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SHORT SAMPLE TESTS OF FULL-SCALE SUPERCONDUCTING CONDUCTORS FOR LARGE HELICAL DEVICE

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Abstract

We have been developing superconducting conductors for the helical coils of the Large Helical Device (LHD). From the test results of scale-down R&D conductors, one conductor, KISO-4B, was selected for its simple structure and good stability. Other conductor named Design-M have been manufactured in its actual scale from the first. These two types of conductors were selected and go forward to the full-scale tests. Since both conductors have multi-layered strand cables without the transposition, it is feared that the uneven current distribution between strands may cause the degradation of the critical current. A new method of measuring the current distribution inside the conductor was introduced. A pick up coil wound on the conductor detects the magnetic flux change in the conductor longitudinal direction and becomes a sensor to measure the current distribution. Using the test facility for full-scale conductors, the Design-M conductor has been tested about the critical current and stability. From the test results of Design-M, the uneven current distribution from the outer layer strands to the inner layer strands inside the conductor was observed. However, no degradation of the critical current was measured.

Introduction

The LHD is a fully superconducting heliotron/torsatron type fusion experimental device [1]. All coils of LHD (two helical coils and three pairs of poloidal coils) are designed to be superconducting. The helical coils are cooled by the pool boiling of normal liquid helium in Phase I and are later going to be cooled by the superfluid helium in Phase II. The poloidal coils are cooled by the forced flow of supercritical helium. The conductors for the helical coils must satisfy the requirements of the mechanical rigidity, the high current density, the enough stability and safety. Especially, the conductor must be enough stable against the coil quench because the LHD is one of the largest superconducting coil system in the world.

Several conductors which have different cross-sectional patterns were designed for the conductor of the LHD helical coils. The scale-down R&D conductors were made on an experimental basis and have been tested about the superconducting characteristics, the stability and the mechanical properties [2]. From the results of these tests, one conductor, KISO-4B, is selected for its simple structure and good stability. Other conductor named Design-M have been manufactured in its actual scale from the first because it was a conductor of the TOKI-MC which is one of the R&D coils for LHD [3]. These two types of conductors are selected and go forward to the full-scale tests.

The helical coils are excited slowly and are operated in the constant current mode. Therefore the conductors set importance on the stability and the mechanical rigidity and are not designed to minimize the pulse losses. However, in phase II experiment, the poloidal coils are operated in the pulse mode. The pulse losses due to the field change of the poloidal coils (0.07T/s at the position of the helical coils) must be reduced in order not to affect the stability of the helical coils. The estimation of pulse losses is also necessary to assume the heat load for the cryogenic system. The pulse losses of the conductors were calculated numerically [4] and were measured experimentally.

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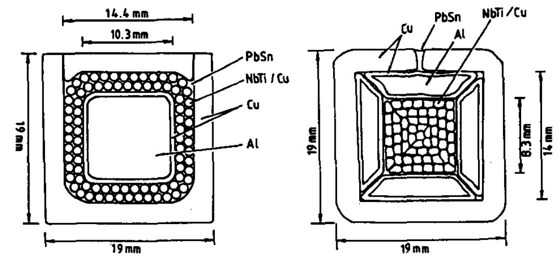
Conductor Design

Fig. 1 shows the cross-sections of KISO-4B and Design-M. Both conductors consist of the NbTi/Cu superconducting cable, the pure aluminum stabilizer, and the half-hard copper sheath, which are soldered together. The surface of copper sheath is coated with copper oxide to enhance the heat transfer to liquid helium. The conductors were designed to be cryostable satisfying the Maddock's stability criterion. The conductors have flat surfaces without a groove and a roughness in order to get the enough area for the mechanical support of the large electromagnetic force in the helical coils. The parameters of the conductors are listed in Table 1.

KISO-4B has a simple structure and good mechanical properties. It has an aluminum stabilizer at the center and two layered superconducting strand cable without



KISO-4B Design-M

Fig. 1. Cross sections of conductors for LHD helical coils.

