Basic Design and Progress of Central Solenoid Model Coil for CFETR

Yu Wu, Yi Shi, Jiangang Li, Jingang Qin, Dapeng Yin, Aihua Xu, Guanghui Ma

***Abstract*—the Central Solenoid Model Coil (CSMC) project of China Fusion Engineering Test Reactor (CFETR) began in 2014 and the purpose is to develop and verify the manufacture technology of the large-scale superconducting magnet. The Nb_3Sn CICC (Cable-in-Conduit-Conductor) is chose for CFETR CSMC as the best conductor type because of 12 T field and 1.5 m inner diameter design requirement. The CFETR CSMC consists of two coaxial solenoid coils named Nb_3Sn coil in the high field region and NbTi coil in the low field region to optimize the manufacture cost effectively. The maximum field of the Nb_3Sn and NbTi coil can reach to 12 T and 6.1 T respectively when the operating current is 47.65 kA. In this paper, the basic design aim and operation requirements of CFETR CSMC are summarized firstly. Secondly, the characteristics of Nb_3Sn superconducting strands and CICCs are described in detailed. Subsequently, the basic structure design of CFETR CSMC is presented in the third part. The current sharing temperature and coupling loss measurement of Nb_3Sn CICC sample, as the most important stage assessment, are performed in SUTLAN test facility and some meaningful conclusions are summed up in the last.**

Index Terms—*Coupling losses; Nb_3Sn CICC; CFETR*

I. Introduction

China Fusion Engineering Test Reactor (CFETR) project plans to build a fusion device similar to International Thermonuclear Experimental Reactor (ITER) before construction of a fusion power plant to verify the technology feasibility for the future fusion reactor. The main design parameters of this device are shown in reference **[1][2]**. 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 **[3]**.

The ITER CS Nb_3Sn Cable-in-Conduit Conductors (CICCs) program led to a Short Twist Pitch (STP) cable option which can withstand the transport current degradation with electromagnetic (EM) cyclic loads **[4]-[7]**. So STP design is proposed for the CSMC Nb_3Sn conductor.

This paper mainly presents the basic design and recent progress of CFETR-CSMC. Firstly, the characteristics of superconducting strands and CICCs design are described in detailed, then, the basic structure design and main features of CFETR-CSMC are shown including the pre-compression and joint design; finally, a qualification measurement and evaluation for Nb_3Sn CICC is made including the DC, AC performance and some meaningful conclusions are summed up.

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II. CICC Conductor Design and Manufacture

A. Nb_3Sn Strand

Fig. 1(a) shows the cross-sectional view of Nb_3Sn strand with 0.82 mm diameter for CFETR-CSMC. The diameter of Nb filament is about 6 μm with about15 mm twist pitch. The ratio of copper to non-copper is 1:1. In order to reduce the AC losses effectively, Ta barrier is introduced. There are total 19 Hexagon sub-elements depicted by about 130 μm diameter which is observed by electron microscope. The highest treatment temperature is 650 holding on 100 hour. The total heat treatment time is about 500 hours in vacuum or Ar atmosphere.

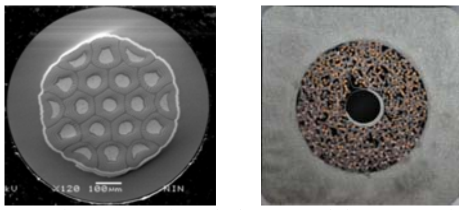

Fig. 1(a). The cross-section of Nb_3Sn strand (b). CIC conductor

Critical current density (J_c) of Nb_3Sn strand is characterized by the deviatoric strain model which is developed by University of Twente **[8]-[9]**. (Critical current) I_c of single strand is about 250 A at 12 T and 4.2 K by 0.1 μV/cm electric field criterion. The scaling parameters are listed in Table Ⅰ. The requirement criterion of hysteresis loss per cycle at ± 3.0 T is less than 500 mJ/cm^3.

