Conductor Performance of Nb_3Sn Samples for CFETR CSMC Coil

Yu Wu, Bo Liu, Jiangang Li, Jinggang Qin, Yi Shi, Arnaud Devred, Pierluigi Bruzzone, Arend Nijhuis, Boris Stepanov, Kamil Sedlak

***Abstract*—The Central Solenoid Model Coil (CSMC) of the China Fusion Engineering Testing Reactor (CFETR) is designed to operate with a max current of 47.65 kA and highest magnetic field of 12 T. The maximum magnetic field rate is designed as 1.5 T/s. The CSMC consists of 5 independent coils, Nb_3Sn Inner and Outer coils, Upper, Middle and Lower NbTi coils. The Nb_3Sn conductor for the CSMC was manufactured in China and was tested in the SULTAN facility. The cabling was done following the short twist pitch sequence of the ITER CS conductor. For the jacket material, 316 LN is chosen for the left leg and JA2LB for the right leg.**

T_{cs} test results show that both legs of the Nb_3Sn CSMC conductor have high T_{cs} performance. Using the electrical method, the T_{cs} in the first test was 6.645 K for the left leg and 6.57 K for the right leg at 45.1 kA /10.85 T. After 9950 electromagnetic (EM) load cycles and two times warm-up and cooling-down the T_{cs} was 6.89 K for left leg and 6.85 K for right leg. Based on the Nb_3Sn conductor sample test results at 47.65 kA and at different fields, the T_{cs} was extrapolated to the peak field of 12 T and current equaled to 47.65 kA. The extrapolated T_{cs} after 9950 EM load cycles and tow times warm-up and cooling-down is is 6.54 K for left leg and 6.48 K for right leg. According to the SULTAN test result, the Nb_3Sn conductor for CSMC meets the design requirement.

***Index Terms*— CSMC , Nb_3Sn conductor , T_{cs}, AC loss**

I. INTRODUCTION

CFETR is a new experimental Tokamak fusion reactor for the next generation fusion energy research and development [1]. At present, concept design and verifications are in progress [2]-[4]. Central Solenoid Model Coil (CSMC) project has been launched in the Institute of Plasma and Physics Chinese Academy of Sciences (ASIPP) at 2014 to develop the large-scale superconducting magnet technology of CFETR. 12 T peak field and 1.5 T/s field rate requirements are the most main design goal for the CFETR-CSMC.

CFETR-CSMC coil is mainly composed of the internal high magnetic field Nb_3Sn coil, external low magnetic field NbTi coil. The inner and outer radius of the CSMC winding is 750 mm and 1760 mm. The height of the winding is about 1545 mm.

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In order to optimize the cost of coil manufacture, the CICC with Nb_3Sn strand is used for the high magnetic field region where the maximum field is 12 T; anther NbTi strand is used for the low magnetic field region where the field is less than 6.1 T. The model of the CFETRCSMC is shown in Fig. 1. Due to the length limitation of conductor production, Nb_3Sn coil consists of two independent coils which are assembled coaxially; NbTi coil consists of three identical coils stacked. All coils are wound with double pancake. The basic coils parameters are list in Table 1.

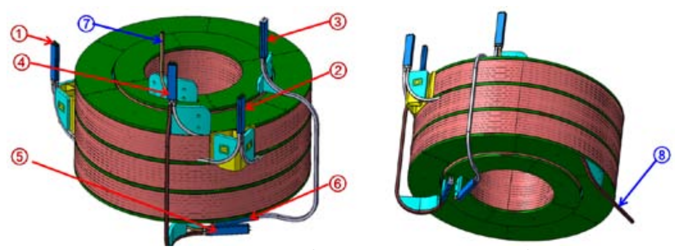

Fig. 1. CFETR CS Model Coil Configuration (Letters in the figure indicate the joints location).

TABLE I
THE BASIC PARAMETERS FOR CFETR CSMC.

	Nb_3Sn Coil		NbTi Coil
Winding type	Inner Pancake	Outer Pancake	Pancake
Conductor dimension	$49^2 \times \Phi 32.6$		$51.9^2 \times \Phi 35.3$
Radial Turn	4	4	10
Axial Turn	30	30	24
Inner radius	750	963.8	1217.6
Outer radius	953.8	1167.6	1760
Height	1545	1545	1308

II. CONDUCTOR AND Nb_3Sn STRAND

The CSMC CS conductors produced in China are based on composite Nb_3Sn strands produced at Western Superconducting Technologies Company (WST), using ITER-like internal tin technology. Cabling operations are performed by ChangTong Company and jacketing operations are executed by the Institute of Plasma Physics Chinese Academy of Sciences (ASIPP) according to the layout determined by the ITER short twist pitch (STP) CS conductor specifications. The CSMC CS cable contains 576 Nb_3Sn strands and 288 copper strands cabled together around a central cooling spiral. The cabling was done following the short twist pitch sequence of the ITER CS conductor [5]-[6]. For Jacket material, 316 LN is chosen for the left leg and JA2LB is chosen for the right leg. Typical cross sections of the strand and conductor are shown in Fig. 1.