Table 1. Parameters of conductors for LHD helical coils

		KISO-4B	Design-M
Superconductor		NbTi	←
Nominal current		21 kA	←
Overall current density		58 A/mm^2	←
Size		19.0 mm X 19.0 mm	←
Surface treatment		Copper oxide	←
Critical current (8T*, 4.2K)		43 kA	38 kA
Critical current density of NbTi (8T*, 4.2K)		1100 A/mm^2	1070 A/mm^2
Number of strands		84	58
Diameter of strand		1.05 mm	1.22 mm
Cu/SC ratio in strand		0.9	1.0
Diameter of filament		28.5 μm	25 μm
Number of filaments		726	1213
Twist pitch of filament		20 mm	17.0 mm
Twist direction of filament		inner Right/Right outer Right/Left	Left for all layers
Twist pitch of cable		inner 232 mm outer 254 mm	127 mm for all layers
Twist direction		inner Right/Left outer Right/Right	Right for all layers
Cross section	Total	361.0 mm^2(100%)	361.0 mm^2(100%)
	Al	83.4 mm^2(23%)	83.0 mm^2(23%)
	NbTi	38.9 mm^2(10%)	36.1 mm^2(10%)
	Cu	216.9 mm^2(60%)	223.8 mm^2(62%)
	PbSn	25.6 mm^2(7%)	18.1 mm^2(5%)

* Include the conductor self-field

transposition. The conductor is covered with a half hard copper sheath whose inside is round-cornered for its reinforcement. The short sample of KISO-4B is going to be tested in August 1991.

Design-M has four copper clad aluminum stabilizers surrounding the superconducting cable. It has five layered strand cable twisted in the same direction without the transposition. Design-M has been designed and fabricated for one of the R&D coils for LHD, TOKI-MC, which can simulate the electromagnetic force, the conductor torsional rate, the magnetic field, the operating current, and the current density of the LHD helical coils. The conductors were already fabricated for the total length of over 800 m using a specially developed production line. The short sample of Design-M was tested about the superconducting characteristics and stability.

Test Facility for Full-scale Conductors

The test facility for full-scale conductors consists of 100 kA vapor-cooled current leads, 9 T bias field split coils, a cryostat and a 75 kA DC power supply. 100 kA vapor-cooled current leads have been specially developed for the short sample test of large current conductors. The parameters of the bias field split coils are the inner diameter of 248 mm, the outer diameter of 907 mm, the coil width of 139 mm, and the gap width of 100 mm. These split coils produce 9 T in the sample bore of 100 mm × 550 mm. Fig. 2 shows the cross-section of the cryostat with the 100 kA current leads, the split coils and the testing short sample conductors. Two short sample conductors (the length of 1970 mm) are arranged parallel with the gap of 3 mm and are inserted into the split coils. The sample conductors are soldered at the bottom (the length of 400 mm) to join the going and returning current. The current loop of sample conductors is directed to reduce the magnetic field of the split coils. Therefore each conductor push each other at the center by the electromagnetic force. The sample conductors are soldered at the top to the U-shaped copper bars which are attached with the indium sheets to the lower electrodes of 100kA current leads. A 75 kA DC power supply consists of three 25 kA thyristor units and was designed extendable to become a 100 kA DC power supply with an additional 25 kA thyristor unit.

Fig. 3 shows the detail of the sample conductors. The sample is bound by the 20 mm wide glass-epoxy tape with the space of 20 mm and the exposure rate of 50 %. The center part of the sample conductors is covered with a GFRP tube to simulate the cooling condition in the helical coils.

Fig. 4 shows the center parts of the sample conductors. Many voltage taps (E1 - E19), Au-Fe thermocouples (T1 - T10), heaters (H1, H2) and a pick-up coil are attached to the sample conductor. The normal zone propagation or recovery can be measured using pairs of longitudinal voltage taps (e.g., VL8 is a pair of E8 and E9). The voltage distribution in the cross section of the conductor can be measured using pairs of transverse voltage taps (e.g., VT9a is a pair of E9a and E9b, and VT9c is a pair of E9c and E9d). The thermocouples are used for the measurement of temperature rise after the quench. Two heaters (0.8 Ω), H1 and H2, are made by the stainless steal tape (0.1 mm thick and 20 mm wide) wound 5 turns with the insulation tape on the surface of the conductor. The H1 is attached at 120 mm upper from the center and is used to measure the propagation velocity of normal zone. The H2 is at the center and is used for the measurement of stability. The pick-up coil is wound 200 turns on the conductor to detect the magnetic flux change in the longitudinal direction inside the conductor.

