STABILITY OF CABLE-IN-CONDUIT SUPERCONDUCTORS FOR LARGE HELICAL DEVICE

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Abstract--The stability of cable-in-conduit superconductors has been experimentally investigated as a program of poloidal field coils for the Large Helical Device (LHD) project. On the excitation tests for the demonstration coil (TOKI-PF), we had found several problems on the stability of a cable-in-conduit conductor; strand movements, current distribution and current transition among the strands. Consequently, a new conductor was designed and fabricated focused on the stability. As a result of a zero-dimensional stability analysis, it was found that the conductor has high stability margin, 5×10^5J/m^3, at the design condition of 20.8 kA and 6.5 T. Current transfer performance after partial quenching has been investigated by a short sample test. In this paper, effects of the current transfer among the strands on the conductor stability will also be discussed.

I. INTRODUCTION

Large Helical Device (LHD) is a heliotron/torsatron type fusion experimental device and its construction is progressing as a 7 year project which began in 1990. In 1991, we started the construction of one of the poloidal field coils, named Inner Vertical Coil (IV-coil) [1]. From the research and development programs, we decided to design the conductor focused on reliability and stability. In this paper, we deal with stability of the conductor used for the IV-coil.

Stability of cable-in-conduit conductors has been theoretically studied by using zero- and/or one- dimensional models [2,3]. Here we include the effects of normal propagation and current transfer in the transverse direction of a conductor. In the excitation tests of the demonstration coil (TOKI-PF), the conductor was found to be unexpectedly unstable [4]. In this coil, the strands were insulated with formvar of 11 μm thickness in order to reduce the coupling losses. We confirm that there are some problems concerning the insulation. First, the formvar insulation reduces the heat transfer coefficient effectively. Second, rapid commutation of current may lower the stability. The quench of a multi-strand cable may originate from the normal transition of some portions of the strands. Vysotsky et al. pointed out that the current transfer from a strand with the normal zone to the adjacent strand occurred rapidly when using insulation or high resistive matrices, and the quench current of the adjacent strand could not reach the DC critical one [5].

In the experiment presented here, the current transfer in the transverse direction was studied using a short sample of the conductor for the IV-coil. A partial normal zone was generated by a resistive heater instead of an inductive heater and the current distribution was monitored by pick-up coils.

II. CONDUCTOR DESIGN

Main parameters of the new conductor are listed in Table 1. In order to improve the stability of the conductor, we decided to use neither resistive layers on the strand surface nor CuNi layers inside the strands. Cu/NbTi ratio and critical/operating current ratio are set to be 2.7 and 3, respectively. Copper resistivity was reduced as small as possible. The critical current measured with a short sample is shown in Fig. 1. The open circles are the measured values and the dashed line is the calculated one by using the critical current of the strand. The measured values agreed with the calculated one, which confirms no damage of the strands. The critical current was extrapolated to be 62 kA at 6.5 T which is just three times as large as the operating one. We designed these parameters in consideration of the stability margin. Figure 2 shows the calculated margin. In the analyses, a zero-dimensional model proposed by L. Bottura and J. V. Minervini [6] was applied. Magnetic field is proportional to the operating current, I_{op}. The results indicate that the margin decreases rapidly when the operating current exceeds 20 kA. The limiting current was, therefore, estimated to be approximately 20 kA. The margin, however, keeps rather high value, 5×10^5 J/m^3, at the designed point.

Table 1. Parameters of conductor for IV-coil.
All dimensions are measured values.

Conduit Dimension	22.9 mm×27.7 mm
Thickness	2.9 mm
Material	SUS316L
Void fraction	38 %
Strand Diameter	0.767 mm
Configuration	$3^4\times6$
Cabling pitch: 1st	60 mm
2nd	95 mm
3rd	145 mm
4th	225 mm
5th	408 mm
Strand Composition	1:2.66 (NbTi:Cu)
Resistivity of Copper	4×10^{-10} Ωm at 6.5 T
Filament Diameter	15 μm

Manuscript received August 24, 1992

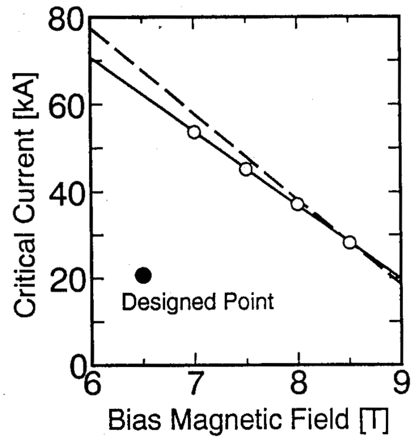

Figure 1. Measured critical current of the conductor. The dashed line is the calculated value using the critical current of the strand.

