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New evaluation method of superconductor characteristics for realizing the Large Helical Device

Abstract

It is necessary to apply extra large scale superconducting magnets for a fusion device like Large Helical Device (LHD). Because of the relatively larger current (10kA or more), new evaluation method to determine the fundamental characteristics of superconductors have to be developed, which are already established for thin superconducting wires. In this paper, a measuring method of critical current, stability margin, current distribution are mainly discussed.

Bath-cooled composite type and supercritical helium force-cooled type NbTi conductors have been chosen for helical coils and poloidal coils of LHD, respectively. A critical current of a conductor was measured as follows. Two 2 m long parallel conductors, which were connected each other at the bottom, were inserted in a 9 T split coil. The surface of the conductor was covered 50% by spacers to simulate heat transfer conditions. The time dependent transition phenomena between normal and superconducting state are observed by voltage distribution along the conductor.

On study of forced flow cooled conductors, the current transfer from a quenching strand to another strand was measured by pick up coils on a conduit. We measured its stability margin by a pancake-type coil as a long sample test.

The major measurement results of bath- and forced-cooled LHD conductors using this system have given enough fundamental data of high current multi-strand conductors for the LHD.

1. Introduction

The Large Helical Device (LHD) is a fully superconducting heliotron/ torsatron type fusion experimental device and its construction has been progressing from 1990 at Toki site of the Institute. All coils of the LHD (a pair of helical coils and three pairs of poloidal coils) are designed using NbTi superconductors, and a stored magnetic energy of 0.9 GJ (phase I) and 1.6 GJ (phase II)[1].

The LHD is the beginning of the extra large superconducting magnet for fusion devices after successfully completed medium size TRIAM-1M and Tore Supra. This paper will describe the many efforts to develop superconductor evaluation methods to realize the LHD, because the most of past large coils are designed without any precise characteristics of the large scale conductor.

2. Basic requirements and design of helical coil conductor

The conductor for the helical coils must satisfy the conflicting requirements of high current density and sufficient stability and safety. The current density of the conductor is 58 A/mm^2 at 6.9 T in order to satisfy the average coil current density of 40 A/mm^2 in phase I. The conductor is designed to be cryostable according to Maddock's stability criterion. The mechanical toughness of the coil and the flexibility during winding are another set of conflicting requirements[2].

The cross-sectional view of the conductor (named KISO-32) is shown in Fig. 1. Fifteen superconducting strands are twisted and formed into a Rutherford-type flat cable. The pure aluminum (5N) stabilizer is co-extruded with a Cu-2%Ni (resistivity : 2.5 x 10 $^{-8}$ Ωm) which was selected for the clad material to satisfy a given recovery current. The conductor surface is oxidized to improve the heat transfer coefficient to liquid helium[3].

3. Basic requirements for poloidal coil conductor

The LHD has three pairs of poloidal coils, which are named inner vertical (IV), inner shaping (IS), and outer vertical (OV) coils. From the points of AC loss and electro-magnetic force, supercritical helium forced-flow type NbTi conductor which is composed of 486 (3 x 3 x 3 x 3 x 6) strands in a stainless steel conduit of 3 mm or 3.5 mm thick, is selected for the coil[4]. This conductor is the first thick conduit type to sustain the high stress of 440 MPa[5] applied to a device.

Uniform current distribution and, in case of partial quench of strands, easy current transfer to another strand are necessary conditions[6]. The critical current and limiting current are extensively measured here.

4. Experimental facilities

Test facility for full-scale conductors consists of a cryostat with 100 kA vapor-cooled current leads, a 9 T bias field split coil and a short superconductor sample, and a 75 kA DC power supply[7]. The flat top (90%) field region is about 250 mm. Two short sample conductors of 1970 mm in length are arranged parallel and are inserted into the split coils. The sample conductor are soldered together at the bottom to join the each other.

For pool-cooled conductors, the sample is supported with FRP jigs to keep the exposure rate of 50% to liquid helium. Many voltage taps, thermometers, heaters and pick-up coils are attached to it. The normal zone propagation and recovery phenomena can be measured using pairs of longitudinal voltage taps. Forced-cooled CIC conductors are also examined with this sample configuration.

5. Evaluation of superconductor

5.1. Critical current of multi-strand conductors

To calculate the critical current, we have adopted the following two assumptions to evaluate the effect of the self field[8]. One is that each strand in a conductor can be individually excited up to its critical current determined by the maximum magnetic field experienced through the orbit of the strand, and the overall critical current of a conductor is determined by the sum of the critical currents of all strands. The other is that we take the representative field for each strand at the center of the strand which gives the critical current of the strand by a measured value of a single strand.