Results of Experiment

The short sample of Design-M conductor has been tested about the critical current and stability using the experimental setup mentioned above. Because of the blocking of the coil current leads, the pressure of the test cryostat was kept at the high value of 0.136 MPa during these experiments, and consequently the temperature of the helium bath was not 4.2 K but 4.54 K.

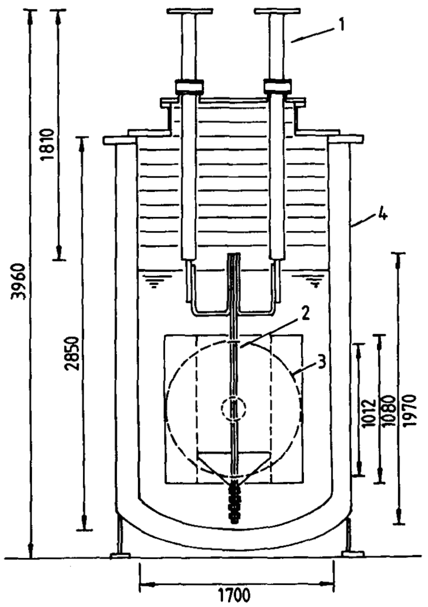


Fig. 2. Cross-section of the conductor test facility.
1) 100 kA current leads 2) Sample conductors
3) Bias field split coils 4) Cryostat

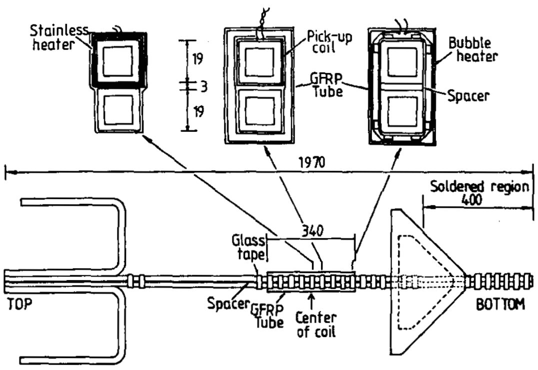


Fig. 3. Detail of the sample conductors

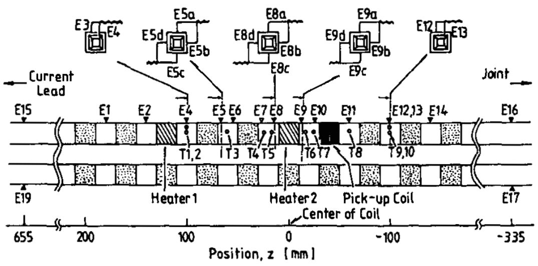


Fig. 4. Measuring points of the sample conductor.

Measurement of Critical Current

Fig. 5 shows the measured quench current versus the bias magnetic field. The measured quench currents (circle mark) agree with the calculated design values (solid line) considering the effect of the conductor self field and the relatively high test temperature of 4.54 K.

The conductor has 5 layered strand cable without the transposition. The maximum self field applied to a strand becomes higher from the inner layer to the outer layer, and consequently the critical current of the inner layer's strands becomes higher than that of the outer layer's strands. It means that the different current can flow for each strand up to the critical current corresponding to the layer position of the strand.

Measurement of Current Distribution in the Conductor

The critical current of the short sample has no degradation. However, for a long conductor as a coil, it can be feared that the uneven current distribution between the strands of each layer may occur during the excitation and which causes the degradation of the critical current. It is necessary to know how the current distributes from the outer layer to the inner layer in a multi-layered strand cable without transposition. A new method of measuring the current distribution inside the conductors was introduced. A pick up coil wound on the conductor detects the magnetic flux change in the conductor longitudinal direction and becomes a sensor to measure the current distribution. The twisted strand cable creates the longitudinal magnetic field at the inner region of each layer. The total longitudinal magnetic flux inside the conductor, which is sum of the magnetic flux of each layer, will change according to the current distribution between each layer's strands.