TABLE Ⅰ
Scaling Parameters of J_C for CFETER CSMC Nb_3Sn Strand

Parameter	Unit	Value
C_{a1}		55.22
C_{a2}		11.2
$\varepsilon_{0,a}$	%	0.293%
ε_m	%	-0.058%
$\mu_o H_{c2m}(0)$	T	31.66
$T_{cm}(0)$	K	16.13
C_1	AT	19948.5
P		0.57
Q		2.0

B. Nb_3Sn CICC

For Nb_3Sn CICC design, the void fraction and twist pitches in different stage cables are the two of the most important parameters affecting the transport performance and coupling loss characterization. 32.7 % void fraction and STP design are used for the Nb_3Sn CICC of CFETR-CSMC which originates from ITER CS Nb_3Sn CICCs development. This design can effectively enhance the cable stiffness and withstand the transport current degeneration under the strong EM load and cycles which has been verified by measurement results of ITER Nb_3Sn CICCs **[10]-[12]**. The detail structure parameters of Nb_3Sn CIC conductor were also shown in Table Ⅱ which is also the same as the ITER CS conductor design. Fig. 1 (b) presents the cross section of the Nb_3Sn strand and CIC conductor.

Besides, the application of Cr coating with 2 um thickness on the surface of Nb_3Sn strands and wrap out of the sub-cable (70 % open surface) are the useful way to control the appropriate R_c between the strands which can achieve the better balance between the DC and AC performance.

TABLE Ⅱ
DETAIL CHARACTERISTICS OF NB_3SN CIC CONDUCTOR

Property	unit	value
Cabling layout		(2SC+1Cu)×3×4×4×6
Final outer diameter	mm	32.6
Void fraction		32.7%
Twist pitch sequence	mm	24/49/89/160/450
Petal stainless steel wrap		70% overlap
Cable stainless steel wrap		overlapped
# of SC strand		576
# of copper wires		288
Heat treatment schedule℃/h		210/50+340/25+450/25+575/100+650/100
Operating current	kA	47.65
Peak field in the coil	T	12

III. BASIC STRUCTURE DESIGN OF CFERT CSMC

A. CSMC Coil

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

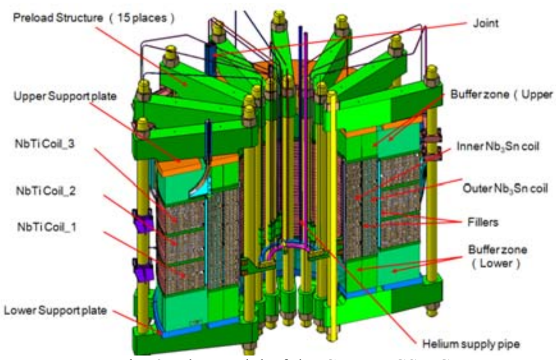

Fig. 2. The model of the CFETR CSMC

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. 2. The total weight of CSMC including the structural components is about 70 tons. Table 3 shows the main structure parameters of CFETR CSMC.

TABLE Ⅲ
THE MAIN STRUCTURE PARAMETERS OF CFETR CSMC (MM)

	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

B. Pre-load Structure

The pre-load structure is one of the most important components for CFETR-CSMC which can withstand the EM load and maintain the compaction and integrity condition of coil at excitation state. Fig.3 shows the preload structure of CFETR-CSMC. The main unit element includes the tension rods, plates and beams.

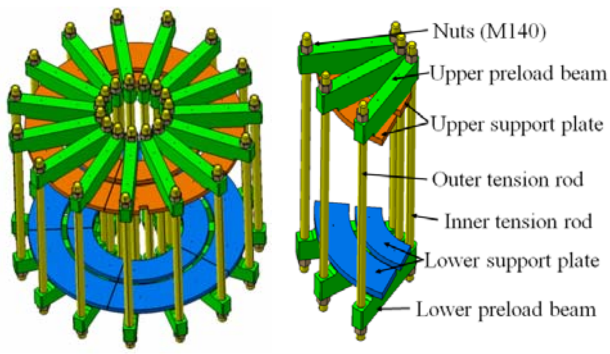

Fig. 3. Concept design of preload structure

15 sets of 316LN stainless steel (SS) beams are uniformly distributed around the top and bottom of the coils. These beams are connected together by 15 pairs of 140 mm diameter, 316L SS tension rods at inner and outer of the coils. The 100 mm thick support plates located between the beams and buffer zones are used to distribute the preload uniformly on the coil modules. Buffer Zone at the top and bottom of the coil is approximately 0.5 m thick and fills the space between the coil and the preload beam. The buffer zone transfers external axial loads to the coil and supports the conductor joints. The buffer zone is made primarily from fiberglass-epoxy materials.