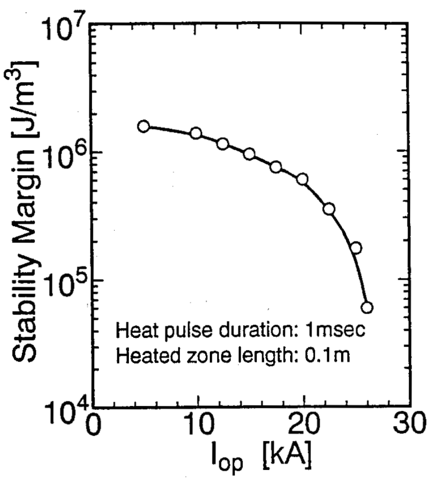

Figure 2. Calculated stability margin. Magnetic field is proportional to the operating current, I_{op}, with a factor of 3.1×10^4 T/A.

III. EXPERIMENTAL SETUP

Experiments were carried out by using a large-scale conductor test facility in which a split coil generates the background magnetic field up to 9 T. A power supply has a capacity of 75 kA. A pair of test conductors was inserted into a bore of the split coil. Length of each conductor was 1.2 m except joint parts. The end of each conductor was jointed to the current leads and the opposite side was soldered each other. In the joint parts, the conduit was removed and the strands were unbound. In this experiment, we used liquid helium (4.58 K) for the coolant instead of the supercritical helium, since the electromagnetic features of the cable do not depend on the coolant condition. The arrangement of a heater and pickup coils is schematically illustrated in Fig. 3. The resistive foil heater of 350 Ω was attached to about ten strands. The heater current pulse had a rectangular shape with a duration of 1 sec and generated heat up to 5 J. Eight pickup coils with 200 turns surrounded the conductor to detect the magnetic field produced by the transport current. Output signals of the coils were integrated to give the magnetic field change.

Figure 4 shows the longitudinal locations of a heater, pickup coils and voltage taps. The heater and the eight coils (PC09~PC16) were located at the center of the background split coil. A pair of eight pickup coils (PC01~PC08 and PC17~PC24) was similarly set at the distance of 200 mm from the center. The distance corresponds to 1/2 of the 5th cabling pitch and the positions of strands then rotate almost 180 degrees. The voltage taps (E_b~E_f) were attached on the conduit at intervals of 68 mm.

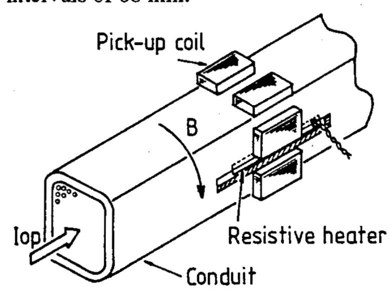

Figure 3. Arrangement of a heater and pickup coils

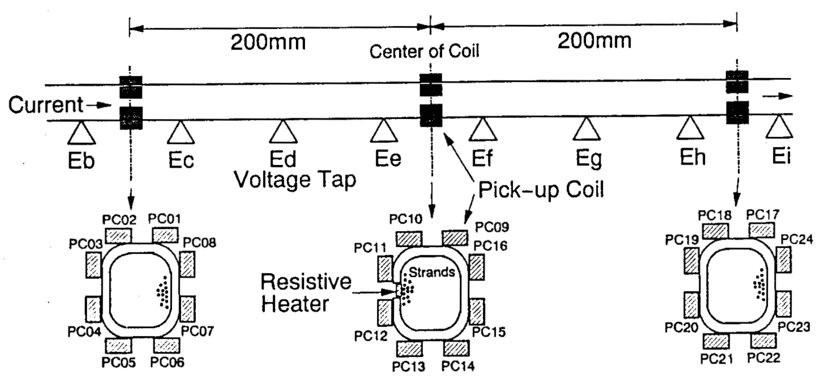

Figure 4. Locations of a heater, pickup coils and voltage taps.

