Performance Test of TFKO2 Qualification Sample of ITER TF Conductor

Dong Keun Oh, Soo-Hyeon Park, Keeman Kim, and Pierluigi Bruzzone

***Abstract*—According to the pre-qualification program for the production of Korean conductor for ITER TF magnet, a CICC(Cable In Conduit Conductor) sample for SULTAN test was developed based on the "Option 2" specification which is the improved one among the two established baseline designs. For the assessment of performance, SULTAN test of the conductor sample was carried out in CRPP employing recently updated instrumentations on the sample and the joint of two conductor pieces, which has been discussed and modified for the proper estimation of T_{cs}. As a course of the analysis, the assessment of T_{cs} values was presented using the basic protocol of data reduction, and the discussion was made on the standard process of analysis. In addition, we investigated some exposed problems in the data manipulation such as non-linear voltage slopes being possible to be related to conductor characteristic itself and the initial offset problem in the calorimetric method. On the presentation of the test results, we also report the manufacture of the conductor with the qualification of the components including carefully designed Nb3Sn internal-tin superconducting strands for an improvement of conductor performance.**

***Index Terms*—Cable-in-conduit conductor, internal-Sn Nb_3Sn, ITER TF, SULTAN test.**

I. Introduction

AFTER the update of baseline design for ITER TF conductor, a prequalification program was activated not only for the preliminary assessment of each participant's technological ability, but also for a verification of the new design known as "Option2" [1]. According to such a program, KO-DA's prequalification for the TF conductor procurement was carried out in SULTAN facility, assessing of the performance of full-size short conductor sample, with prepared CPQS (Conductor Performance Qualification Sample) in July 2008.

Two pieces of full-size conductors are fabricated based on the cabling scheme which corresponds to the "Option 2" baseline design of ITER TF conductor [2]. In spite both conductors have undergone the same fabrication process with identical design for cabling and jacketing, different types of superconducting strand are employed for each one.

For the superconductor in KO's CPQS, K.A.T (Kiswire Advanced Technology, Korea) developed two types of internal-tin Nb_3Sn strand RC48 and RC49 to hold higher J_c (about 1000 A/mm^2) strands for KO's TF conductor than previously used one. Analyses of the previous test result of KO sample in 2007 provided a basis of such a development as an R&D activity for the design change of TF conductor [3]. As a matter of convenience, each piece of conductor is named as RC48 and RC49 according to the identification of strands in each conductor.

Cabling in "Option 2" was carefully performed by Nexans Korea due to known troubles of the long-twist pitch cabling. In spite those problems, the production of test conductor was successful avoiding any serious damage or tangling in the cables for the 4 m length of well-made parts of fabricated cables. The 2-roll multi-stage roller system, which owned by NFRI (National Fusion Research Center, Korea) installed in the cabling facility of Nexans Korea, was also employed for the jacketing process.

Two conductors prepared for CPQS test was assembled into one piece of hair-pin sample by CRPP, which is call as TFKO2 sample. This SULTAN sample consists of two legs of conductor, one is RC48 conductor (right leg) and the other is RC49 (left leg). Basic descriptions of TFKO2 CPQS are shown in Table I.

During the design works for strand, tentative strand performance was assumed to satisfy the critical current density of about 1000 A/mm^2 under the consideration of some previous results and analyses in the R&D phase (2007) [2], [3]. In spite of the performance without any significant degradation in R&D test [3], the performance (T_{cs}) was only a little bit above the acceptance criterion employing the RC38 strands of relatively low critical current density about 890 A/mm^2 with 3325 filaments, whose design was based on an idea of trade-off expecting enhancement of mechanical characteristics against the intentional spoiling of J_c performance.

Now, the numbers of filaments on the strands of new design are 3344 for RC48 and 3420 for RC49 respectively. RC49 whose number of filaments is more than RC48 shows higher critical current as expected—the critical current of RC48 is about 260 A which corresponds to 994 A/mm^2 and RC49 has about 270 A which is above 1000 A/mm^2 in current density.

