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***Abstract*—The Fusion ENgineering International eXperiments (FENIX) Test Facility recently has successfully completed the testing of a pair of Nb3Sn cable-in-conduit conductors developed by the Japan Atomic Energy Research Institute. These conductors, made of bronze-processed strands, were designed to operate stably with 40-kA transport current at a magnetic field of 13 T. In addition to the measurements of major design parameters such as current-sharing temperature, FENIX provided several experiments specifically designed to provide results urgently needed by magnet designers. Performed experiments include measurements of ramp-rate limit, current-distribution, stability, and joint performance. This paper presents the design and results of these special experiments.**

I. Introduction

The main goal of the International Thermonuclear Experimental Reactor (ITER) Conductor Testing Program is to validate the design and the fabrication process of the cable-in-conduit conductor (CICC) and its joints, in full-size samples. Equally important is to determine the ramp-rate limits and the stability of the Nb3Sn CICC. As part of the ITER collaboration on the magnet R&D program, a test sample was prepared by Japanese industries under contract with the Japan Atomic Energy Research Institute (JAERI). The sample represents the most recent ITER prototype conductors, except that the test sample had a titanium sheath and that it was cooled without the central hole circuit. Similar conductors were tested earlier [1] at JAERI in a smaller facility. The test revealed unexpected conductor behavior, namely, "limitation of the transport current" as a function of current ramp rate. However, it was generally postulated that the limitation was the result of unbalanced current distribution due to the sample's short length. It was also conjectured that the limitations were due to inadequate cooling at excessive high currents.

II. Experiment

The FENIX facility provides test conditions that closely simulate ITER operation. These include a long sample length and supercritical helium cooling with temperature control.

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To investigate the current-distribution effect, both JAERI and LLNL designed and installed pickup-coil systems on the sample. The tests are also expected to provide critical information on ration-of-resistivity values, current-sharing temperatures T_{CS}, stability margins and joint performance.

A. Sample Descriptions

The sample consists of two straight legs of CICC, leg F and leg H; each was fabricated by a different manufacturer, with different Nb3Sn strands and different cable patterns. Cross-sectional views of both conductors and their major parameters are shown in Fig. 1 and Table I respectively.

B. Experimental Arrangements

The sample was designed with individual cooling circuits for both of the conductor legs as well as the lower joint. The FENIX heat-exchanger system [2] has ample plumbing for each cooling circuit to be independently controlled, thus allowing each of the conductors and the lower joint to be tested separately or in any combination for their critical parameters. The assembly is heavily instrumented with different types of sensors, as shown in Table II.

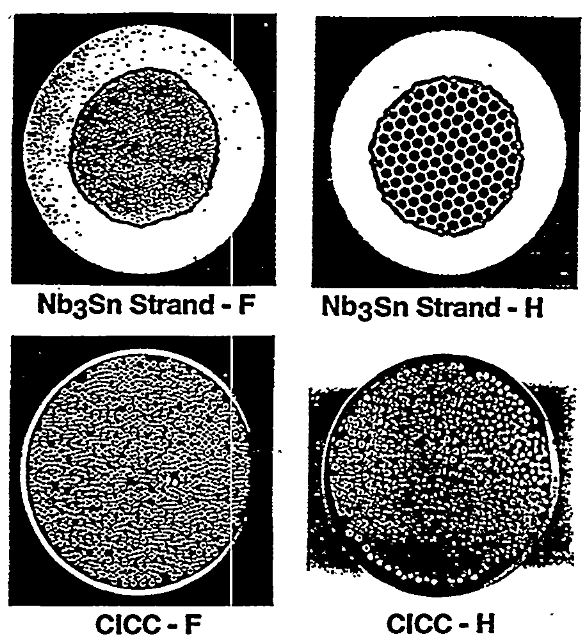

Figure 1. Strand and CICC cross-sections

Table I

MAJOR PARAMETERS OF TEST SAMPLE

		F Leg	H Leg
Strand	Material	$(NbTi)_3Sn$	$(NbTi)_3Sn$
	Process	Bronze	Bronze
	Diameter (mm)	.92	.92
	Cu/non-Cu	1.58	1.47
	Cr Plating (μm)	2.0	2.3
CICC	Outside Diameter (mm)	33.60	32.80
	Inside Diameter (mm)	31.88	30.48
	No. of Strands	768	675
	Sheath Material	Titanium	Titanium
	Cable Space (mm^2)	798.23	729.66
	Strand Cross Section (mm^2)	514.99	453.21
	He Area (mm^2)	283.24	276.45
	Void Fraction (%)	35.5	37.9