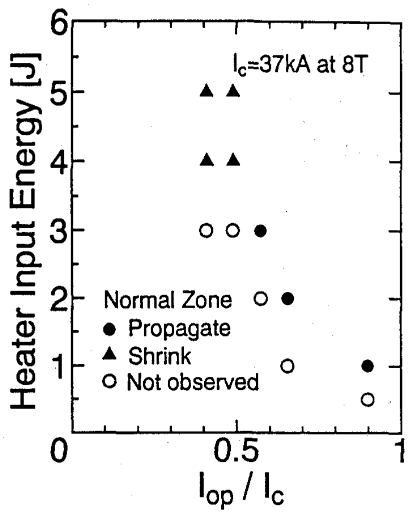

Figure 5. Plots of the minimum heater input energy required to initiate the normal transition versus the operating/critical current ratio, I_{op}/I_c.

IV. RESULTS AND DISCUSSION

Figure 5 shows the plots of the minimum energy required to initiate the normal transition versus the operating/critical current ratio, I_{op}/I_c. Though the normal zone propagated for $I_{op}/I_c>0.5$, it shrank for $I_{op}/I_c<0.5$. It should be noted that the operating current of $I_{op}/I_c=0.5$ corresponds to the recovery current which is observed for pool-boiling type conductor.

Figure 6 shows the time evolution of voltages and field changes, ΔB, at 18.2 kA ($I_{op}/I_c=0.49$) where the normal zone shrank. When the voltage generation was initiated, the field at the positions of PC07, PC11 and PC24 decreased, since the field produced by the initial transported current has a positive sign. These pickup coils were located near the strands attached to the heater (see Fig. 4). So, the field decrease indicates that the current in the strands with the normal zone was transferred to adjacent strands which were far from these pickup coils. Though the heater input continued for 1 sec, the voltage vanished in about 0.2 sec. This can be explained as follows: the current with the normal zone dropped down to nearly zero and then the voltage vanished. Although the current of the adjacent strands increased, they were still superconducting. The data also show that ΔB saturated after the vanish of the voltage, which indicates that the distribution of the transport current has been changed due to the generation of the partial normal zone.

Figure 7 shows the time evolution where the normal zone propagated at 21.3 kA ($I_{op}/I_c=0.57$). The change of ΔB seems to be composed of two phenomena. ΔB for the initial 0.08 sec (period I in the figure) was almost similar to the previous data at 18.2 kA. ΔB at PC11 decreased and then saturated. This means that only the strands near the heater quenched in the period I. In the subsequent period (II in the figure), ΔB at PC11 and PC13 decreased and the others increased along with the increase of the voltage signals. The distribution of ΔB indicates that the current was transferred in the transverse direction.

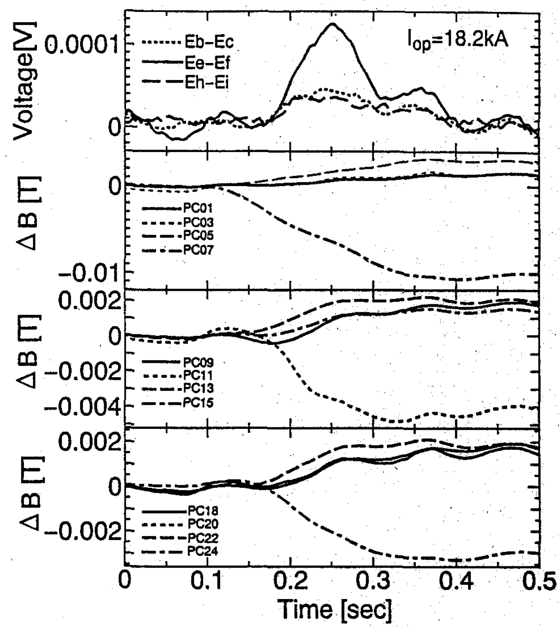

Figure 6. Time evolution of voltages and field changes, ΔB. The normal zone shrank at 18.2 kA and 8 T. Heater was on from -0.1 sec to 0.9 sec.

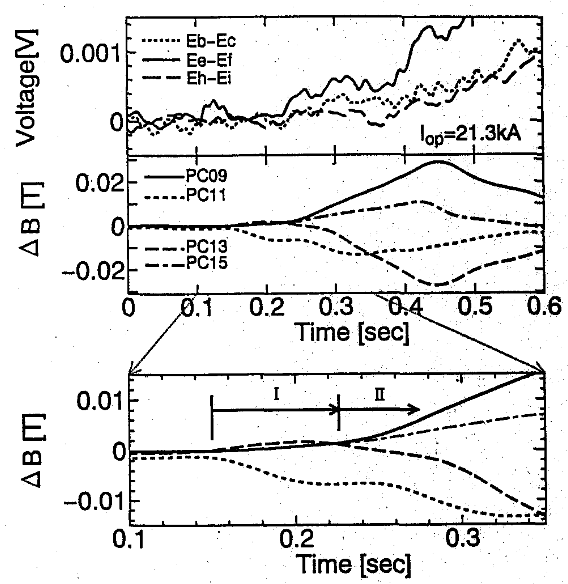

Figure 7. Time evolution of voltages and field changes, ΔB. The normal zone propagated at 21.3 kA and 8 T. Heater was on from -0.1 sec to 0.9 sec.