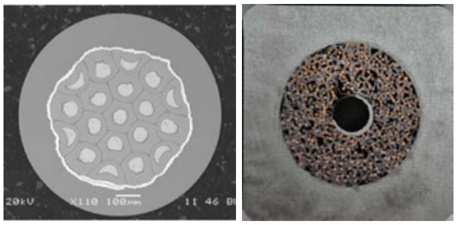

Fig. 2. Cross section of the Nb_3Sn strand and CS conductor.

As Nb_3Sn strands are very sensitive to strain and experience severe loads by electromagnetic force and thermal contraction, it is important to understand the relationship between the critical current and strain. Therefore, the critical current of the Nb_3Sn strand is measured in detail as a function of magnetic field, temperature and strain to obtain the extensive scaling relation.

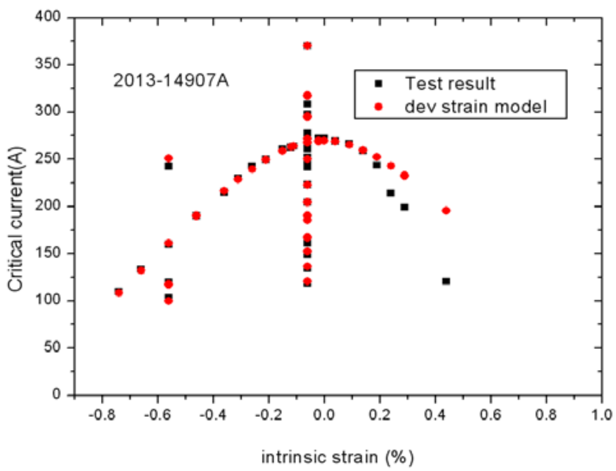

Fig. 3. Critical current as a function of intrinsic strain

The strand was tested in the Pacman facility at the Institute of Plasma Physics, CAS at a range of magnetic field from 4 to 14 T, temperature from 4.23 to 12 K and applied axial strain from -0.9 to +0.5 %. The results of I_c measurements as a function of strain, temperature and magnetic field are summarized in Fig. 2.

The strain description model (DEV-model) is used in ITER to calculate the critical current of Nb_3Sn composites [7]-[8]. The parameters for the ITER scaling law are listed in Table II [9]-[10].

TABLE II
PARAMETERS OF THE STRAND SCALING LAW

Ca1	*Ca2*	$\varepsilon_{0,a}$(%)	ε_m(%)	B_{cm}(T)	T_{cm}(K)	*C1(AT)*	*p*	*q*
46.5	0	0.306	-0.061	31.5	16.4	20069	0.57	2

III . SULTAN SAMPLE AND TEST

The CSMC sample for the SULTAN test is of hairpin type, made of two parallel conductor sections and each 3.6 m long, which are connected with an overlapping joint [11], [12]. The entire sample was received a heat treatment at Swiss Plasma Center (SPC). The heat treatment schedule was 50 hours at 210 °C, 25 hours at 340 °C, 25 hours at 450 °C, 100 hours at 575 °C and 100 hours at 650 °C. The temperature ramp rate was kept at 5 °C /h. The two conductor sections were assembled together, and an array of voltage taps and temperature sensors was attached. The voltage taps were attached at two locations at each conductor leg, i.e. in total there were 12 voltage pairs over a distance of 450 mm. The sample was equipped with 17 temperature sensors to monitor the temperature before and after the SULTAN high field region [12].

The sample was inserted into the SULTAN facility, and subsequently cooled down to 4.2 K. The SULTAN magnet generates a high magnet field of up to 10.85T, which covers 450 mm of sample length. A SULTAN tests consist of AC and DC measurements. Both types of measurements were performed on a sample in its initial state and after applying cyclic loading.

The AC measurements are aimed to determinate the total AC loss of the conductor. The major purpose of the DC test for the CFETR CSMC sample was to assess th current sharing temperature (T_{cs}) at the SULTAN background magnetic field of 10.85T and operating current of 45.1 and 47.65kA. After the first T_{cs} test, the sample undergoes a cyclic electromagnetic loading, during which the operating current of 48.81 kA was repeatedly ramped-up and down in a background field of 10.85 T. The T_{cs} evolution was recorded after applying different number of cycles.