Table II

LIST OF SAMPLE DIAGNOSTICS

Sensor Type	Number Installed
Thermometer (Carbon-glass)	12
Hall Probe	2
Voltage Tap	26
Pickup-Coil Set	5
Inductive Heaters	4

Table III

SUMMARY OF RR MEASUREMENTS

Measurement Condition	
Magnetic Field	6 T
Current	5000 A
Voltage-Tap Span	> 16 cm
Measured Average RR	
F Leg	95
H Leg	150

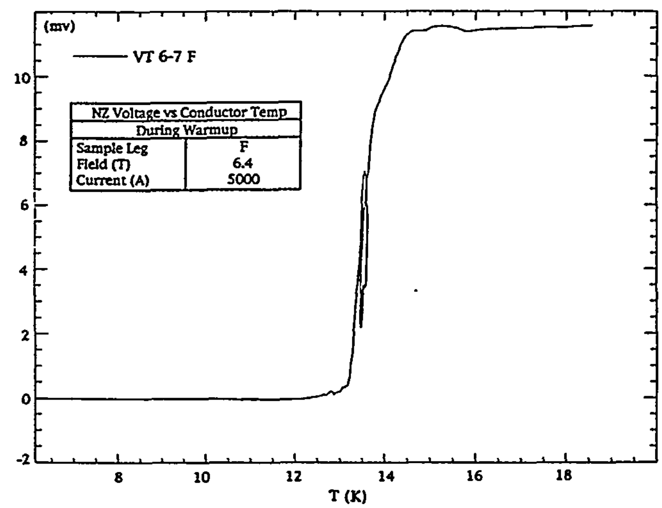

Fig. 2. Measurements of NZ Voltage of F Leg

C. Experimental Results and Discussions

1. Measurements of RR Values

Copper stabilizer is needed for stable operation and safety protection of magnets made of Nb_3Sn CICC. Electrical conductivity of the copper matrix is generally measured in ratio of resistivity (RR), a value that requires both measurements of resistivity at room temperature and at 20 K. Here, we have chosen the ratio of copper resistivity at 273 K to 20 K as the RR value. In order to obtain the correct Cu resistivity at 273 K, two steps were taken after the measurements of resistivity of the CICC at room temperature: (1) We performed proper correction of the contribution due to the conductivity of the bronze, and (2) We converted the resistivity value for 273 K from ambient temperature. For large-size conductors such as ITER prototypes, accurate measurement of resistivity at 20 K is rather difficult to perform, especially during cooldown. In FENIX, the sample was slowly warmed up with a constant transport current of 5000 A at a field of 6.4 T. After T_{CS} was reached, the growth of the fully normal zone was then measured all the way to 20 K. The zero-field Cu resistivity was finally deduced with the magneto-resistance effect taken into account. Figure 2 illustrates the measurement of the growing normal zone in the F leg. A Summary of RR values is shown in Table III. It indicates that the H leg possesses a higher RR value than the F leg.

2. Measurements of Current-Sharing Temperatures and Ramp-Rate Dependence

The most critical element in such experiments is the temperature sensors located on the sheath in the high-field region. Several carbon-glass resistors (CGRs) had to be installed on each leg to provide accurate measurements with fast time response. These CGRs were calibrated in LHe (liquid helium) at high field to compensate for the magneto-resistance effect. Different methods of controlling temperatures and currents were used to obtain each data point [2]. In controlling the transport currents, ramp rates from 1 kA/s to 10 kA/s were used. Results indicate that measured Tcs was virtually independent of these rates. Measured Tcs at 40 kA for the F leg is shown in Fig. 3. In this plot, the Bmax includes the self field due to transport current, which amounts to 0.5 T for 40 kA. It should be noted that the voltage gradient criteria for current-sharing temperature measurement is 0.1 μV/cm, identical to that used in the strand short-sample critical-current test. Results indicate that the final effective strain on Nb_3Sn strands is within the range of -0.22% and -0.34%, suggesting that the use of titanium sheath did not introduce any significant degradation. Although they were designed for the same current/field capability, the F leg performed appreciably better than the H leg [3]. At the ITER central solenoid (CS) design operating point of 5.5 K at 13 T, it has a temperature margin of more than 2 K. Similar to previous observations,