Figure 2 shows the measured critical currents of KISO-32 against the bias magnetic field. The results (20 kA at the bias field of 7 T) were in good agreements with predicted values indicated by the dashed curve.

5.2. Hall effect in a composite conductor and its recovery current

As for the cryogenic stability, we have observed an extreme enhancement of the effective resistivity of aluminum stabilizers which deteriorated the cryogenic stability of the conductor. This is due to the 'Hall effect' which occurs in a metal-metal composite[9]. We have derived an exact formula of the effective resistivity of composites based on the 'Hall effect'[10]. Figure 3 shows the measured normal resistivity of the stabilizer of KISO-32 after normal transition[3].

5.3. Limiting current and stability margin measurements of the cable-in-conduit conductor

In order to measure the stability margin of the poloidal conductor, the demonstration conductor of 70 m was formed into a double-pancake (named IV-S) and mounted on the back-up field coil named TOKI-PF[11,12]. Both coils have the same inner radius of 0.6 m. Supercritical helium flows from the inner turns to the outer turns with a pressure of 1 MPa or less. Peak magnetic field was 2.7 T with the current of 20 kA. By raising the working temperature up to 7.5 K, the sample experiences the same load line as the LHD coils. The Figure 4 shows instrumentation required for the experiments. If assuming that the heat was not lost to the neighboring layer, the input energy can be calculated from the integration of the increase of helium enthalpy.

The margin of IV-S was measured at 7.5 K with the pressure of 1.0 MPa and 0.5 MPa. The heating was repeated with sufficient intervals until the coil quenched. The results are shown in Fig. 5. The dashed and the dash-dotted line indicate the available helium enthalpy for 1.0 MPa and 0.5 MPa, respectively. The margins were all very close to the calculated available enthalpy in the both cases of 1.0 MPa and 0.5 MPa. Thus the conductor stayed in the upper stability region[13] up to 21 kA, which was about 94 % of the critical current.

5.4 Stability for partial quenching of the cable-in-conduit conductor

The measurements of the stability margin have been done in a condition that all strands were simultaneously heated. In case of the actual conductor, we had better consider that the quench originates from the normal transition of a few strands. Thus we have investigated normal propagation and current transfer in the transverse direction after partial quenching by using a short sample[6]. The partial normal zone was generated by a heater and the current distribution was monitored by pick-up coils. The resistive foil heater of 350 Ω was attached to about ten strands. Eight pick-up coils with 200 turns surrounded the conductor to detect the magnetic field produced by the transport current.

The experimental results indicated that the current in the strands with the normal zone was transferred to adjacent strands and the normal zone vanished when the critical/operating current ratio exceeded two.

6. Conclusion

Superconductors for LHD have been evaluated with newly developed methods. Bath-cooled conductors for the helical coils have been tested in a short sample, and forced-cooled one for the poloidal coils have been tested in double pancake coil and also in a short sample. Many diagnostic sensors are used to carry out these precise evaluation.

As for the bath-cooled conductors, the measured critical current can be well explained as the summation of critical currents of all the strands under a magnetic field including the self-field. The enhancement of the magnetoresistivity of an aluminum stabilizer was observed and the 'Hall effect' well explained this phenomenon.

The stability margin of the force-cooled conductor was measured by a long sample shaped as a coil using an inductive heater. In a short sample experiment, the current transfer from a quenching strand to another strand could be observed by pick-up coils on the conduit.

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Figure Caption

Fig. 1. Cross-sectional view of the helical coil superconductor named KISO-32.

Fig. 2. Measured critical current and recovery current. Calculated values are also shown for each specific current.

Fig. 3. Measured longitudinal resistance after a transition to the normal state.

Fig. 4. Instrumentation of the stability margin measurements. A resistive heater (RH) was attached on the inlet pipe to increase gas temperature. An inductive heater (IH) was wound around the conductor in order to measure the stability margin.

Fig. 5. Results of the stability margin measurements at 7.5 K.

