Results of the First Excitation of Helical Coils of the Large Helical Device

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Abstract–**The helical coils of the Large Helical Device are large scale pool-cooled superconducting coils. A conductor made of NbTi/Cu compacted strands and a pure aluminum stabilizer was developed to attain high cryostability. The design current of the conductor is 13.0 kA at 4.4 K, which produces a toroidal magnetic field of 3 T at a major radius of 3.9 m. The first excitation test up to 6.5 kA was conducted successfully in the beginning of the first cooling period. The higher excitations were tried in the second cooling period. The first propagation of a normal zone was observed when reaching 11.2 kA, and it recovered within 5 s. In the next step, a wide propagation occurred at 11.4 kA, and the quench detection system worked. The coils were designed to satisfy 'cold-end' stability by using the recovery current measured in short samples, but a normal zone propagates at lower than the recovery current in the composite conductor stabilized by very low resistive metal.**

Index Terms--**composite conductor, aluminum stabilizer, minimum propagating current**

I. INTRODUCTION

The Large Helical Device (LHD) is a Heliotron-type fusion experimental facility for the research of a fusion plasma near a reactor region [1]. In order to demonstrate a steady operation of high performance plasma, the magnet system consists of a pair of superconducting helical coils (HCs) and three pairs of superconducting poloidal coils (PCs). The expected toroidal magnetic field is 4 T at a major radius R of 3.9 m, and the current density of the HC must be 53 A/mm^2 in order to attain the necessary distance between the plasma and the plasma vacuum vessel. The construction of LHD was determined to be divided into two phases. The HC is cooled by normal helium in the first phase, and the expected field was set to 3 T. The helium temperature will be lowered to 1.8 K in the second phase. The PCs were designed to perform with enough cryo-stability at 4 T by pressurized normal helium cooling.

The construction of the first phase was completed at the end of 1997, and the first cool-down was performed from the middle of February in 1998. In order to establish the reliability of the whole system of LHD, the first excitation of the coils was limited to 1.5 T. After 6 weeks' plasma experiment at 1.5 T, the coils were warmed up for upgrade of the plasma heating devices and diagnostics. The second cool-down was performed from the middle of August. Excitation up to the design value of 3.0 T was attempted in October, and a wide normal propagation occurred when reaching 11.4 kA. The quench detection system acted, and all the coils were discharged by protection resistors. Since the coil protection circuit and the cooling system worked precisely, we continued the plasma experiments at 1.5 T and repeated excitation tests. The LHD is now operated at below 2.8 T at R= 3.6 m in the third cooling period. This paper intends to summarize the results of these excitation tests and to clarify the cryostability of the HC.

II. DESIGN OF HELICAL COILS

A. Design concept

The HC rotates five times around the plasma vacuum vessel, and three pairs of the PCs are arranged to change the vertical and quadrupole magnetic field, while minimizing the stray magnetic field, as shown in Fig. 1. In order to attain high accuracy of coil winding and a high current density, a pool-cooled composite conductor of medium size was selected for the HC. Since a disturbance by movement of the conductor should be unavoidable in such a large coil, the HC is expected to satisfy 'cold-end' stability at least.

B. Design of cryostability

Many types of NbTi superconductors with various internal structures were proposed and examined practically with short sample tests [2]. The final size of the conductor was determined to be 12.5 mm × 18.0 mm by considering the cryostability, mechanical flexibility for winding and the induced voltage during a shut-off. The nominal current is 13.0 kA at 4.4 K and 17.3 kA at 1.8 K, and the standard operation current at 4.4 K is 12.5 kA which produces 3.0 T

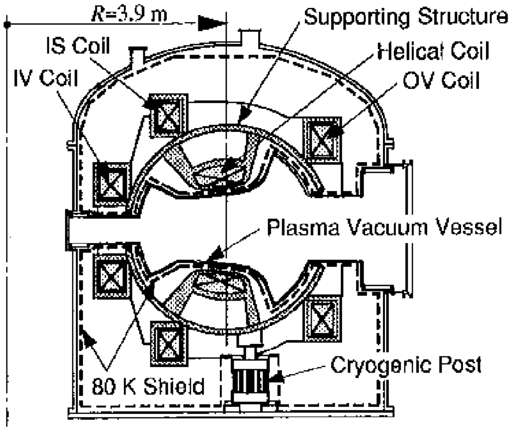

Fig. 1. Layout of superconducting coils and surrounding structures of LHD.