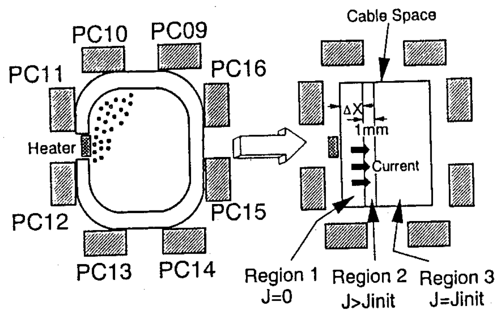

Figure 8. A Model for calculating the field changes due to the transverse transfer of the transport current.

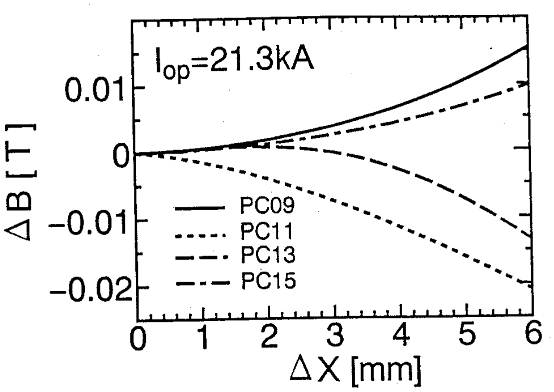

Figure 9. Calculated results of the field change due to the current transfer. ΔX is defined in Fig. 8.

We calculated ΔB by using a simplified model as shown in Fig. 8 in order to confirm the current transfer process. In this model, the current in the region 1 with the width of ΔX drops down to zero and this current is added to the region 2 of 1 mm width. The width of 1 mm simulates a row of strands. The current density in the region 3 is assumed to be constant. The calculated results are shown in Fig. 9. ΔB at PC11 decreases and ΔB at PC09 and PC15 increase with increasing ΔX. ΔB at PC13 decreases as $\Delta X>2$ mm. These tendencies were consistent with the experimental results. In period I, ΔX was evaluated to be 2~3 mm. In Fig. 7, all ΔB's approached zero again from 0.45 sec, which indicates that the current density became uniform since all the strands turned into normal states.

It should be noted that the stability boundary appeared at $I_{op}/I_c \sim 0.5$. At 21.3 kA, the normal propagation started after the commutation. The reason may be that the current in the adjacent strands increased and finally exceeded the critical current. The strands over the critical current must have quenched in a long region if the magnetic field is constant. If considering a two-strand cable, it is clear that the stability boundary is $I_{op}/I_c=0.5$. In the experiment, the phenomenon similar to the two-strand system may occurred. Vysotsky et al. reported that quench current of the adjacent strand cannot reach the critical one if the duration of commutation is rapid, the order of 1 msec [5]. The duration was, however, about 100 msec in our sample. The joint resistance between strands may be effectively reduced because of no insulation of strands.

The experimental results suggest that the critical current should be more than twice as large as the operating one in regard to a cable-in-conduit conductor. The IV-coil has the critical current of three times. Therefore, we expect high stability in the operating condition.

V. CONCLUSIONS

Stability of the conductor for LHD poloidal coils was experimentally investigated concentrating on partial quenching using a resistive heater installed in the conduit. The summary of the results is shown below.

(1) Propagation of normal zone was observed when the operating/critical current ratio exceeded 0.5. In the case of $I_{op}/I_c<0.5$, the current in the quenching strand dropped down to zero and the adjacent strand could carry the superconducting current. In the case of $I_{op}/I_c>0.5$, the current in the adjacent strand seemed to exceed the critical one and then the transverse and longitudinal propagation of the normal zone progressed.

(2) The experimental results showed that it took approximately 100 msec to commutate the current fully from the quenching strand to the adjacent one. This duration was much larger than Vysotsky's observations, which may be related to no insulation of strands.

(3) In the actual design of IV-coil, the operating/critical current ratio is set to be 0.33. High stability margin is, therefore, expected in regard to the partial quenching.

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