Preliminary Performance Test Results of First CICC From Korea Destined for an ITER TF Magnet

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Abstract—**The Republic of Korea is participating in the ITER project to construct and operate the ITER tokamak for the purpose of demonstrating the feasibility of fusion power. ITER Korea, the implementing agency for the Republic of Korea that is procuring items for the ITER project on behalf of the Korean government, has established domestic and international contracts for the procurement of cable-in-conduit conductor (CICC) that will be used in the ITER toroidal field (TF) magnets. The CICC for the ITER TF magnets is made of superconducting Nb_3Sn and copper strand cable inside a cylindrical stainless steel jacket, and is designed to operate at a nominal peak field of 11.8 T at 4.5 K with 68 kA of nominal operating current. Recently, the first CICC from Korea, which will be installed in an ITER TF magnet, has been manufactured and tested including testing performed on a 4 m sample near ITER operating conditions at the CRPP-EPFL SULTAN facility in Villigen, Switzerland under the coordination of the ITER International Organization. This paper provides a brief description of the CICC along with preliminary results of the tests and the conductor performance characteristics derived from the results.**

Index Terms—**Cable-in-conduit, internal tin Nb_3Sn strand, ITER, SULTAN, superconducting coils.**

I. Introduction

THE REPUBLIC of Korea (South) is responsible for procuring 27 of the 133 conductor unit lengths (ULs) needed to fabricate the 18 plus one spare toroidal field (TF) coil magnets for the ITER tokamak [1], [2]. Of the 27 conductor ULs, 19 are 760 m or regular double pancake (rDP) conductor ULs, and 8 are 415 m or side double pancake (sDP) conductor ULs. Each ITER TF coil requires 5 rDP ULs and 2 sDP ULs.

ITER Korea, the official agency designated to perform the procurement on behalf of the Korean government, referred to as the Domestic Agency for the Republic of Korea (KODA), has established contracts for the fabrication of its allocated TF conductor ULs. The fabrication of the Nb_3Sn superconducting multifilament strands, the cabling of the Nb_3Sn strands with copper stabilizer strands, the manufacturing of the stainless steel tube jackets, and the final assembly of the cable with the jacket have all been contracted separately. The contract for final assembly and manufacturing of finished conductor ULs was awarded to the Italian Consortium for Applied Superconductivity (ICAS) whose jacketing facilities are at Criotec Impianti S.r.l. of Chivasso, Italy [3]. Superconducting cable and stainless steel jacket sections are shipped from Korea to Italy for this process. After final assembly, a finished conductor UL is tested for flaws and performance.

In January 2012, fabrication of the first KODA responsible TF conductor UL destined to be included in one of the ITER TF coils, hereafter referred to as TF13/rDP2, was completed. Performance tests on TF13/rDP2 were performed including low temperature measurements on a 4 m sample near operating conditions as would be found in the ITER tokamak.

This paper provides a brief description of the fabricated TF conductor UL, the tests performed to verify its performance, and the preliminary results including the conductor performance characteristics derived from the results.

II. The Conductor UL

A. Superconducting Nb_3Sn Strand

The ITER TF conductor UL is a Cable-in-Conduit Conductor (CICC) of either rDP or sDP length made with superconducting multifilament Nb_3Sn and oxygen-free copper (Cu) strand cable inside a cylindrical stainless steel jacket [2], [4]. At liquid helium (He) temperatures the current in the conductor UL is mainly carried by the superconducting Nb_3Sn whose critical temperature can be as high as 18.5 K at zero magnetic field and whose maximum upper critical field can be up to 28 T [5].

The superconducting Nb_3Sn strands from KODA for ITER are fabricated using the internal-tin route which was earlier adopted for fabricating Nb_3Sn strand for KSTAR magnets [6]. Heat treatment is required to form the superconducting A15 structure of Nb_3Sn. Due to various complications in the manufacturing process, especially heat treatment, variations in superconducting characteristics occur between Nb_3Sn strand lots. These characteristics are measured and recorded for each strand lot destined for an ITER magnet. Table I shows the main characteristics of the Nb_3Sn strands in TF13/rDP2.