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of toroidal magnetic field at R= 3.75 m. A pure aluminum stabilizer and a copper sheath were selected to attain a high recovery current and enough strength. Furthermore, the pure aluminum is cladded by Cu-2%Ni to reduce magneto-resistance by Hall currents while maintaining smooth current transfer from the superconducting strands.

The recovery currents of the straight short samples from all the actual conductors were measured in a bias field of split coils, and the values exceeded the target value, as shown in Fig. 2 [3]. It is the current at which the normal zone disappears in process of decreasing a current after inducing a certain length of normal zone by a heater. However, the recovery current in a uniform field is estimated to be 15 to 20% lower than the short samples by analytical study [4]. The wetted surface fraction of conductors of the actual coil was enlarged to 0.692 at the edge region, where transverse fields become the largest but the electromagnetic forces on the insulators are not large. The minimum propagating currents of all the conductors can be estimated by using the typical values of the heat transfer coefficient and magneto-resistance. The lowest value was estimated to be 13.09 kA at 3 T operation, which means that some regions may not satisfy 'cold-end' stability. Still, the HC was considered to be stable, because almost all the conductors satisfy the cryostable condition.

Though the HC is pool-cooled, the cooling channel is narrow due to the requirement of high current density. It is very important to keep a good cooling condition of the conductors. Liquid helium is supplied from the bottom, and the generated gas is taken out from the top. Longitudinal cooling channels inside the coils are arranged at the higher ends of each layer, as shown in Fig. 3, and both corners of the top cover of the case. Even the latter area is 300 mm^2, but it is not useful for the conductor around the bottom. The ends of the first layer are under the most severe condition around the bottom region of the coil, because the field is near its peak and the cooling condition is easy to be deteriorated by accumulation of helium bubbles.

C. Mechanical design and manufacturing

From the aspects of cryostability and mechanical reliability, the conductor motions due to electromagnetic forces must be small. Then, the rigidity of the coil must be high. The HC is expanded in the minor radius direction by the excitation. Tensile stresses of the conductors become the largest in the first layer, and it mainly depends on the compressive modulus of the insulators between conductors. We have developed an insulator with a high compressive modulus, larger than 22 GPa, and small thermal contraction. The movement of the first layer was calculated to be 1.1 mm at 4 T operation even in the ideal case. Since the fabrication gaps between the conductor and insulator will be collapsed by large electromagnetic forces, the gaps decrease the equivalent rigidity of the coil. The effect was evaluated by assuming that the total gaps are equal to the increase of the displacement of the first layer. The average fabrication gap should be less than 0.065 mm/layer to keep the stress of the copper sheath under the yield strength of 290 MPa. The attained average gap was 0.047 mm/layer, and the conductor will be operated in the elastic region. Nevertheless, the first layer will move by about 2 mm due to the excitation.

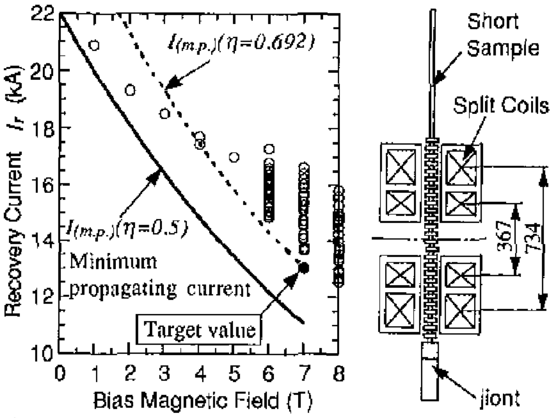


Fig. 2. Measured recovery currents of short samples and estimated minimum propagating currents. The circles are measured data of short samples at the wetted surface fraction of conductor η=0.5.

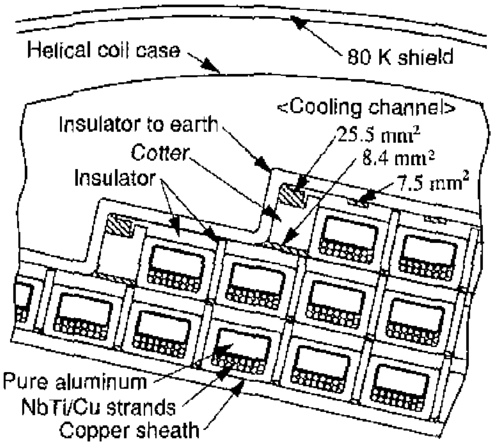


Fig. 3. Cross-section of a higher corner of 1st to 3rd layer of the HC.