II. TFKO2 Test Sample and Instrumentation

The present configuration of voltage taps and temperature sensors on the SULTAN sample is the result of several updates based on the agreement and discussions after some previous SULTAN tests in 2007 and 2008 [4].

Now, the basic protocol for T_{cs} assessment is watching the average of 6 voltage-drops between the terminals parallel to

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TABLE I
BASIC DESCRIPTION OF TFKO2 SAMPLE

	TFKO2 (Left) : RC49	**TFKO2 (Right) : RC48**
Reference Design	ITER Baseline (Option 2) for TF conductor	
Superconducting Strands	RC49 (K.A.T, RC4980221A) : *Nb_3Sn internal-tin, 3420 filaments, I_c ~ 271 A (1036 A/mm^2)**, OD=0.82 mm, Cr plating=2.0 μm Cu/nonCu=1.0, RRR>100	RC48 (K.A.T, RC4880219A) : *Nb_3Sn internal-tin, 3344 filaments, I_c ~ 260 A (994 A/m m^2) **, OD=0.82 mm, Cr plating=2.0 μm Cu/nonCu=1.0, RRR>100
Copper Strands	OD=0.820~0.821 mm, Cr plating=1.8 μm, RRR>400	
Cabling Patterns	((2S/C + 1Cu) x 3 x 5 x 5 + 3 x 4 Cu) x 6	
Twist Pitch (mm)	(80/140/190/300+80/140)/420	
Conductor Size	O.D = 43.7 mm (±0.1 mm) I.D = 39.9 mm (±0.1 mm) Thickness = 2.0 mm (±0.1 mm)	
Central Channel	OD = 10 mm (±0.1 mm), Thickness = 1.0 mm (±0.05 mm), Strip Width = 6 mm, Twist Pitch = 9 mm, Material 316L or 304L	
Jacket Material	SS316LN (316LN-IG-HT)	
Void Fraction	~29 %	

*I_c at 4.2 K in the external field of 12 Tesla.

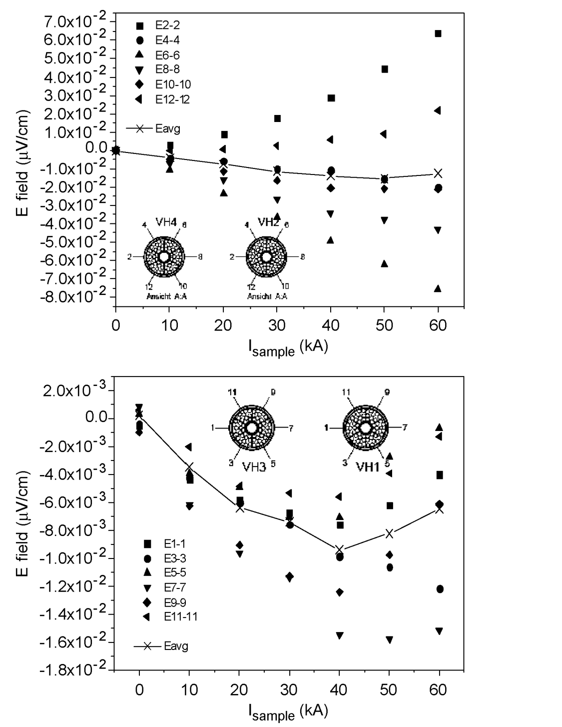

Fig. 1. The maximum level of early voltage (for averaged signal) is about 10% $\sim$ 20% of the voltage criterion for T_{cs} assessment. The early voltages from the individual V-tap pairs are presented for RC48 right leg (upper) and RC49 left leg (lower).

the axis of conductor to determine the critical level of current sharing [5]. 6-crown voltage taps were introduced to reduce such an error by averaging the voltage from the six V-tap pairs equally spaced on the perimeter of conductor [6], because the transverse voltage is one of the main sources of error in T_{cs} assessment as a parasitic component of the voltage signal.

For the calorimetric method, 4 temperature sensors were located also around the jacket on the position of the upstream and the downstream position centering about the high field zone to average the temperatures which depend on the location along the perimeter. During the TFKO2 experiment, another calibration test with simulated heat load was attempted, for which a strain gauge at the high field center took a part of an external heater, to check how much feasible the calorimetry with the average of those temperatures are to assess the performance of conductors by such a simulation.