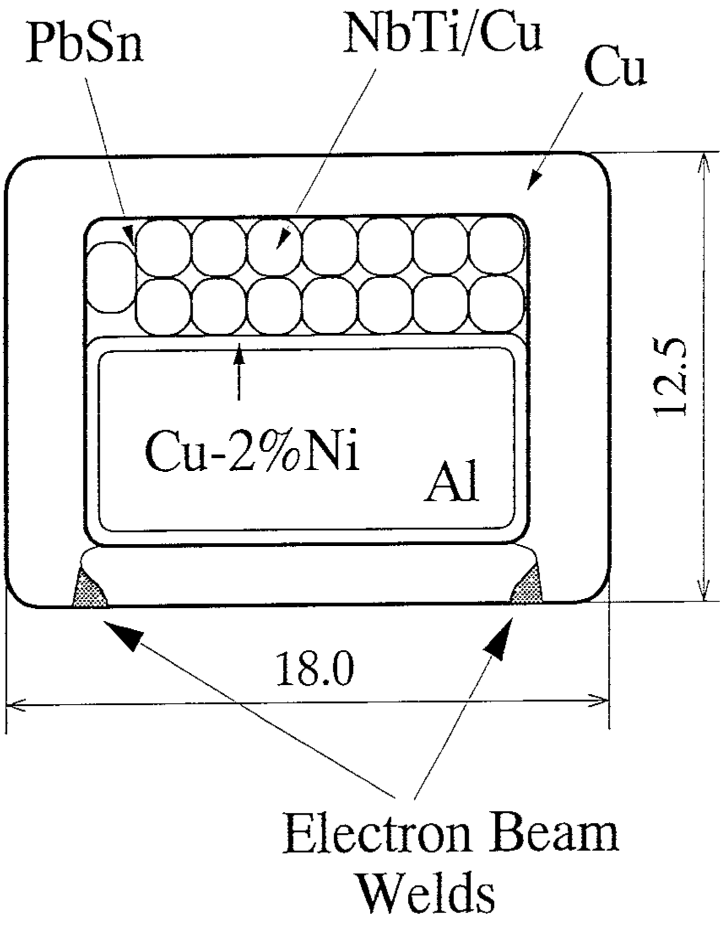


Fig. 1

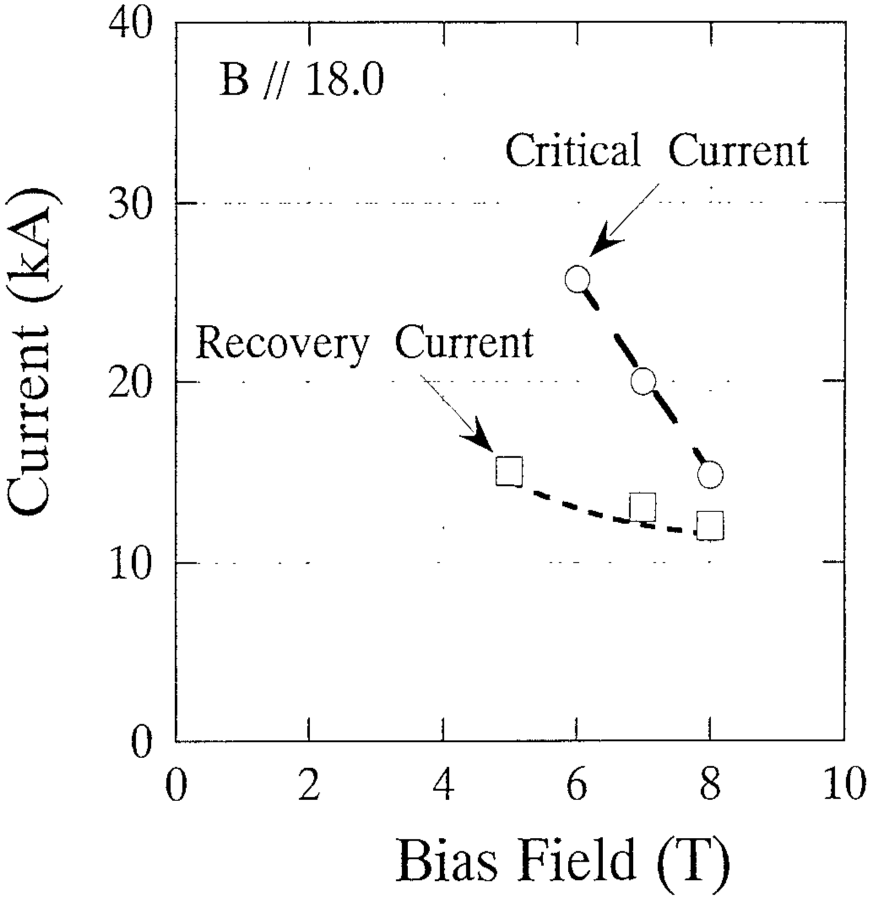

B // 18.0
Critical Current
Recovery Current
Current (kA)
Bias Field (T)
40
30
20
10
0
0
2
4
6
8
10