D. Result of small coil test

In order to study the effect of bias field distribution on recovery currents, we made a coil sample of 10 turns. The inner diameter is 0.3 m, and the cooling channel is similar to the actual coil. A normal zone was induced by a heater in the innermost layer. When the current is somewhat higher than the minimum propagating current, it propagates to adjacent turns and stops in the lower field. After that, it recovers or stagnates at a certain length. In the latter case, the recovery current is measured by decreasing the transport current. The obtained data were significantly lower than the expected value, as shown in Fig. 4. The reason may be deterioration of the cooling. Another important result is that the normal zone propagates at a current lower than the recovery current. The reason was revealed to be an excess heat generation by the current diffusing into the pure aluminum stabilizer [5, 6]. When the propagation stops once by the change of field or cooling conditions, the current penetrates into the stabilizer in the whole normal zone, and it begins shrinking. However, it cannot recover after wide propagation, because the cooling conditions become worse by the accumulation of bubbles in the narrow channel between the conductors.

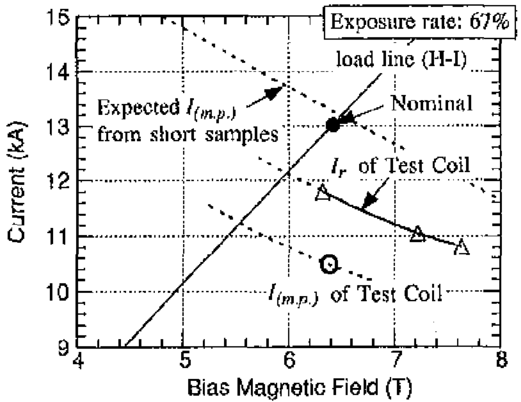


Fig. 4. Recovery current I_r and minimum propagating current $I_{(m.p.)}$ of HC Test Coil.

III. EXCITATION TEST OF THE LHD

A. Method and results of the excitation tests

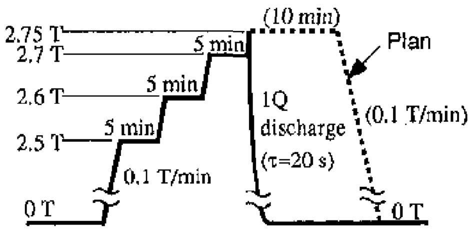
In order to change the current center and to reduce the voltage during a current shut-off, the HC is divided into three blocks that are called H-I, H-M and H-O. Each pair of the blocks is connected to each power supply. Since the mutual coupling factor during the blocks is larger than 0.9, each current is easy to transfer to the other. The normal transition of the coil is detected by monitoring the balance voltage that is the difference between the H1 and H2 coils.

The first excitation tests up to 6.5 kA were carried out successfully within a week in March 1998. After totally 10 weeks' plasma experiments at 1.5 T, excitation up to 3.0 T was tried in the second cooling period. Excitation up to 2.5 T was attained without any abnormal signals at a ramp rate of 0.1 T/min. After twice charging and discharging up to 2.5 T, we tried 2.75 T by holding the current for 5 min at 0.1 T step, as shown in Fig. 5 (a). The first propagation of a normal zone was observed when reaching 2.7 T, and it recovered within 5 s, as shown in Fig. 6. The outward movement of the conductor induces a positive voltage. The normal propagation also induces a negative voltage due to the inward shift of the current center in addition to the resistive voltage drop. Since the inductive voltage appears in the other blocks by strong mutual coupling, the resistive voltage of the normal zone is almost separated by subtracting the balance voltage of the neighboring blocks. A large disturbance should have occurred before the normal propagation, but the signal was masked by the higher voltage induced by propagation.

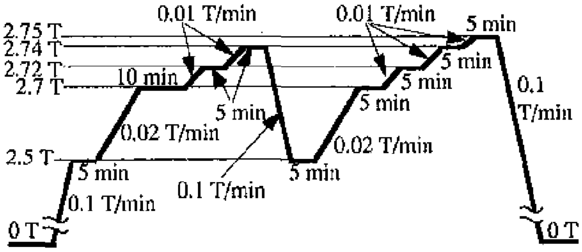
In the next step, a wide propagation occurred at 11.4 kA, as shown in Fig. 7. The normal zone expanded more than 15 m, and shrank gradually. On the way to recovery, it propagated again rapidly and very widely, and the quench detection system worked. It was set to act when the balance voltage higher than 0.2 V continued more than 3 s. The reason for the second rapid normal propagation is probably deterioration of cooling conditions. Liquid helium would be pushed aside by the generated gas. The estimated resistive losses of the H1-I, M and O block were 2.5, 1.4 and 0.92 MJ, respectively, in addition to the AC losses of 11 MJ in the HCs and HC cases. The temperature rises of the case are shown in Fig. 8. It shows that the normal propagation occurred near the coil lead of H1-I, that is located at #5 sector. It also shows that H2 coil kept superconductivity during this quick discharge in spite of the large AC losses.

