it flows into the superconductor from the stabilizer at current holding. Therefore, the smaller a current sweep rate is, the more stable the helical coils become.

A stored energy scaling law map of overall current densities for pool boiling cooled magnets constructed since 1980 is shown in Fig. 5. The scaling law was introduced on the basis of full stability and coil protection conditions [7, 8]. Designed points of the helical coils in Phase I and Phase II are plotted for LHD-HC according to the data in Table 1. A stored energy of 740 MJ and an overall current density of 36 A/mm^2 for the helical coils plotted in the figure were calculated from the maximum current of 11.4 kA. A line of the -1/7 power law of a stored energy on overall current density is drawn in Fig. 5. The overall current densities designed and excited in the helical coils, which are fairly high, were given as an inevitable consequence of plasma physics design.

5.2 Poloidal Coils

A stored energy scaling law map of overall current densities for CICC magnets [8] is shown in Fig. 6. There plotted are the nominal and measured points of the poloidal coils (IV-L, IV2, IS2, and OV2) for LHD. Two lines of the -1/7 power law and -1/3 power law (from mechanical force limit) of a stored energy on overall current density are drawn for reference. The maximum currents excited for the poloidal coils are fairly small compared with the -1/7 power line.

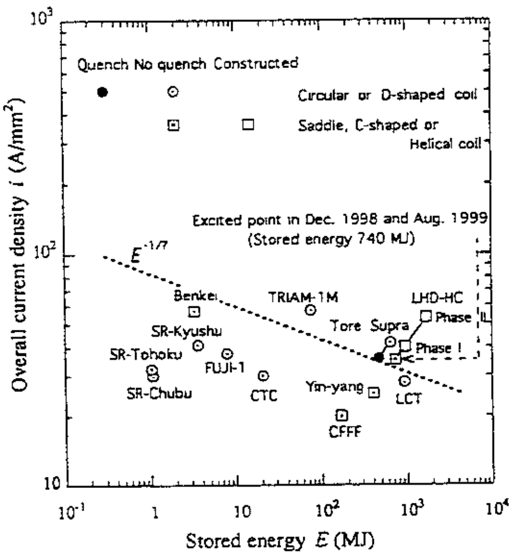

Fig. 5. Stored Energy Scaling Law Map of Overall Current Density in Pool Boiling Cooled Magnets (since 1980)

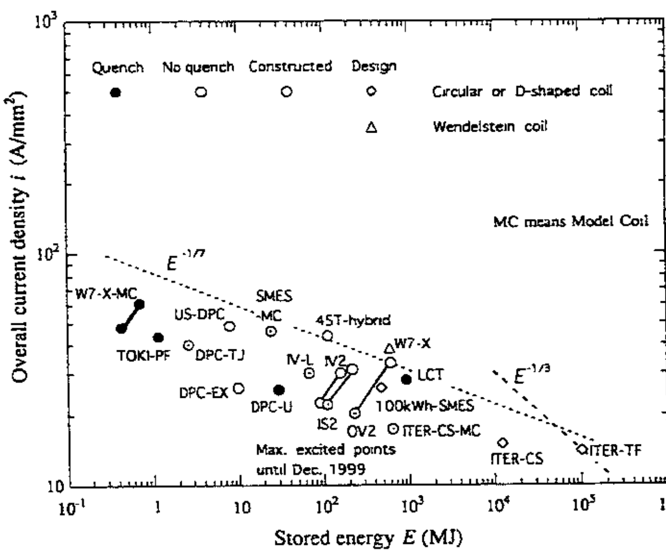

Fig. 6. Stored Energy Scaling Law Map of Overall Current Density in CICC Magnets

6. Future Schedule in LHD Project

The fourth experimental campaign started on 28 August 2000 and will be carried out until February 2001. The maximum excitation test to the plasma field of 2.95 T is expected. Moreover, two kinds of design studies and R&Ds such as sub-cooled helical coils, pressurized superfluid helium cooled helical coils, are now performed.

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