Fig. 2

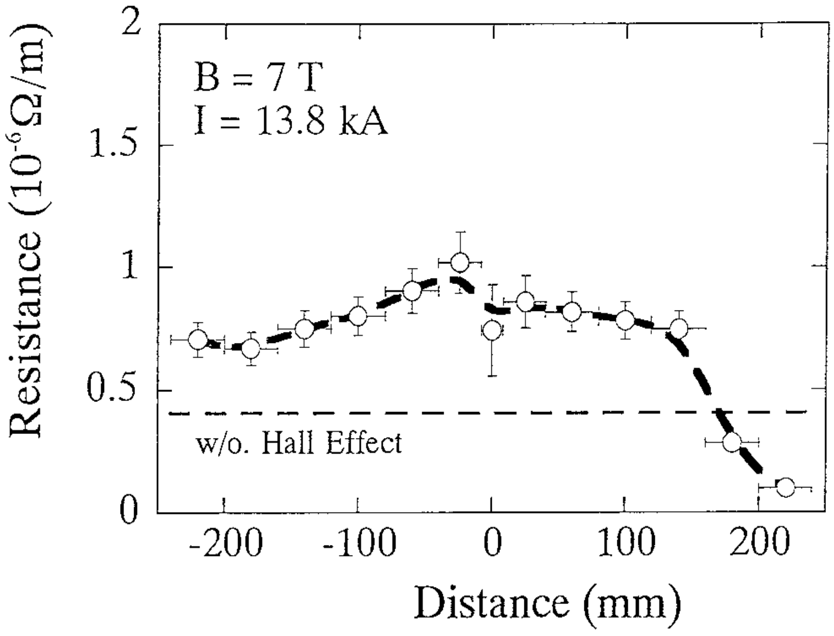

B = 7 T
I = 13.8 kA
w/o. Hall Effect
Resistance ($10^{-6}\Omega$/m)
Distance (mm)
0
0.5
1
1.5
2
-200
-100
0
100
200