The quick discharge with a time constant of 20 s, that is called 1Q, worked precisely, and the coils did not suffer any damage. Since AC losses in charging by 0.1 T/min are larger than the steady heat load, the ramp rate was lowered to 0.01 to 0.02 T/min at a field higher than 2.5 T. After repeating excitations, the second excitation up to 2.75 T was attained at 0.01 T/min, as shown in Fig. 5 (b), without any abnormal signals. In these excitations listed in Table 1 and 2, the number and amplitude of the balance voltages decreased in the second and later excitations, and these do not appear in the discharging process from high field to near 2.1 T.

After the third cool-down, the excitation tests were conducted by the same pattern. A normal propagation and recover was observed when reaching 2.72 T of #1-o. The number and amplitude of the balance voltages were clearly larger than the last excitation in the previous cooling period. The effect of slow excitation seems to be not large, and the training effects by repeated excitations will be lost partially by warm-up.



(a) 1st #1-o 2.75 T @ 3.75 m on October 21, 1998



(b) 2nd #1-o 2.75 T @ 3.75 m on December 18, 1998

Fig. 5. Excitation patterns of #1-o 2.75 T.

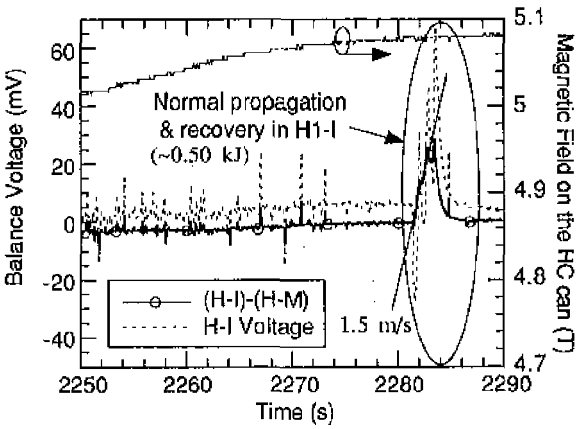


Fig. 6. Voltage of the HC at the first excitation up to 2.70 T.

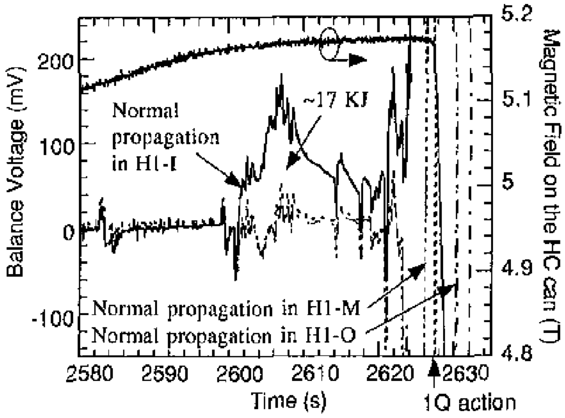


Fig. 7. Voltage of the HC at the first excitation up to 2.75 T.

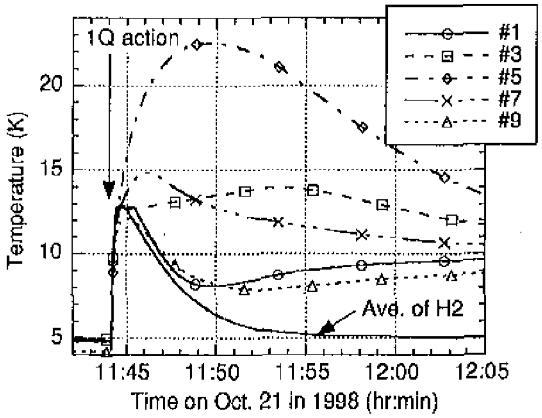


Fig. 8. Temperatures of the HC case at the outer equator after 1Q discharge from 2.75 T. The deviation of H2 coil case was less than 1 K.