III. T_{cs} ASSESSMENT WITH ELECTRIC METHOD

As we mentioned above, a basic protocol to assess the T_{cs} is based on "the average of 6 signals" with which it is to check whether it cross the critical level of current sharing defined as 0.1 $\mu\mathrm{V/cm}$ with respect to the temperature. Even though such an average is introduced, one should compensate the offset in the voltage at the base temperature (about 5 K) after the magnetic field was presented, and the sample current was loaded. Such an offset may affect seriously on the assessed T_{cs} value so that we cannot neglect or regard it as zero, because a current sharing is also possible even at the condition of base temperature [6].

In our case, every test runs showed a similar tendency of initial slope which is small enough but had to compensate for a proper assessment, even though a T_{cs} value without any correction could be a quite reasonable estimation. Essentially, such a measurement of the performance is an assessment based on the strict criterion, and a standardized judgment is required for the current sharing temperature being precise as the lowest significant digit should be least 0.1 K. To make it possible, the unique compensation method should be obeyed to avoiding any ground of controversy.

A typical early voltage during current ramping up is presented in the Fig. 1.

The standard procedure of the compensation is "linear extrapolation" of the early voltage whose data points are so early that there is little contribution of "real current sharing" in the signal.

The actual process is subtraction by the linear fitting of early voltage data with respect to the current with initial 3 points (I_{sample} = 10, 20 and 30 kA) excluding zero point in the early voltage. For such correction, the extrapolation of linear fitting is illustrated in the Fig. 5. Judging from such an example, the compensated voltage signal can be changed slightly depending on detail conditions of such a least square fitting and its influence on the T_{cs} value will not be negligible even if it's small. So, it can be said that there is still enough room of argument even if the standard compensation method is generally accepted and good enough without any significant problem.

Early voltage slopes are basically error in the experiment which is expected to be improved by the instrumentation or the sample fabrication. Actually, according to recent efforts for a

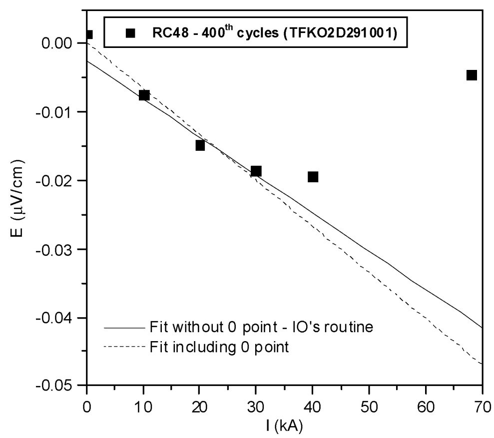

Fig. 2. Here is an illustration of the IO's standard method for linear extrapolation to compensate early voltage. The solid line is the same way in IO's routine comparing with the deviation from another linear fitting of dashed line including the zero point.

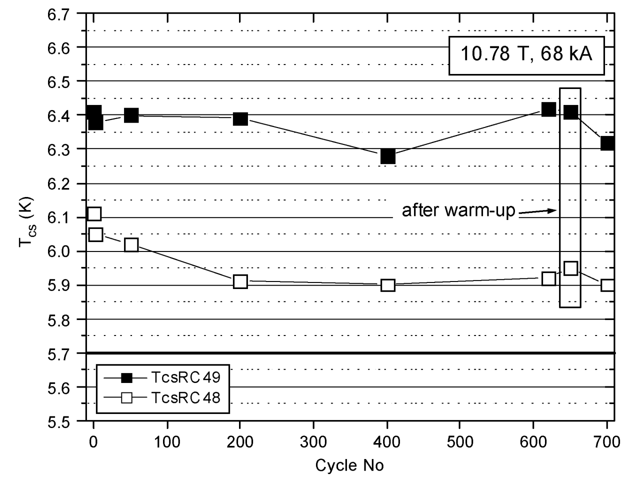

Fig. 3. T_{cs} versus number of cyclic loads for RC48 and RC48 sample, the horizontal line at 5.7 K is the acceptance criterion.

better SULTAN joint, the voltage slope has been decreased, and it is so small enough that an estimation of T_{cs} is quite reasonable even without any correction. Taking into account such an experience, we tried to investigate the relation between the joint resistance and the voltage slope.