TABLE Ⅳ
THE STRESS HISTORY OF PRELOAD STRUCTURE

Component/state	P	P+T	P+T+E
Upper beam (MPa)	189.8	359.7	378.0
Low beam (MPa)	160.7	357.5	379.9
Out rod (MPa)	149.2	119.7	142.3
Inner rod (MPa)	143.1	121.1	170.3
Upper support plate (MPa)	281.9	393.6	423.6
Lower support plate (MPa)	207.3	377.1	402.4

Three load conditions had been considered. First load is the initial preload (2.5 MN) of every preload rod at room temperature (RT) (P); second is from cool-down from RT to 4.0 K (P+T) and the last is Electromagnetic load when the running current is 47.65KA (P+T+E). A global finite element model of pre-load unit was created to investigate the mechanical properties at the different load. The simulation results show in the Table Ⅳ which indicates that the stresses in preload structure and support plate are acceptable.

C. Joint Design

CFETR-CSMC contains 6 joints and 2 leads, ① CS3L&CS2M joint; ②CS2M&CS1U joint; ③ CS1I&CS2I joint_1; ④CS1U&CS2I joint_1; ⑤CS1U& CS2I joint_2; ⑥ CS1I&CS2I joint_2; ⑦CS1I lead; ⑧ CS3L lead. ①-⑥ are joints ⑦ and ⑧ are leads，①-④ are praying hands joints and ⑤-⑥ are shaking hand joints as shown in Fig.4. The design resistance of these joints is in the range of less than 5nΩ. The prototype joint is now being developed in ASIPP.

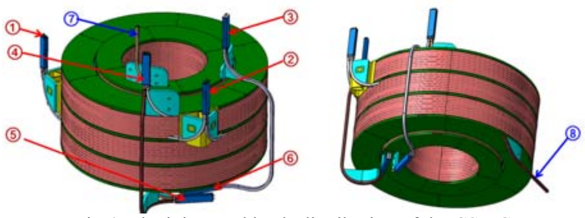

Fig.4. The joints and leads distribution of the CSMC

The every joint includes the same separate components for easy assembly: copper sleeve termination, copper saddle transition, stainless steel clamps, eyeglass piece and end plate. The detail process for joint is as follow:

- SS-copper brazed sleeve welded to CICC to provide Helium channel with 20% void fraction;
- Copper sleeve and copper saddle provide current transfer pathway;
- Stainless steel clamps compress copper sleeve and copper saddle and welded;
- The eyeglass piece is welded to the conductor with 4 plug welds and with a seal weld around the periphery of the eyeglass piece;

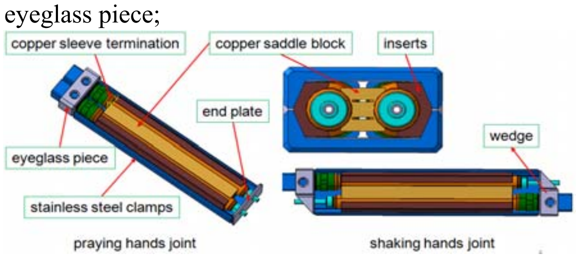

Fig.5. structure design of joints

At present, the prototype of single NbTi joint has been manufactured and planed to qualification test at the second half of this year shown in Fig. 7.

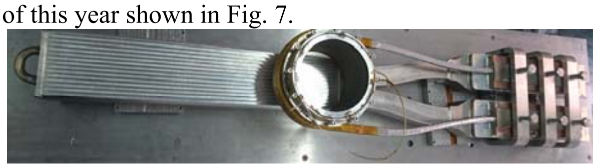
Fig.6. Tested joint sample connected to transformer

IV. Measurement Results of Conductor Sample

Full-sizes Nb_3Sn CICC sample were tested at SULTAN facility at spring of 2016 as a milestone progress. The details of sample preparation and instrumentation are the similar as the ITER Nb_3Sn CICCs sample **[13-14]**. Current sharing temperature (T_{cs}) and coupling loss measurements are the main assessment performance for the Nb_3Sn CICC sample.

A. Temperature Current Sharing (T_{cs})

The results of T_{cs} measurement electrically evaluated along the cycling loading at 45.1 kA and 10.85 T background field are shown in the Fig. 7. The number of cyclic loading was 9950. After the end of 3850 and 9949 cycles, T_{cs} measurement was performed after a warm-up and a cool-down.