B. The TF Cable

Nine hundred superconducting Nb_3Sn strands are wound with 522 Cu strands to form a cable. The winding of the strands is performed in five stages with the first stage consisting of two

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TABLE I
MAIN CHARACTERISTICS OF THE Nb_3Sn STRAND IN TF13/rDP2

	Measured	Target
I_c (A)†	280±14	> 250
J_c (A/mm^2) of non-Cu area†	1024±47	
RRR	136±17	> 100
Hysteretic Losses (kJ/m^3)	407±88	< 600
Cu/non-Cu	0.94±0.04	1.0±0.1
Diameter (mm)	0.82±0.001	0.82±0.005

† at 4.2 K with a background field of 12 T

TABLE II
CHEMICAL COMPOSITION OF THE JACKET MATERIAL FOR TF13/rDP2

(Weight %)	Measured	Target
C	0.013±0.001	< 0.015
Si	0.16±0.02	< 0.75
Mn	1.691±0.007	< 2.0
P	0.018±0.001	< 0.04
S	0.002±0.0005	< 0.03
Ni	13.54±0.03	11.0–14.0
Cr	17.29±0.03	16.0–18.0
Mo	2.57±0.02	< 0.1
Co	0.029±0.005	0.14–0.18
N	0.162±0.0004	< 0.015

Nb_3Sn strands and one Cu strand. In the final stage, cabling is performed with 6 sub-cable "petals" being wound around a stainless steel central spiral for He flow and to limit pressure drops.

C. Jacket and Final Assembly

The jacket sections are tubes of 316LN-IG-HT grade stainless steel which meets certain low temperature mechanical properties while satisfying nuclear activation requirements [7]. The 13 m long jacket sections are produced in lots, and their chemical compositions are monitored during production. The measured chemical compositions of the jacket material for TF13/rDP2 are given in Table II.

The jacket sections are welded end to end to form a jacket assembly as long as 780 m. The TF cable is then pulled through the hollow center after which the jacket is compacted to the desired diameter to complete the TF conductor UL.

D. Conductor UL Characteristics

The cable and sub-cable twist pitches are important characteristics of the final TF conductor UL. So, these are measured through destructive testing of 1 m samples taken immediately after compaction. The values can be compared with the twist pitches that were similarly measured on 1 m samples taken from the TF cable after final stage cabling. The measured values for TF13/rDP2 are given in Table III which shows changes in the values before and after jacketing. Such changes in cable and sub-cable twist pitches after jacketing are still a matter of debate and are being investigated further.

Other major characteristics of TF13/rDP2, some of which were measured on a short sample taken from the point end of the conductor UL, are given in Table IV. A photograph of a cross section of the CICC is given in Fig. 1.

TABLE III
CABLE TWIST PITCHES BEFORE AND AFTER JACKETING OF TF13/rDP2

Stage	Before (mm)	After (mm)	Target (mm)
Final	423±3	415	420±20
4th	300±10	325	300±15
3rd	193±3	190	190±10
2nd	138±3	132	140±10
First	82±1	78	80±5

TABLE IV
MAJOR CHARACTERISTICS OF THE CICC IN TF13/rDP2

	Measured	Target
Outer diameter (mm)	43.7±0.2	43.7±0.2
Jacket thickness (mm)	2.0	2.0±0.1
Total cable area (mm^2)	1243.7	
Total petal area (mm^2)	1102.3	
Total flow area outside sub-wraps (mm^2)†	23	< 15

† not including central spiral

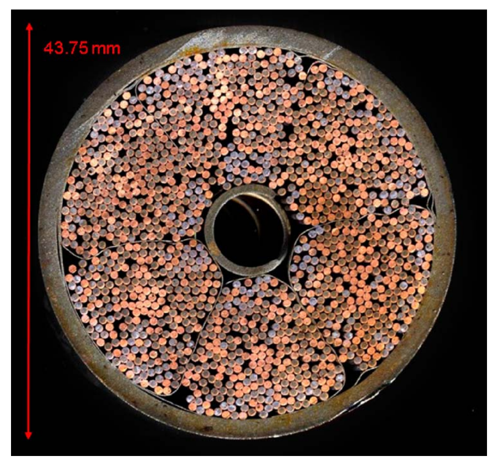

Fig. 1. Photograph of CICC sample cross-section from TF13/rDP2 (photograph taken by ICAS).