After 9950 EM load cycling tests, the conductor experienced the warm-up/cool-down (WUCD) procedure twice, i.e. warming up to room temperature and then cooling down back to 4.2 K. After that, both AC and DC tests were repeated to check the change of conductor performance.

IV. RESULTS AND DISCUSSION

A. *Self magnetic field analysis*

The T_{cs} test magnetic field consisted of the SULTAN background field, which varied slightly along the 450 mm of the high field zone, and the self field generated due to the sample configuration. The cross-section of the CS conductor SULTAN sample is shown in Fig. 4, where *r1* is cable radius, *r0* is radius of the center spiral, and *a* is distance between the two legs of the SULTAN sample [13].

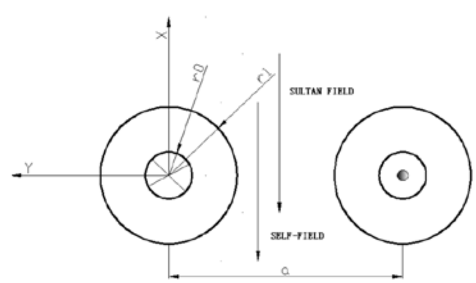

Fig. 4. Self-field analysis 2D model of the CSMC conductor SULTAN sample.

The self-field of the CSMC conductor SULTAN sample was analyzed by a 2-D model based on ANSYS, with the parameters are listed in Table III. For the analysis a uniform current density was assumed. Fig. 5 shows the analysis result of the self-field produced at 10 kA and zero background fields.

The maximum generated self-field is approximately 0.0180 T/kA. The CS conductor was tested at 45.1 kA with the SULTAN magnet producing a background magnetic field of

10.85 T. The maximum test field on the sample is therefore approximately 11.66T.

TABLE III
MAIN PARAMETERS

Parameter	Numeric values
Current (kA)	10
r1 (mm)	16.3
r0 (mm)	10
a (mm)	51

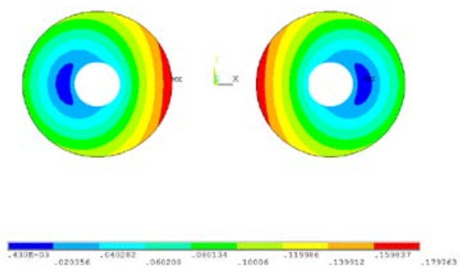

Fig. 5. Self-field distribution at 10 kA calculated using ANSYS.

B. AC Losses

The AC loss of the CFETR CSMC sample was measured before any electromagnetic loading of the sample was applied and the measurement was repeated at the end of the test campaign at 2T/0 kA, 9T/0 kA and 9T/47 kA. The AC loss was measured by helium flow calorimeters; the test result is shown in Fig.6.

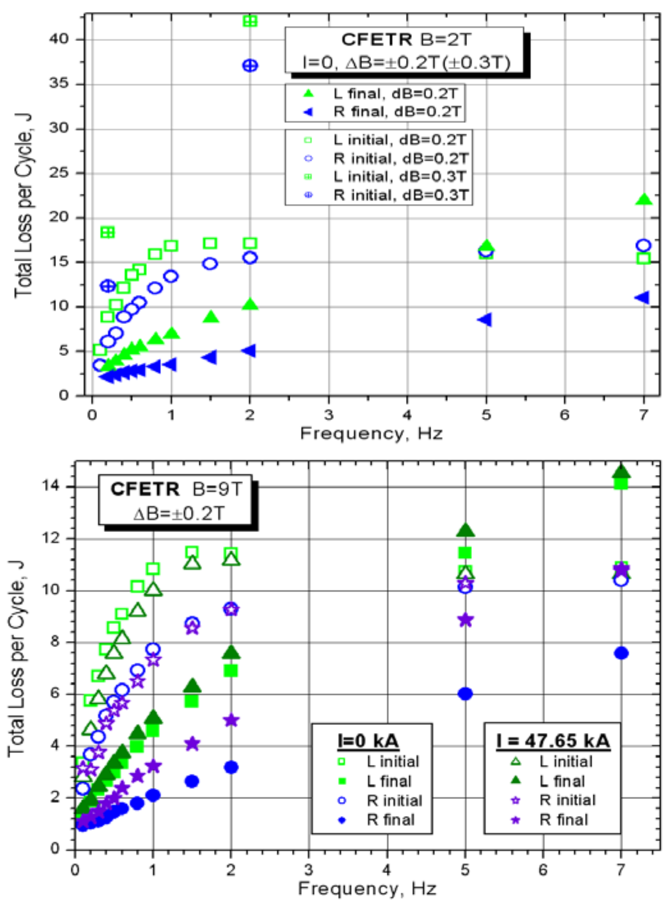

Fig. 6. CSMC CS Conductor AC loss results before (top) and after (below) cyclic load.