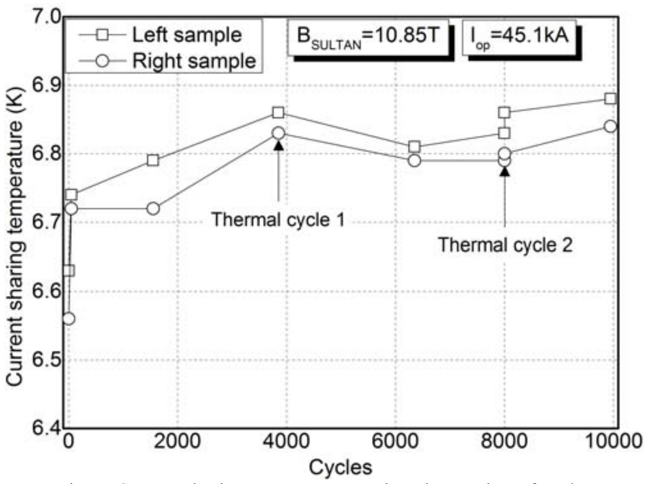

Fig. 7. Current sharing temperature against the number of cycles

The T_{cs} of two conductor samples at initial state is 6.63 K and 6.56 K respectively, however, increases sharply at the second T_{cs} measurement (at 50th cycles), then T_{cs} rises gradually against the EM cycles by 1.414×10^{-2} mK/cycles for left sample and 2.829×10^{-2} mK/cycles for right sample. T_{cs} of two conductors seem not be change after first thermal cycle, but the increase become larger for the second thermal cycles. At last, the performance of two conductor samples are almost identical, the T_{cs} is 6.88 K for left sample and 6.84 K for the right sample at 9950th cycle.

The measurement results are agreement with the ITER CS conductor using the STP structure **[15]**. It shows that the STP conductor prevents the EM force from lateral deformation of strands effectively which can inhibit the T_{cs} degradation against the cycling.

B. Coupling Loss

The AC losses of samples are obtained by calorimetric method. The amplitude of the sinusoidal AC applied field was 0.2 T The frequency of AC applied field was from 0.1 Hz to 7 Hz to obtain the AC losses in the wide frequency range. A biased DC field of 2 T and 9 T were applied to avoid the interference from diffusion barrier out of the Nb_3Sn filaments and also can acquire the AC loss characteristic dependence on the background field.

8000 cycles have been applied with transport current of 48.8 kA under 10.85 T to meet the EM force in the CFETR-CSMC.

The total measured AC losses energy per cycle includes the hysteresis and coupling losses. If it is assumed that the hysteresis losses at full penetration of the applied field are independent of the frequency, the coupling losses can be represented by the energy losses per cycle versus frequency.

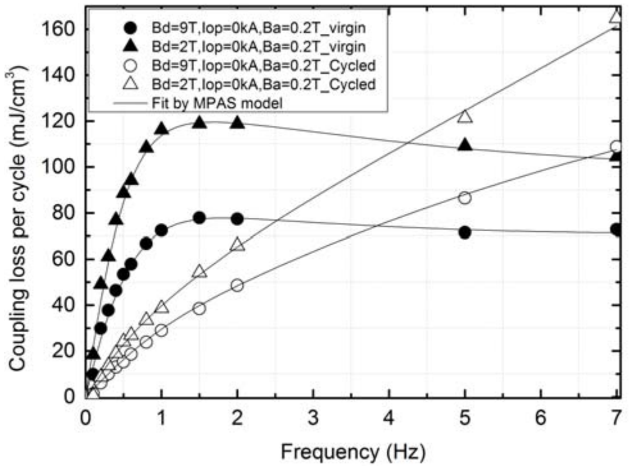

Fig. 8. Experimental data and MPAS fitting curve with different state.

The coupling losses measurement results of Nb_3Sn CICC sample for CFETR-CSMC subtracted by hysteresis loss is shown in Fig.8. According to the results, the coupling losses show a wide plateau extending to higher frequency in virgin state. The maximum coupling loss energy is 120 mJ/cm^3 per cycle at 2.0 Hz with 2 T biased DC field which is 50 % higher than at 9 T biased DC field.

V. Conclusion

A superconducting magnet named CFETR-CSMC has been launched at ASIPP from 2014 to develop and verify the large-scale magnet technology. A STP structure is adopted for Nb3Sn CICC due to the good transport current performance under transverse EM load and cycles. The coil structure, pre-compression component and joint design is developed and makes some progresses. At last, the T_{cs} and coupling loss measurement of Nb_3Sn CICC sample, as the most important stage assessment, are performed in SUTLAN test facility. The measurement results show that the performance of Nb_3Sn CICC meets the design requirement.

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