III. HELIUM LEAK TESTING OF THE CONDUCTOR UL

After fabricating a TF conductor UL, a test is conducted on the vacuum tightness of its jacket assembly [4]. Acceptable performance in this test is usually the final criterion to be satisfied by the conductor UL unless it is to further undergo low temperature performance testing.

To perform the vacuum leak test, a TF conductor UL is placed inside a vacuum chamber with He gas at 3 MPa inside the CICC. The leak rate inside the chamber is monitored for a sufficient time to check for stabilization or drifts in the leak rate due to leakage coming from the conductor UL. The acceptance criterion is a leak rate lower than 10^{-7} mbar · l/s with a background noise signal less than 10^{-8} mbar · l/s. The recorded stable maximum leak rate for TF13/rDP2 was 5.7×10^{-9} mbar · l/s with a background at 5.0×10^{-9} mbar · l/s satisfying the criterion.

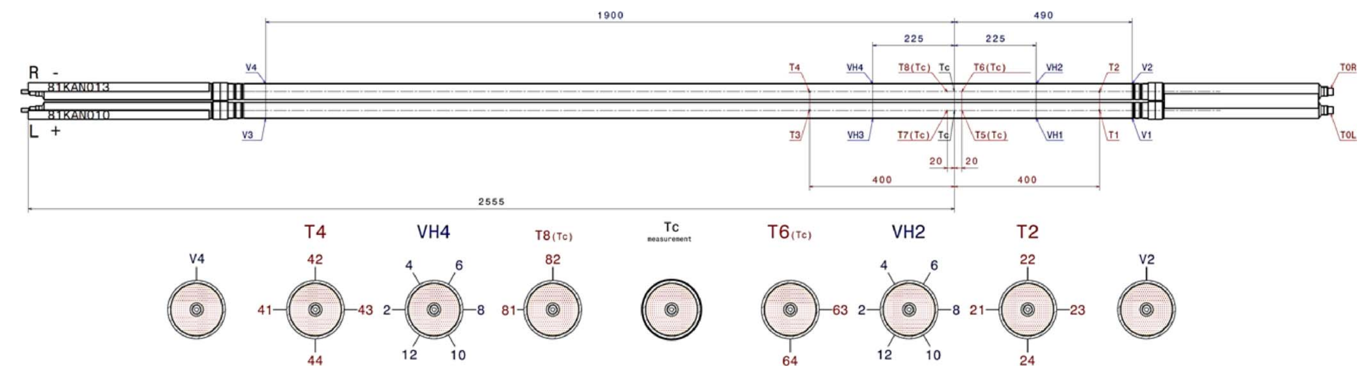

Fig. 2. Diagram of the TF conductor CICC performance test sample. The upper (R) leg is the CICC sample from TF13/rDP2. Instrumentation is concentrated around the high field zone shown at right of center. VH indicates a voltage tap. T indicates a temperature sensor. Lengths are in millimeters.

IV. Low Temperature Performance Testing

A. Sample Preparation

To comply with ITER requirements, TF13/rDP2 has to undergo low temperature performance testing. The designated facility for this test is the CRPP-EPFL SULTAN facility in Villigen, Switzerland. Straight samples tested at this facility are limited in length to 4 m, which in the case for TF13/rDP2 was taken from the point end of the conductor UL.

The 4 m TF conductor CICC performance test sample was prepared according to standardized procedures agreed to amongst ITER Domestic Agencies (DAs) and the ITER International Organization (IO) [4], [8], [9]. The procedures involve first straightening and cutting the 4 m sample to exactly 3419 mm. Then the jacket, cable wrappings, and Cr plating of individual cable strands at each end are removed after which termination joints are attached. Next, the sample undergoes heat treatment according to a heat profile optimized to form the A15 structure of Nb_3Sn. After that, voltage taps and temperature sensors are attached to the sample surface at specific locations, and then connectors for supercritical He coolant and electrical power are incorporated into the joints.

For SULTAN, two CICC legs must be paired together to form the performance test sample [8]. So, a CICC leg from a different TF conductor UL produced for qualification purposes was prepared, heat treated, and tested together with the leg from TF13/rDP2. The two legs are electrically joined at one end and clamped together.

It happens to be that the TF cable of the other leg was used in a previous CICC performance test sample [10]. So, comparisons can be made to check for consistency in results.