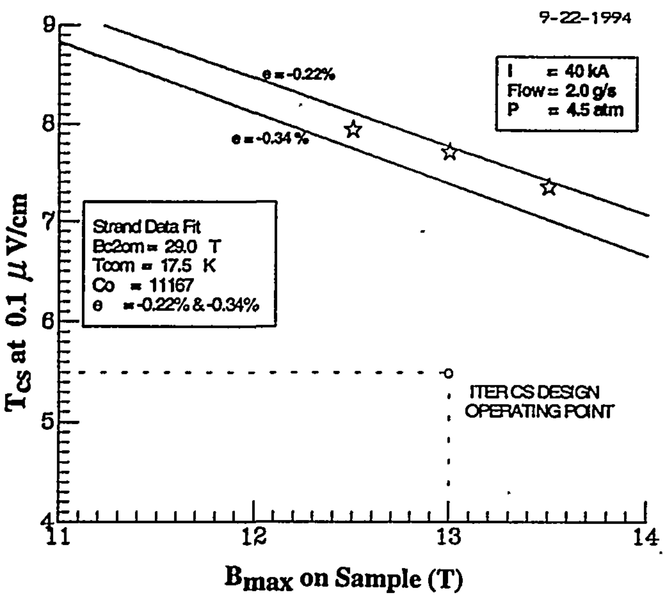

Fig. 3. Measured Tcs for F Leg

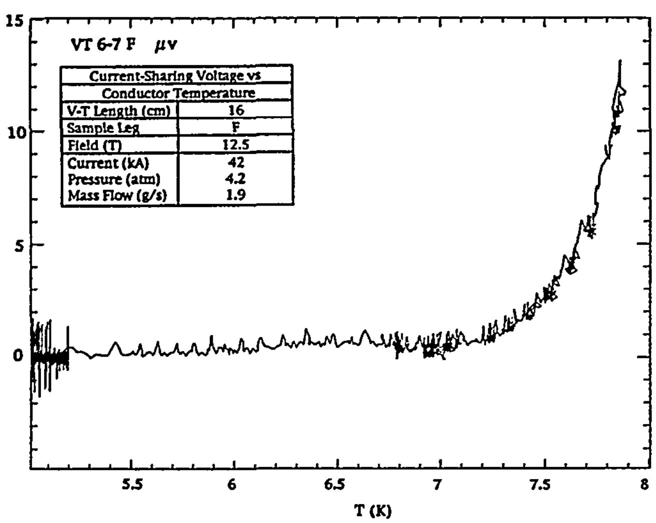

Fig. 4. Measured Current-Sharing Curve for F Leg

the full-size CICC exhibited distinctive current-sharing effects under supercritical helium cooling. Such effect is illustrated in Fig. 4 for the F Leg. From such curves, most values of T_{CS}'s were determined.

3. Measurement of Stability Margins

Several inductive heaters were installed on both legs in the high-field region. By energizing these heaters with a capacitor-bank power supply, fast pulsed energy can be deposited into the conductor that carries transport current at 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. FENIX stability experiments provided calibration of energy margins using a downstream temperature sensor to measure the helium enthalpy changes due to the inductive heater pulses. After each pulse, energy delivered to the primary of the inductive heaters was also calculated as a reference. Detailed results of all inductive heater tests will be published separately later.

4. Measurement of Current Distribution

Five sets of pickup coils were installed on the sample. The coils are in the shape of a segmented Rogowski coil [4]; 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. Most measurements were made in the region with a peak field of about 9 T. 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 mostly resulted 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 superconducting state. Nearly identical distribution was obtained, and the same calibration constant was again verified. The integrated voltages of each coil were checked and found to be consistent with that expected from the experimental arrangement, as shown in Fig. 5. During high-field tests, the CICC was subject to a 9-T peak field in the measured region.

