

Conf-9503127--2

UCRL-JC-120076
PREPRINT

Measurements of Stability Margins and Current Distribution in Large-Scale Nb₃Sn Cable-in-Conduit Conductors

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This paper was prepared for submittal to
The 9th US-Japan Workshop on High-Field Superconducting Materials, Wires & Conductors
and Standard Procedures for High-Field Superconducting Wires Testing

Kyoto, Japan
March 13-15, 1995

March 7, 1995



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Measurements of Stability Margins and Current Distribution in Large-Scale Nb₃Sn Cable-in-Conduit Conductors

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Abstract: For testing large-scale cable-in-conduit conductors, several practical experimental techniques have been developed to specifically address the issues of conductor stability. The following described techniques enable experimentalists to quantify the effects and thus provide useful tools to improve the conductor performance in magnet applications. In this paper, we present two experimental techniques: a) stability margin calibration and b) current distribution. Both are much needed in the laboratory for testing the conductor stability.

1. INTRODUCTION

The main goal of the ITER¹ Conductor Testing Program is to validate the design and the fabrication process of the CICC (Cable-In-Conduit Conductor) and its joints, in full-size samples. Equally important is to determine the stability of the Nb₃Sn CICC. The latter is a technical issue, which currently attracts the greatest concern and needs to be resolved expeditiously to clearly understand the effect in the full-size CICC conductors. Achieving these goals during the ITER EDA (Engineering Design Activities), requires an extensive test program for full-size CICC samples. The following experiments and findings are results from a series of full-size conductor testing recently performed^{2,3,4,5}.

2. TEST PREPARATION- Conductor Sample and Instrumentation

A typical conductor sample was described in previous publications. The distribution of relevant sensors is illustrated in Fig. 1. Under nominal test conditions, the high-field region of the conductor is subject to a 13-T magnetic field and the peak transport current is 40 kA, which is a simulated operating condition for ITER magnets.

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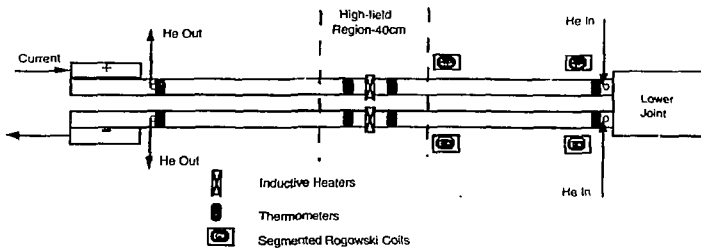


Fig. 1 Sample and Instrumentation Arrangement

3. EXPERIMENTS AND RESULTS

A. Stability Margin Calibration

As shown in Fig. 1, inductive heaters are installed on both legs in the high-field region. By energizing these heaters, fast pulsed energy can be deposited into the conductor that carries transport current at the operating field. As the energy level reaches certain limits, the normal zone will appear. Eventually, the conductor will quench with increasing energy levels. The energy threshold is referred to as the stability margin. The purpose of such experiments is to compare the measured energy margin with that which is available from the heat capacity of the surrounding supercritical helium. Here the stability experiments provided calibration of energy margins using a downstream temperature sensor to measure the helium enthalpy changes due to the inductive heater pulses (Fig. 2 and 3). After each pulse, energy delivered to the primary of the inductive heaters was also calculated as a reference (Fig. 4 and 5).