C. DC Results

The major purpose of DC tests for the CFETR CSMC sample is to assess the T_{cs} at the SULTAN background magnetic field of 10.85 T and the operating current of 45.1 kA. During DC test, the current at a constant magnetic field was increased step by step to the operating current, and the temperature was increased step by step until a quench occurs. The T_{cs} was evaluated in accordance with a standard ITER analysis procedure. The T_{cs} evolved along the cyclic loading until final 9950 cycles, including the T_{cs} measured after the intermediate WUCD1 and final WUCD2 procedure. The test result is shown in Fig. 7.

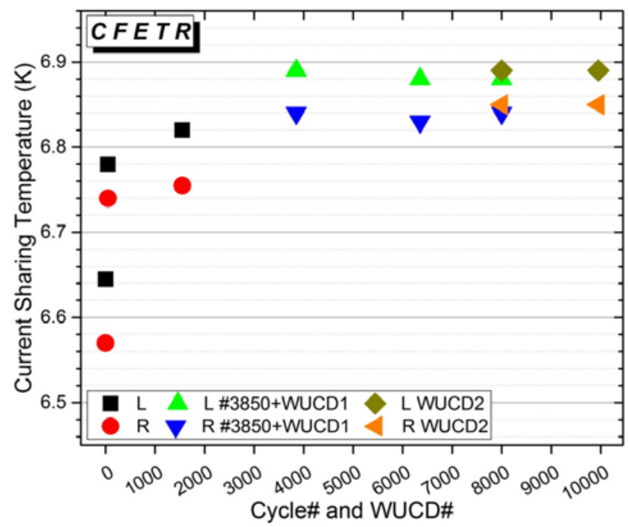

Fig. 7. T_{cs} assessment along cyclic loading and intermediate WUCD

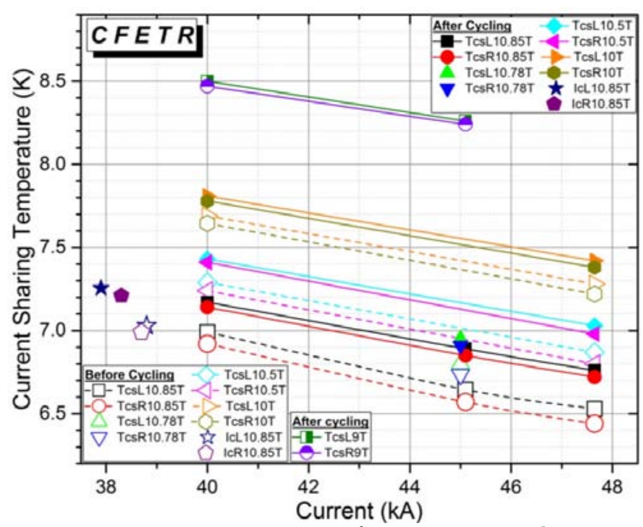

Fig. 8. T_{cs} assessment summary of CFETR CSMC conductors.

T_{cs} tests for CFETR CSMC sample was also tested at different SULTAN background magnetic field and the operating current of 40kA, 45kA, and 47.65 kA. Test result is shown in Fig.8.

Based on Nb_3Sn conductor sample test results at 47.65 kA and different fields, the T_{cs} was extrapolated to the peak field of 12 T and current equaled to 47.65 kA. The extrapolated T_{cs} is 6.54 K for left leg and 6.48 K for right leg after 9950 electromagnetic load cycles and two times warm-up and cool-down. According to the SULTAN test result, the Nb_3Sn conductor for the CSMC meets the design requirement.

V. Conclusion

A superconducting magnet named CFETR-CSMC has been launched at ASIPP from 2014 to develop and verify the large-scale magnet technology. The Nb_3Sn conductor sample with STP structure for the CFETR-CSMC has been tested in the SULTAN facility. Both legs of the sample show good T_{cs} performance after 9950 electromagnetic load cycles and two times warm-up and cool-down. Performance of legs, one with 316LN and the other with JK2LB jacket show no deviation.

Acknowledgment

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