B. Instrumentation

Fig. 2 shows the locations of the temperature sensors and voltage taps that were attached to the final TF conductor CICC performance test sample. Both legs of the performance test sample are shown with the bottom end where the two legs form an electrical joint and where supercritical He enters each leg oriented to the right. The right (R) leg corresponds to the CICC sample from TF13/rDP2.

The voltage taps are attached to the stainless steel jacket surface by spot welding. The temperature sensors are also attached to the jacket surface, but an adhesive is used [8].

The sensors and taps are concentrated around the high field zone which is toward the bottom end of the vertically inserted test sample and which is approximately 40 cm along the sample's length with a peak field of 10.9 T [11], [12].

C. Test Procedure

Like the procedures for sample preparation, the procedures for low temperature performance testing were also defined and agreed to amongst the DAs and the IO [4], [9]. The testing consists of instrumentation checks followed by an AC loss measurement, a background measurement at high field but without conductor current (baseline run) and then initial measurements of the current sharing temperature (T_{cs}), the critical current (I_c), and n-index. Afterward, the T_{cs} measurement is repeated at regular intervals between multiple conductor current cycling that simulates electromagnetic loading over the operational lifetime of an ITER TF coil. Finally, the various measurements are repeated including a last set of measurements after a warm-up to room temperature then cool-down (WUCD) of the test sample.

After each measurement, data reduction and compensation are performed to account for temperature and voltage signal noise, differences among sensor readings, and offsets. The final result is obtained after line fitting and interpolation [9].

There are two different approaches to the T_{cs} measurement which forms the bulk of the performance test. One is estimating the average E-field inside the CICC sample, and the other is a caloric measurement using temperature differences. Studies on the accuracy of the techniques have concluded that the caloric measurement has a greater uncertainty than the E-field estimation approach [13], [14]. In addition, significant deviations from constant He mass flow through the test sample occur during measurements, complicating the caloric approach. Therefore, only the voltmetric approach using estimations of the average E-field are taken into account [9].

D. Results

T_{cs} measurements are taken at a background field of 10.78 T with the conductor current ramped up stepwise to the nominal value of 68 kA followed by a stepwise temperature ramp up. The rise in voltage is analysed at the end of which a T_{cs} value is determined. The T_{cs} values at increasing current cycle for the

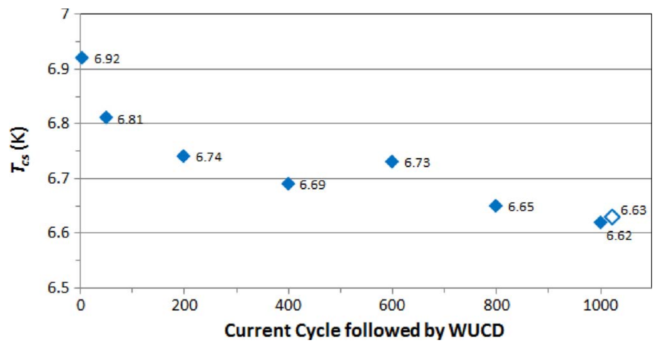

Fig. 3. Evolution of the T_{cs} value for the CICC sample from TF13/rDP2. The opened data point is the T_{cs} after WUCD.

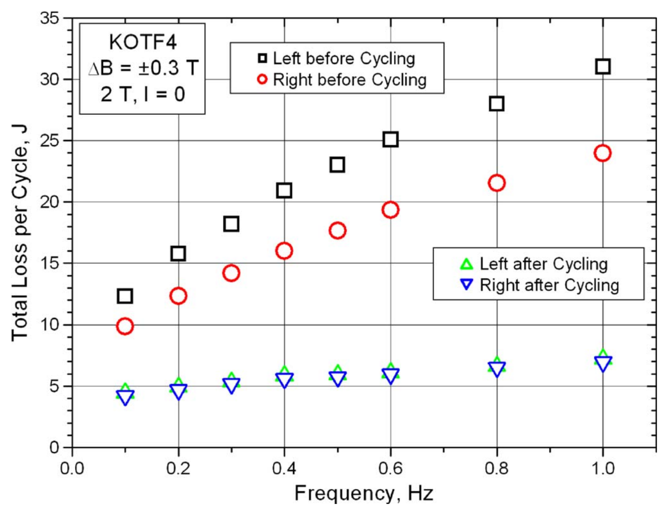

Fig. 4. Plot of the AC loss results for the TF conductor CICC performance test sample. The right leg corresponds to the CICC sample from TF13/rDP2.