Fig. 3

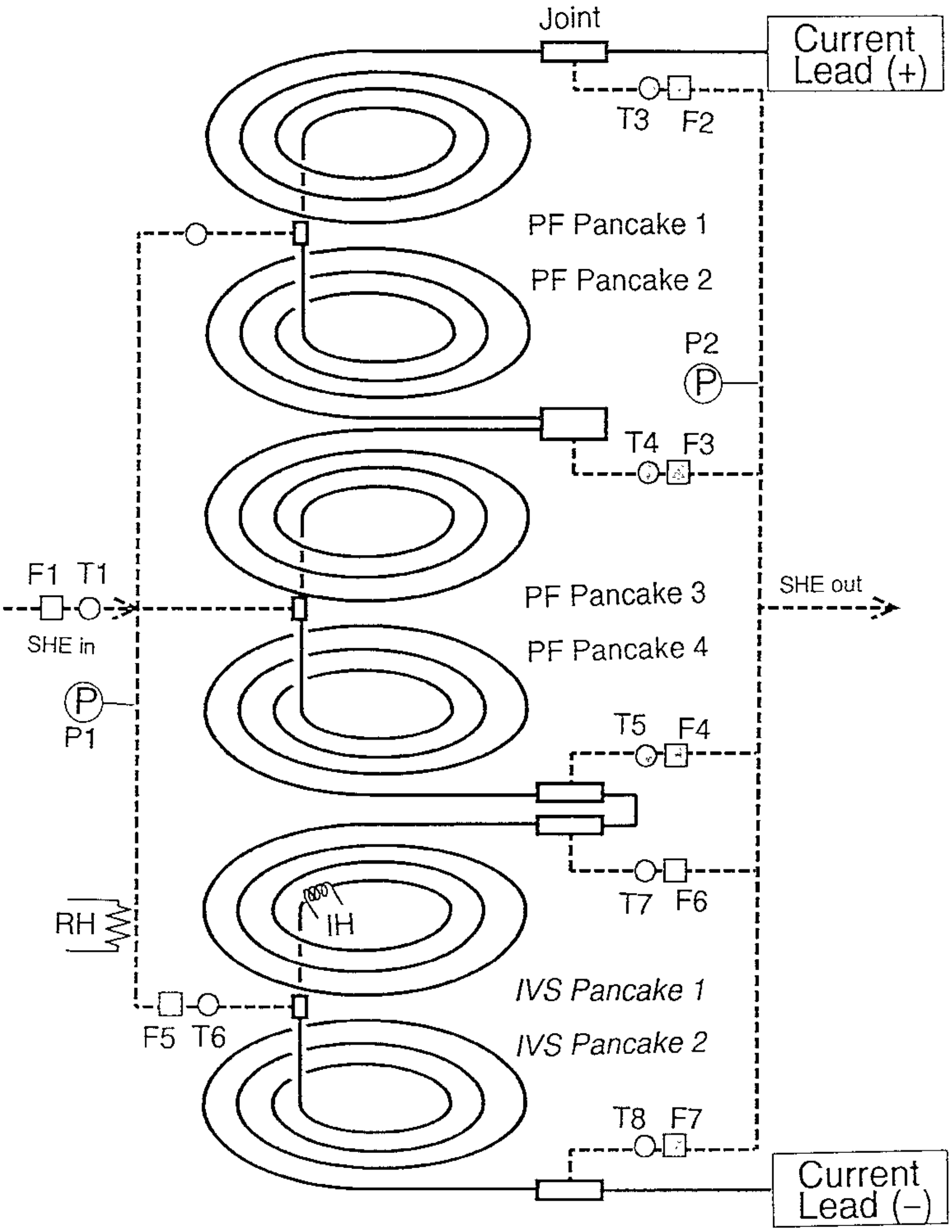
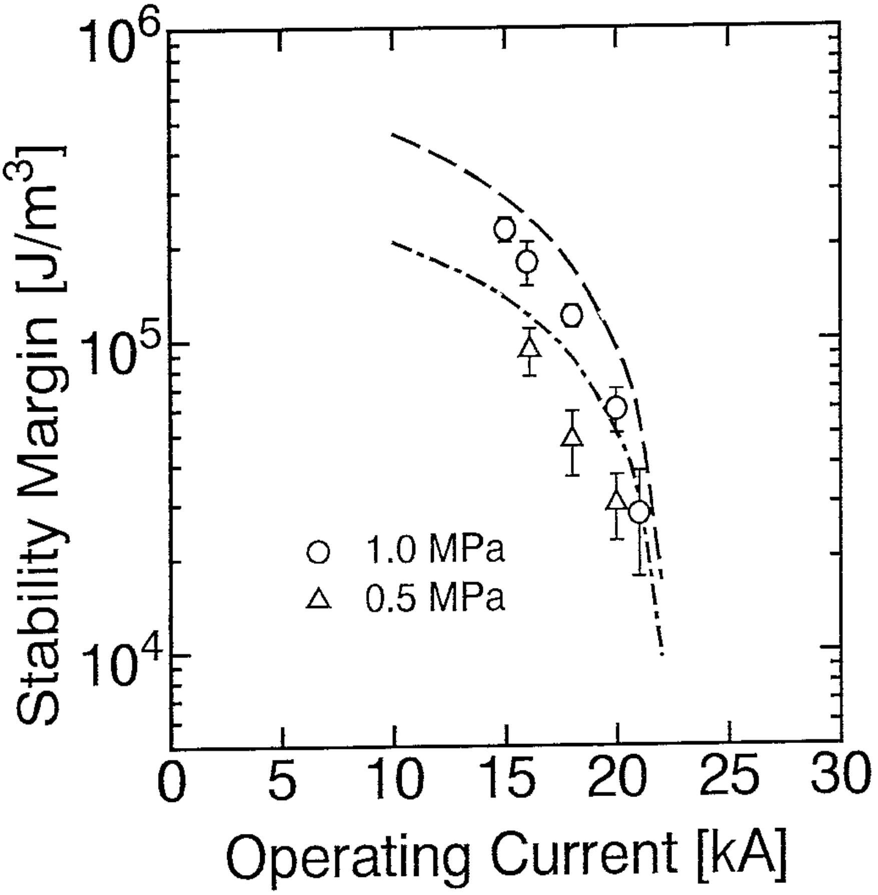

Joint
Current Lead (+)
T3
F2
PF Pancake 1
PF Pancake 2
P2
P
T4
F3
F1
T1
SHE in
SHE out
PF Pancake 3
PF Pancake 4
P
P1
T5
F4
T7
F6
RH
IH
IVS Pancake 1
IVS Pancake 2
F5
T6
T8
F7
Current Lead (–)

Fig. 4



10^6
10^5
10^4
Stability Margin [J/m^3]
0
5
10
15
20
25
30
Operating Current [kA]
○ 1.0 MPa
△ 0.5 MPa

Fig. 5

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