Using a pick-up coil, the longitudinal magnetic flux was measured as follows. At first, the bias field and the sample current were set to the constant values. Then the change of magnetic flux was measured by initiating a normal zone with the heater H2. Fig. 10 shows an example of a signal of a pick-up coil. When the current transfers from the superconducting cable to the aluminum stabilizers which are not twisted, the longitudinal magnetic flux disappears and its flux change is detected by the voltage signal of a pick-up coil.

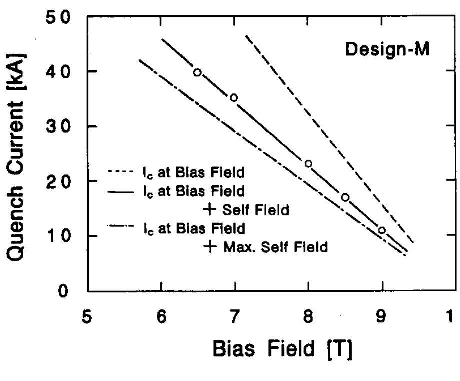


Fig. 5. Quench current of Design-M vs. bias magnetic field. Where the circle mark shows the measured quench current, the dotted line is the critical current of the conductor without the self field, the solid line is the critical current considering self field at each position of strand, and the chain line is the critical current supposing that all strands have the same critical current corresponding to the maximum self field of outermost layer.

Fig. 6 shows the measured longitudinal magnetic flux versus the sample current with the parameter of the bias magnetic field. Where the solid straight line shows the magnetic flux corresponding to the uniform current distribution. The measured values agree well to the calculated convex curves considering the uneven current distribution in which the current flows in order from the outer layer to the inner layer up to the critical current of each layer. Fig. 7 shows this calculation model of the uneven current distribution and the corresponding longitudinal magnetic flux. In the above calculation, the effect of the longitudinal magnetic flux inside a strand created by the twisted filament currents is also considered.

As a result, even for a short sample the current flows partially from the outer layer to the inner layer. However there is no degradation of the critical current and no sign of the instability is observed during the rump up of the sample current.

Measurement of Stability

The stability margin and the recovery current are measured using the central heater H2. The plots of the minimum heater input energy required to initiate a quench versus the sample current as the parameter of the bias field are shown in Fig. 8. The conductor is very stable against the external heat input because of the extremely large thermal conductivity of the high purity aluminum. The normal zone propagation were measured using both heaters H1 and H2. The propagation velocity could not be measured because it was so high that all voltage taps detected normal signal at the almost same time.

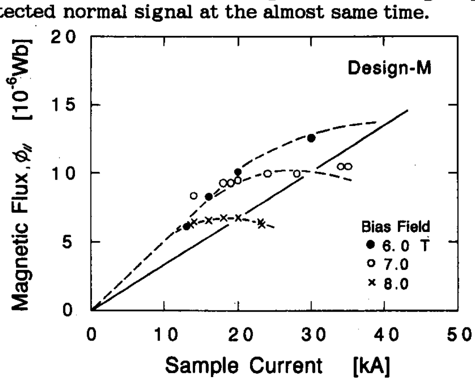


Fig. 6. Longitudinal magnetic flux inside the conductor measured by a pick-up coil.

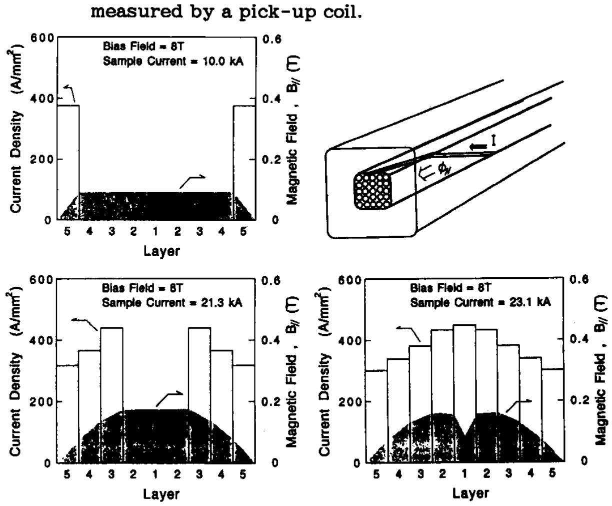


Fig. 7. Calculation model of the current distribution of each layer's strands inside the conductor.