CICC sample from TF13/rDP2 are plotted in Fig. 3. The initial T_{cs} is 6.92 K, but it degrades to 6.62 K after 1000 cycles. The change in value after a WUCD at the end is minimal.

The conductor T_{cs} must stay above some minimum value despite repeated TF coil operation. The ITER requirement is $T_{cs} \geq 5.7$ K at the end of 1000 cycles or until stabilization [4]. However, studies on T_{cs} measurements using the voltmetric approach have shown that an uncertainty of at least 0.1 K exists with data reduction and compensation performed on a typical measurement. Consequently, the T_{cs} requirement for ITER has been modified to $T_{cs} \geq 5.8$ K [9]. The CICC sample from TF13/rDP2 satisfies this requirement. For comparison, the other leg of the performance test sample showed a final T_{cs} of 6.65 K which is close to the final T_{cs} of 6.61 K for the lower performing leg of the previous CICC performance test sample from Korea [10].

The jump in T_{cs} at 600 cycles in Fig. 3 is an artifact of the data compensation due to a significant average negative slope in the zero voltage state during conductor current ramp up.

Fig. 4 shows the results of the AC loss measurements on both legs of the performance test sample. The tests are performed with a 2 T background field, no conductor current, and a He mass flow rate of 10 g/s. The AC loss is determined by applying an AC field of 0.3 T amplitude on the test sample at various low frequencies and then estimating the generated heat from temperature measurements at different locations. The AC loss results are consistent with those from other test samples previously measured at the SULTAN facility [9].

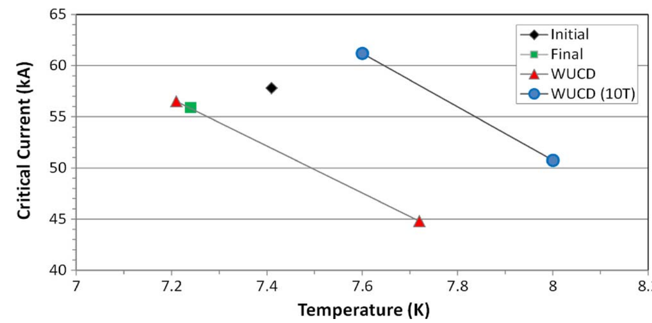

Fig. 5. Plot of the critical current I_c measurement results for the CICC sample from TF13/rDP2.

TABLE V
TF13/rDP2 CICC SAMPLE CRITICAL CURRENT I_c AND n-VALUES

	Initial	Final	After WUCD at 10.78 T		After WUCD at 10 T	
Temperature (K)	7.41	7.24	7.21	7.72	7.6	8
I_c (kA)	57.8	55.9	56.5	44.8	61.2	50.75
n-value	16.9	12.3	12.2	10.3	12.5	10.8

Fig. 5 shows the I_c measurement results for the CICC sample from TF13/rDP2. Measurements are taken right after the first current cycle and a second time after 1000 cycles and then again after WUCD. The I_c measurements are taken at a background field of 10.78 T with the He mass flow rate set to 4 g/s. The temperature of the performance test sample is set, using heaters at the joint, in accordance with the T_{cs} measured just prior to the I_c measurement. A final set of I_c measurements are taken with the background field at 10 T. As in the case with T_{cs} measurements, a significant change in the measured I_c value is observed after current cycling, but the results before and after WUCD show little change.

Table V shows the determined n-values of the CICC sample from TF13/rDP2, which are derived from the same data used for the I_c measurements. The values are consistent with and show a trend that is also consistent with other TF conductor CICC performance test samples previously measured at the SULTAN facility [9].

V. Conclusion

The preliminary results of performance tests on the first ITER TF conductor UL and its CICC sample from KODA, especially the results of the low temperature performance test conducted at the SULTAN facility, indicate that the TF conductor UL satisfies the requirements for acceptance. A second 4 m CICC sample from the same TF conductor UL, TF13/rDP2, is available, and low temperature performance tests on it are in consideration.

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