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Study on Current Sharing Phenomena Observed During the Testing of ITER Prototype Cable-in-Conduit Conductors in the FENIX Test Facility

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ABSTRACT

Current sharing phenomena were studied during the testing of ITER (International Thermonuclear Experimental Reactor) prototype sample conductors in the FENIX (Fusion Engineering International Experiments) test facility at the Lawrence Livermore National Laboratory. During steady-state operation in the current sharing region, voltage drops of up to 200 μV were measured across the conductor. These experimental results were studied in detail using computer program CICC. Differences between the computer predictions and experimental results are postulated to be due to inter-strand cross-currents.

INTRODUCTION

The cable-in-conduit conductor (CICC) is considered the prime candidate for use in the cryogenic superconducting toroidal and poloidal field coil by the ITER [1]. It is made by twisting copper stabilized Nb_3Sn superconducting wires into cables and enclosing them tightly in a conduit. The conductor is cooled by forcing supercritical helium through the spaces between the twisted superconducting wires. Performance testing of the full size conductor at the design conditions of 40 kA and 12.5 T was conducted at the FENIX test facility at Lawrence Livermore National Laboratory [2]. One of the test objectives was to study the performance of the conductor at current sharing conditions. The test results show that the conductor can maintain steady-state operation at current sharing conditions with the voltage drop of up to 200 μV across the conductor. The voltage drop phenomenon was studied using the computer program CICC developed by Wong [3].

A BRIEF DESCRIPTION OF THE FENIX TEST

Various types of the cable-in-conduit conductors have been tested at the FENIX test facility at the Lawrence Livermore National Laboratory since December of 1991. The test results have been discussed in detail elsewhere [4]. Samples prepared for the test consist of straight, paired conductors, connected in series together at one end and connected to the FENIX busbars at the other end. The length of each

conductor, including termination, is 4.7 m. The conductor was cooled by supercritical helium at 5 – 7 atm pressure. The background magnetic field of 12.5 T at the center of the conductor was produced by the FENIX magnets. The typical background magnetic field along the conductor length is shown in Fig. 1. In addition to the background field, a self magnetic field will be generated by the current passing through the conductor.

Five CICC samples have been tested at the facility. Only two of these have been examined for this analysis: a conductor manufactured by the European Community (NET/EM-LMI) and a conductor provided by Japan (JAERI) [5, 6]. The major physical parameters of these conductors are summarized in Table I. To observe the current sharing phenomena, the inlet temperature of the helium was slowly increased until the voltage across the conductor was detected. When the voltage across the conductor was detected, the system was maintained at steady-state. Voltage drops and the temperature of the conductor wall at the center of the conductor were recorded. The voltage drops were recorded by pairs of voltage taps attached at the conductor wall across the high field region of the conductor. All the voltage measurements showed the same value, indicating that the voltage drop occurs at the high field region of the conductor.

Fig. 1 Background Magnetic Field Strength Along the Conductor Length at the FENIX Test Facility

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TABLE I
Main Physical Parameters of Conductors

	EM-LMI	JAERI
Number of Strands	864	23
Strand Diameter(mm)	0.78	2.4
He Area(mm ²)	361	126
Cable Space Cross Section(mm ²)	806	301
Fraction of Cu Area(mm ²)	0.55	0.654

The voltage drop in the conductor as a function of helium temperature is plotted in Fig. 2 and 3 for the EM-LMI conductor and JAERI conductor respectively. The temperature measurement at the conductor wall is assumed to be the average of the helium inlet and outlet temperatures of the conductor. The helium inlet and outlet temperatures are calculated from energy balance assuming there is no energy loss through the conductor wall. As shown in these figures, the voltage drop slowly increased to 200 μ V as the helium outlet temperature increased from 5.2 K to 7.2 K for EM-LMI conductor, and increased to 30 μ V as the temperature increased from 5.8 K to 6.6 K for JAERI conductor. When the helium outlet temperature is increased further, the conductor quenches.

ANALYSIS OF THE CURRENT SHARING PHENOMENA USING COMPUTER PROGRAM CICC

The current sharing phenomena observed at the FENIX test facility were studied using the computer program CICC. This program, developed by Robert Wong at the Lawrence Livermore National Laboratory, models transient thermodynamic and fluid-dynamic state of the helium coolant in the CICC. The computational algorithm in the code couples a one-dimensional compressible pipe model with a two-dimensional axisymmetric heat conduction model of the superconductor cables, the conduit and the

Fig. 2 Voltage drop as a function of He temperature for EM-LMI conductor-- experiment data and CICC predictions.

Fig. 3 Voltage drop as a function of He temperature for JAERI conductor -- experimental data and CICC predictions.

insulation. The code also calculates the heat generation rate and voltage rise in the superconductor cables during the current sharing conditions. Since the code treats the helium flow as one-dimensional pipe flow, the parameters of the cable space are assumed to be uniform across any cross-section. The code with its present structure can not account for non-uniform current superconducting properties, such as magnetic field, strain and temperature in calculating the critical current of the superconducting strands.

To begin the calculation, the steady-state operating condition just below the current sharing temperature was established at the measured helium flow rate. After establishing this steady-state condition, the helium inlet temperature was gradually increased until the voltage drop across the conductor appeared. However, the code predicts that the conductor cannot be operated stably at steady-state under any current sharing condition, even 10^{-5} K above the starting temperature of the current sharing. The code can predict the steady-state operation of the conductor under current sharing conditions when the conductor heat transfer area is increased significantly. The increase required to maintain steady-state under current sharing conditions depends on the type of conductor and the amount of the voltage drop. This behavior is an agreement with tests of single superconductor strands.