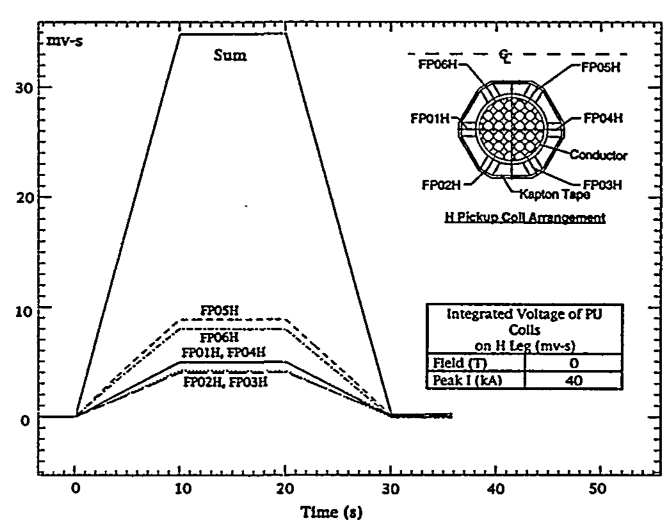

Fig. 5. Measurement of current distribution around H Leg at zero field

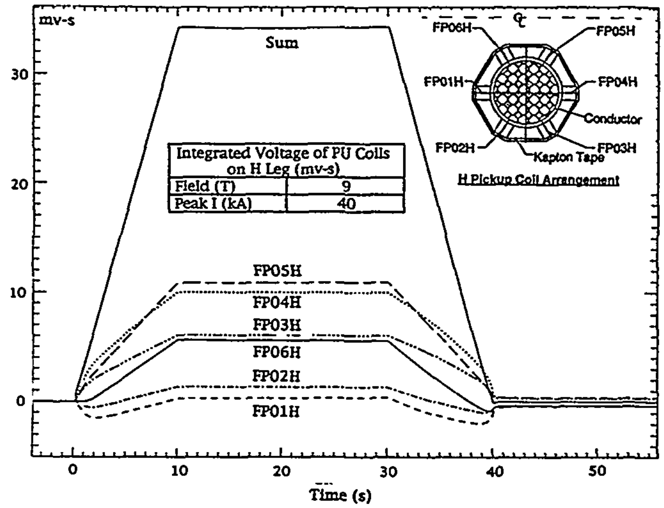

Fig. 6. Measurement of current distribution around H Leg at 9 T

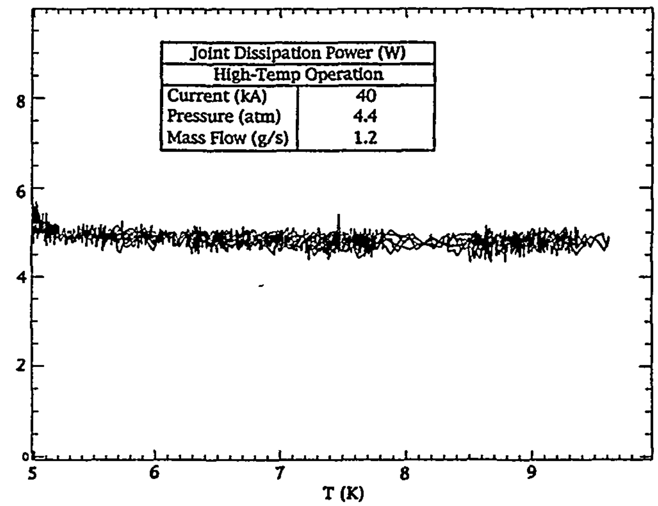

Fig. 7. Power dissipation of the lower joint up to 9K

The behavior of each coil drastically changed, as shown in Fig. 6, exhibiting 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, 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 FENIX facility. For future testing, these coils are recommended to be installed on the sample in the high-field region to investigate its effect on the CICC performance.

5. Joint Performance

The bottom joint was designed for dc operation, having a large volume of copper and being mechanically bolted. A separate cooling circuit was provided. In addition to the dc resistance, the transient response due to current pulses of different ramp rates was also measured. In a 42-kA test at 13 T, the dc dissipation was found to be 7 W. To determine the operation limits of the joint, the operating temperature was raised slowly all the way to 9 K. As shown in Fig. 7, the dissipation power of 5 W remained unchanged during the 9-K temperature excursion, indicating a comfortable operation margin for this type of joint.

III. Conclusions

FENIX testing of CICC sample made of Nb_3Sn bronze processed strands has been successfully completed. Several special features worth noting include the titanium sheath and the bronze-process strands. Preliminary experimental results can be summarized as follows:

1. Current-sharing temperature: Both legs are found to have high values of current-sharing temperatures, indicating that the titanium sheath did not introduce additional strain on the strands. It also suggests that the degradation due to fabrication processes was minimal.
2. Ramp-rate limits: Contrary to previous findings, no current ramp-rate limits were observed in the FENIX tests. This is possibly due to the long-length sample effect.
3. RR values: A reliable measurement technique was developed. High RR values of 95 and 150 were found for the F and H leg respectively.
4. Current distribution: Segmented Rogowski coils were demonstrated for studying the current-distribution effect. Non-uniform current distribution has been measured. Its effect on CICC performance needs to be studied further.
5. Joints: Transient properties of the joint were measured up to 42 kA. It was also demonstrated that joints of this type can perform satisfactorily above 9 K.

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