As an auxiliary comment, even if such a linear extrapolation is the simplest way to describe the early voltage, it is doubtful that the linear compensation is the most accurate method to estimate the initial offset in the voltage drop, because it can be thought that there are several reasons of non-linear early voltage as following [7] (Fig. 2)

I) The electric potential on the jacket varying with the sample current which corresponds to the change of contact resistance distribution between cable and jacket depending on the transverse load by Lorentz force on the cable.
II) The redistribution of current on the cable due to the EM load on the joint
III) The uneven current flow by partially saturated superconducting strands, which is originated not from the joint but from the conductor itself.

In spite those kinds of efforts for a proper estimation, the T_{cs} assessments were accomplished employing the standard routine which has been established by IO. As a result, T_{cs} versus number of cyclic loads was presented in the Fig. 3.

The final T_{cs} after 700 cycles is 6.33 K for RC49 and 5.89 K for RC48 (Table III).

IV. Calorimetric Method for T_{cs} Estimation

As an alternative method, the calorimetric analysis has been acknowledged for T_{cs} measurement. In spite of known merits to be a robust verification method, the calorimetric assessment is still questionable showing uncertain interpretations on the source of error and large background signals comparable to actual thermal responses of current sharing. Even if considerable improvement has been achieved, the ultimate sensitivity of calorimetric measurement is not satisfied yet to be an accurate qualification so that the voltage method is now considered as a primary tool for the assessment indeed. However, we cannot neglect the necessity of calorimetry for a subsidiary measurement, because a wrong estimation is always possible if we apply the electric method alone. Even if the explicit description has been developing to calculate the potential drops on the jacket, all parameters are not predicted as much as we wish, which can mislead us to a wrong interpretation of the average of 6 V-taps.

Now, we present the calorimetric T_{cs} measurement of TFKO2 reviewing the performance of calorimetric method reflected on the result of this test program through a discussion about known-and-improving issues and newly emerged problems. As it has been discussed, the calorimetric method has practical difficulty to be a proper method for the assessment of conductor performance. Mostly appeared trouble in the calorimetry is uncertainty in the assessment, because only a small amount of temperature difference about tens of mK corresponds to a hundred mW in Joule heating which is comparable to the critical level of current sharing, 306 mW. Even though the temperatures itself can be measured very accurately, such a small amount of offset is hardly avoidable spoiling a recovery of net amount of thermal output from the current sharing.

For example, even if the temperature on the cross-section is absolutely homogeneous, deviations in a few tens of mK between the sensors around the conduit may happen due to anchoring between the sensors and jacket surface or thermal background by coupling between the sample and the surrounding, which were able to make the assessment uncertain. In particular, the interpretation of calorimetry is based on the assumption of homogeneous temperature on the cross-section. Thus, the deviation between equally spaced sensors around the cross-section can be regarded as a statistical error in the measurement. The soundness of such an assumption in real world should be verified. So, that's why people in CRPP additionally carried out the calibration test after the campaign of TFKO2 using strain gauge as an external heater between upstream and downstream thermometers to simulate an inhomogeneous or a homogeneous Joule heating in the calorimetry [8]. According to the result of such a calibration by those attached heat sources of 'strain