The results obtained by the code with the heat transfer area increased by 100 are summarized in the Fig. 4 and 5 for the EM-LMI conductor with a 5.67 K helium inlet temperature. Fig. 4 shows the voltage drop across the conductor, and Fig. 5 displays the helium temperature variation along the conductor 20 s after current sharing condition begins. Fig. 4 shows that the conductor reaches steady-state within 5 s by the computer simulation.

The voltage drop across the conductor calculated by the CICC code is plotted as a function of the helium inlet and outlet temperature along with the experimental data in Fig. 2 and 3 for EM-LMI conductor and JAERI conductor respectively. As demonstrated in these Figures, the voltage

DISCUSSION ON THE DISCREPANCY BETWEEN EXPERIMENTAL DATA AND CODE PREDICTION

Fig. 4 Voltage drop across the conductor as a function of time (EM-LMI conductor).

Fig. 5 He temperature variation along the conductor length after 20 s (EM-LMI conductor).

drop due to current sharing predicted by the code increases much more sharply with temperature increase than does the experimental data. The code predictions represent the commonly understood one-dimensional current sharing phenomena in which the excess current from the superconducting wires passes through adjacent copper. The voltage drop observed in the FENIX test cannot be explained by this one-dimensional current sharing model. Additional modeling including cable-space non-uniformities is needed.

The differences between experimental data and code predictions (Fig. 2 and 3) in the quench temperature are caused by the selecting lower strain values in the code, and it will not effect the analysis.

Part of the discrepancy between the experimentally observed voltage drop and that predicted by the code can be explained by inter-strand cross-currents due to the non-uniform magnetic field across the radial direction in the conductor. As discussed in the previous section, the *CICC* code assumes uniform magnetic field across the cable space. The total magnetic field in the conductor is the sum of three contributions: the background field produced by the FENIX magnets, the self field of the individual leg and the field generated by the neighboring leg. When the sample carries a large current, a gradient of magnetic field occurs across the cable space. The magnetic field distributions in both EM-LMI and JAERI conductors are shown in Fig. 6 (a) and (b) respectively. The average, maximum and minimum fields are summarized in Table II for both conductors.

The critical current of the strands is not only function of temperature but also the magnetic field. The critical current will not be the same for all strands; the critical current is smaller for strands in a higher magnetic field. If the current is initially distributed in the conductor based on the critical current variation, the voltage drop due to the current sharing will be the same as the uniform field as calculated in the *CICC* code. However, the current is not distributed based on the critical current variation. Rather it will be distributed uniformly if the inlet and outlet connections are designed properly. If the current is uniformly distributed throughout all the strands, and the strands have different critical current values due to the magnetic field distribution, the current in the strand with the lowest critical current value will transfer its current to the strand with a larger critical current value when the temperature of the conductor becomes higher than the current sharing temperature of the strand with the lowest critical current.

This phenomenon is quite different from the commonly known current sharing phenomena where the excess current is transferred through the copper attached to the superconducting material. Furthermore, the low voltage drop during the inter-strand cross-currents phenomena indicates that most of the cross-currents occur at the busbar where the resistance between the strands is minimum. The resulting cross-currents can explain 23% of current sharing temperature range during the current sharing observed in the FENIX test in EM-LMI conductor and 47% in JAERI

TABLE II
Magnetic Field Strength at High Field Region

	Magnetic Field (T)		
	Average	Maximum	Minimum
EM-LMI Conductor	12.5	12.96	12.04
JAERI Conductor	12.0	12.41	11.59

(a) EM-LMI Conductor

(b) JAERI Conductor

Fig. 6 Distribution of the self field over the sample across section

conductor. Voltage drop caused by the local magnetic field variation vs. helium outlet temperature was plotted in Fig. 2 and 3 for EM-LMI and JAERI conductor respectively. It was assumed that the voltage drop varied linearly with the amount of the cross-current caused by the local magnetic field variation.

The rest of the voltage drop resulting in a large current sharing temperature range can be explained by other phenomena. The design of the busbar connections may produce a non-uniform conductor current distribution. The strand with the highest current will transfer its current to other strands as the conductor temperature increases. This effect on the voltage drop could be much larger than that due to the magnetic field if the magnitude of the non-uniform current distribution is large. The current distribution and redistribution among strands by cross-current is a very complex problem and further study is needed. Another possible contribution to the voltage drop is the non-uniform physical characteristics of each strand, such as the strain and diameter and critical current variation. Also, there will be a small contribution from the assumption that the magnetic field varies linearly across the radial direction while the large area of the conductor is covered by the lower magnetic field. Total voltage drop observed in the FENIX test could be explained by the combination of all these effects discussed above and more. However, a further study is needed to quantify these various contributions to the current sharing voltage drop.

CONCLUSION

During ITER conductor testing in the current sharing region at the FENIX facility, the conductor could be operated throughout a 1 K - 2 K current sharing temperature range with voltage drop of less than 200 μ V. The one-dimensional current sharing model used by the CICC computer code

predicted a steeper rise in the voltage drop vs. temperature. This leads to the conclusion that cross-currents occur between the strands before the conductor reaches critical current in all strands. This inter-strand cross-current phenomena could be developed due to the radial magnetic field distribution, the initial non-uniform current distribution among strands, and the non-uniform critical current characteristics created by manufacturing.

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