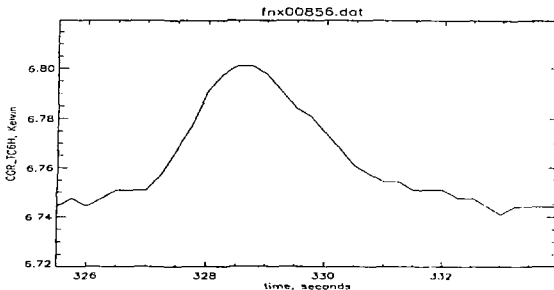


Fig. 2 Measured downstream helium temperature rise after heater pulse

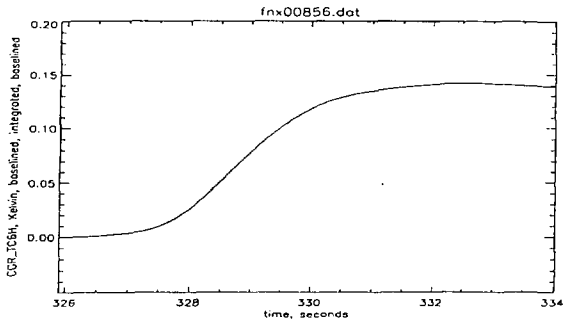


Fig. 3 Plot of $\int \Delta T dt$ for helium enthalpy calculation

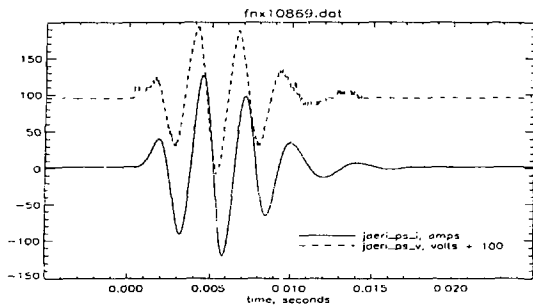


Fig. 4 Waveforms of Current and Voltage in the inductive coil

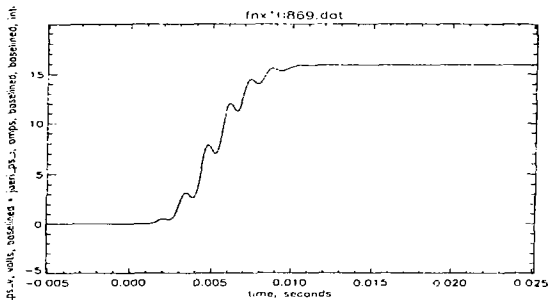


Fig. 5. Plot of $\int V i dt$ for calculation of energy in the primary circuit

B. Measurements of Current Distribution

There have been several applications of segmented Rogowski coils for current distribution measurements⁶. Several sets of pickup coils were installed on the sample. The coils are in the shape of a segmented Rogowski coil; therefore, they are expected to measure the total transport current as integral; and by comparing the output of each segment, the local current distribution can be studied. However, due to space limitation, no coil was mounted in the high-field region. Fig. 6 illustrates the arrangement of typical coil set. Most measurements were made in the region with a peak field of about 9 T.

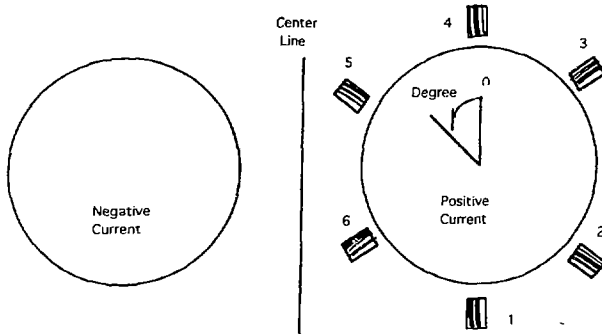


Fig. 6 Arrangement of Segmented Rogowski Coils

As shown in Fig. 7, these coils first underwent low-current calibration tests at room temperature, a condition under which uniform distribution was expected and was indeed verified. The measured distribution resulted mostly from the return current in the other leg; thus, a calibration constant for the coil set was obtained. Next, the 40-kA ramp tests were performed at 4.5 K, when the CICC was in its superconducting state. A nearly identical distribution was obtained, and the same calibration constant was again verified.

However, the behavior of each coil drastically changed during high-field tests, as the CICC was subject to a 9-T peak field in the measured region. As shown in Fig. 9, it exhibits some negative current flows in certain regions in the beginning of the current pulse. However, the total 40-kA transport current was still correctly measured by the sum of all integrated voltages with the same calibration constant (Fig. 10), which implies that current was redistributed due to inter-strand current flow at a 9-T field. This preliminary result strongly suggests that non-uniform current distribution existed between the leads and the high-field region in the current test arrangement.

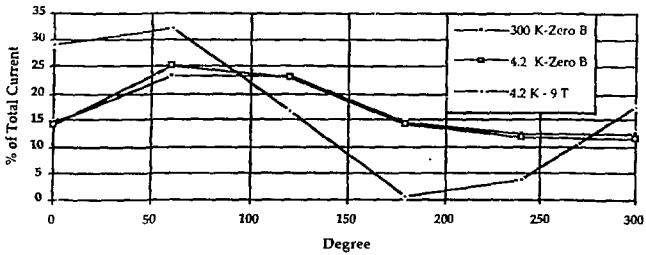


Fig. 7 Measured current distribution for three test conditions

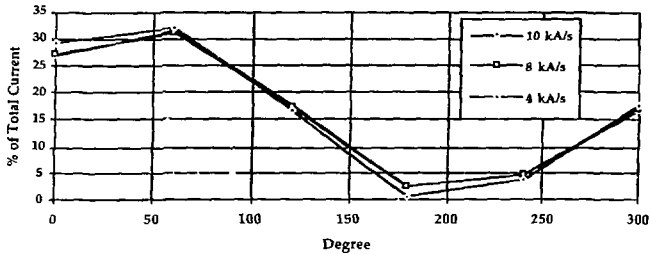


Fig. 8 Measured current distribution for different di/dt

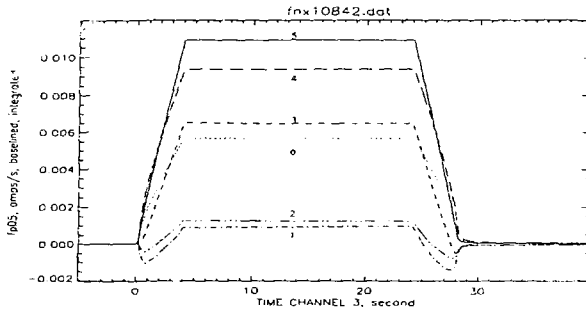


Fig. 9 Measured current distribution with 6 segmented Rogowski coils

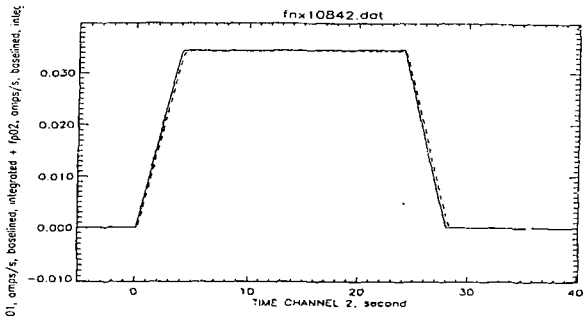


Fig. 10 Overplot of power supply current and the measured complete Rogowski coil

4. SUMMARY

Two experimental techniques are described to measure the stability margins and the current distribution in CICC experiments. The observed effect of irregular current distribution needs further investigation, especially for large-scale applications such as fusion magnets.

5. ACKNOWLEDGMENT

This work was performed under the auspices of the U.S. Department of Energy by Lawrence Livermore National Laboratory under Contract W-7405-Eng-48.

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