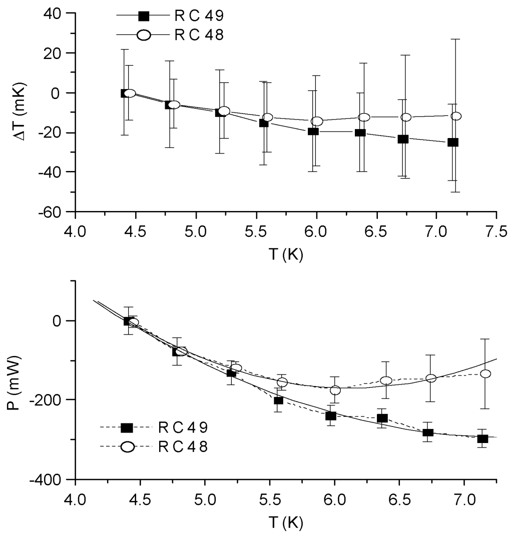

Fig. 4. The thermal background of calorimetric measurement is given in this figure. The temperature differences without current will be interpreted as a background heat power which had to be subtracted from the data, temperature vs. power. The standard deviation of 4 sensors was regarded as the statistical error which can be employed to estimate the error of power with the error propagation formula of $\sigma_p^2 = (C_{p2}^2\sigma_{T2}^2 - C_{p1}^2\sigma_{T1}^2)(dm/dt)^2$.

gauge', the averages of 4 thermometers were appeared to be successful to detect the power from the heaters (strain gauges), regardless of homogeneity of heat source which was suspected spoiling the precondition of calorimetric analysis. Moreover, the test results after such a calibration are consistent with our T_{cs} estimation after the compensation of thermal background shown as the Fig. 11, which is our usual way having been applied since the first SULTAN test of KO conductor.

Even after the compensation of thermal background or the calibration with external heater, the initial offset after ramping up the sample current was still observed in the result of temperature versus Joule heat power, which is conceptually identical to the initial offset problem appeared in the electrical method. However, different from the voltage signal, the initial offset of power is very hard to estimate by the extrapolation of early values, because their change with respect to the sample current has large scatterings and it has a tendency to change suddenly after 40 kA, which makes it hard to predict their behaviour. We present an example of $T(K)$ vs. $P(mW)$ curve in the Fig. 5 without any correction of initial offset after subtraction of the thermal background in the Fig. 4 [8], [9].

Therefore, none of proper assessment is available without any strong assumption on the offset after the ramping-up in the calorimetry. In this case, the estimated T_{cs} values appeared to make sense, if we neglect the initial difference of temperature between upstream and downstream, contrary to the electrical assessment—the T_{cs} of RC49 was estimated as 6.13 K and RC48 was 5.91 K at the first cycle, and the T_{cs} of RC49 was appeared as 6.12 K and RC48 was 5.93 K after 620th cycles, as a result of such a manipulation of calorimetric data.

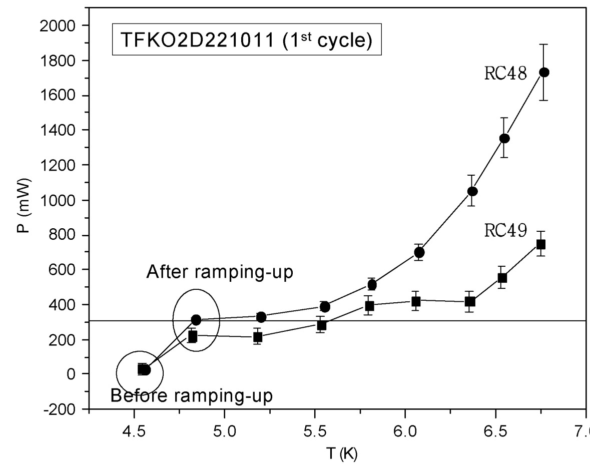

Fig. 5. Temperature versus Joule heat power without any correction of initial offset after the compensation of thermal background (1st cycle).

V. Summary

According to the prequalification program described in the PA for ITER TF conductor, the CPQS sample of KO-DA was fabricated and delivered to CRPP to carry out SULTAN test for the assessment of conductor performance. Two piece of conductor based on the "Option 2" cabling specification which is the revised one of two baseline design. For each piece of conductor sample, RC48 or RC49 Nb_3Sn superconducting strands were employed as primary material, which developed by K.A.T. The performance of both conductors was assessed successfully against the 700 cyclic loadings up to the condition of maximum operating point. Discussion was made about the accuracy and errors in both electrical and calorimetric method on the basis of experimental result of TFKO2 SULTAN test.

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