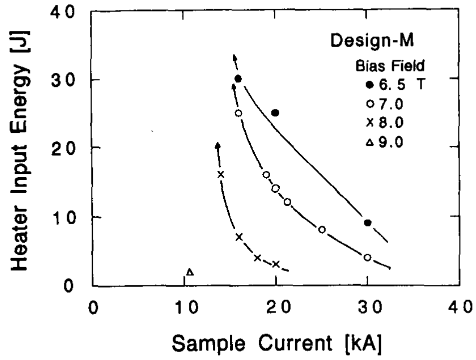


Fig. 8. Minimum quench energy vs. sample current.

Fig. 9 shows the quench recovery current of Design-M versus the bias field. The measured recovery currents were less than the design values which are calculated from the resistivity of each elements of the conductor as listed in Table 2. The reason of the degradation of recovery currents is considered as follows. As shown in Fig. 10, the transverse voltage drops were observed after the normal transition. It means that the unbalanced current sharing to the four pure aluminum stabilizers occurred and the virtual resistance of the conductor became larger than that of the uniform current sharing.

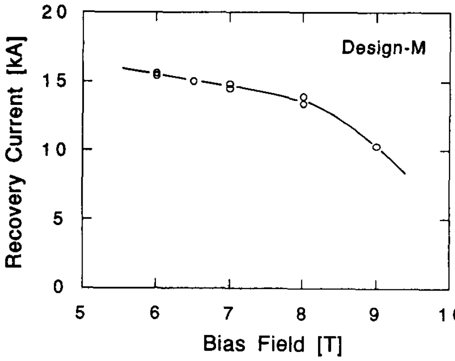


Fig. 9. Recovery current of Design-M vs. bias field.

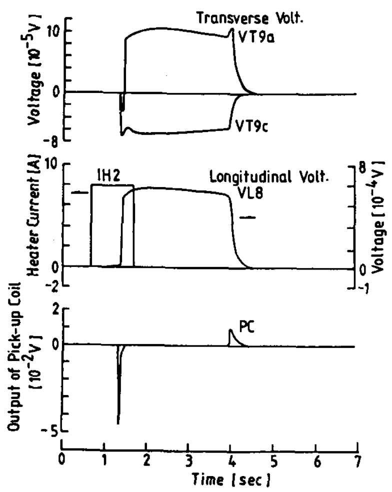


Fig. 10. Signals of voltage taps and a pick-up coil after the initiation of the normal zone by the heater H2. (Bias field of 6.0 T, Sample current of 15 kA and Heater input of 50 W, 1 s.)

Table 2. Recovery Current of Design-M

Bias field (T)	6.0	7.0	8.0
Resistance (D) Ω/m	3.51×10^{-7}	3.53×10^{-7}	3.55×10^{-7}
Resistance (M) Ω/m	8.38×10^{-7}	9.09×10^{-7}	1.00×10^{-6}
Recovery (D) kA	26.8	25.9	23.2
Recovery (M) kA	15.5	14.8	13.4
Recovery (C) kA	17.6	16.4	15.2

Where '(M)' means the measured value, '(D)' is the design value, and '(C)' is the calculated value using the measured virtual resistance.

It can be seen from the precise observation of VT9a signal in Fig. 10 that the current flowed to the outer aluminum at the beginning of normal transition (VT9a had a minus peak) and then diffused to the inner aluminum (VT9a was plus flat top) and at the end returned to the superconducting cable (VT9a had a plus peak and became zero). The measured recovery currents almost agree with the calculated values using this virtual resistance of conductor measured by the longitudinal voltage signal after the quench. The reason of the unbalanced current sharing is not clear at this time and is being investigated as an important problem.

Conclusion

The Design-M conductor was tested about the superconducting characteristics and the stability using the test facility for full-scale conductors. The current of a multi-layered strand cable without transposition distributes unevenly from the outer layer to the inner layer. However there is no degradation of the critical current and no instability is observed during the ramp up of the sample current. The measured recovery currents of Design-M were less than the design values. It is considered that the unbalanced current sharing to the four pure aluminum stabilizers occurred and the virtual resistance of the conductor became larger than that of the uniform current distribution. The reason of the unbalanced current sharing is not clear at this time and is being investigated as an important problem.

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