Table 1 Excitation tests in the second cooling period

Date	Field (mode, major radius)
10/20	2.5 T (#1-o, R=3.75 m) (0.1 T/min)
10/21	1Q from 2.75 T (#1-o, R=3.75 m)
12/1	2.2 T (#1-o, R=3.75 m)
12/3	2.55T (#1-o, R=3.75 m)
12/10	2.7 T (#1-o, R=3.75 m)
12/16	2.7 T (#1-b, R=3.75 m), 2.5 T (#1-b, c, d, o)
12/17	2.74 T (#1-o, R=3.75 m), 2.85 T (#1-d, R=3.6 m)
12/18	2.75 T (#1-o, R=3.75 m)

Table 2 Currents of coils for 3 T at the plasma axis [kA]

mode	HC	OV	IS	IV
#1-o (standard)	12.5	-19.62	-5.01	10.21
#1-a (vertical elongation)	12.5	-21.74	5.24	5.74
#1-b (horizontal elongation)	12.5	-17.49	-15.27	14.68
#1-c (outward shift)	13.0	-19.60	-6.80	8.09
#1-d (inward shift)	12.0	-19.60	-3.28	12.25

The major radii of the plasma axes are 3.75 m for #1-o, a and b, 3.9 m for #1-c, and 3.6 m for #1-d.

B. Abnormal balance voltage after normal transition

We observed the drastic change of the balance voltage in the first excitation after the 1Q discharge on October 21, as shown in Fig. 9. Since we were afraid of a short circuit in the HC, we checked the change of inductance of the coils and repeated the coil excitations by using small power supplies, after disassembling of the temperature sensor cables. Since nothing wrong was detected, we tried higher excitations step by step. The abnormal balance voltage disappeared at an excitation higher than around 0.8 T. The main reason is considered to be a change of magnetization of the superconducting cables of the H1 coil that was heated up by the 1Q discharge. However, it does not explain the whole phenomenon. A second circuit or magnetization of other components must be involved.

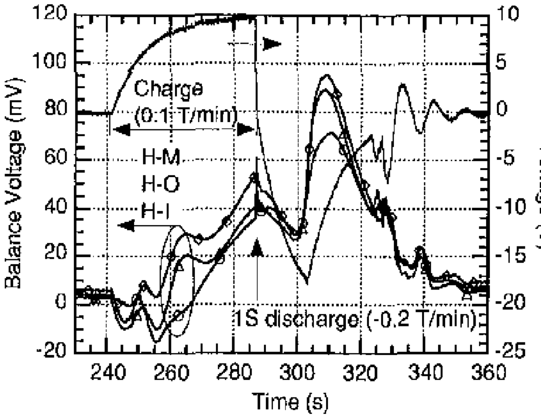


Fig. 9. Balance voltage of the HCs after 1Q discharge on Oct. 21 in 1998.

IV. SUMMARY AND DISCUSSION

LHD, the world's largest stellarator, was completed, and excitations were attained up to 2.75 T which is 88% of the design value. The HCs were expected to satisfy 'cold-end' stability, but it was revealed that a normal zone propagates at lower than the expected value by excess heat generation during current diffusion into a low resistance stabilizer. A kind of training effect was observed in repeated excitations. The disturbance seems to be reduced in the second and later excitations, and the disturbance does not occur in the discharging process from high field to 2.1 T. The coils are used safely for plasma experiments by being charged once up to slightly higher field. Furthermore, a higher excitation is expected by improving the cooling condition or by grading the current of each block.

REFERENCES

[1] A. Iiyoshi, M. Fujiwara, O. Motojima, N. Ohyabu and K. Yamazaki, "Design study for the Large Helical Device", Fusion Technology **17** (1990) pp.169-187.

[2] T. Mito, K. Takahata, N. Yanagi, et al., "Short sample tests of aluminum-stabilized superconductors for Large Helical Device", Fusion Eng. Des. **10** (1993) pp.233-242.

[3] N. Yanagi, T. Mito, S. Imagawa, K. Takahata, T. Satow, J. Yamamoto, O. Motojima and The LHD Group, "Development and quality control of the superconductors for the helical coils of LHD", Fusion Engineering and Design 41 (1998) pp.241-246.

[4] S. Imagawa, S. Masuzaki, N. Yanagi, S. Yamaguchi, T. Satow, J. Yamamoto, O. Motojima and LHD Group, "Design and construction of helical coils for LHD", Fusion Eng. Des. 41 (1998) pp.253-258.

[5] S. Noguchi, A. Ishiyama, T. Satow and N. Yanagi, "Transient stability of large aluminum stabilized superconductors", ASC'98, LIB-11.

[6] N. Yanagi, A. V. Gavrilin, T. Mito, et al., "Stability characteristics of the aluminum stabilized superconductor for the LHD helical coils", Advances in Superconductivity XI (1999) pp.991-994.