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$_3$Sn 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$_3$Sn coil in the high field region and NbTi coil in the low field region to optimize the manufacture cost effectively. The current sharing temperature and coupling loss measurement of Nb$_3$Sn 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$_3$Sn 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$_3$Sn 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$_3$Sn 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$_3$Sn CICC is made including the DC, AC performance and some meaningful conclusions are summed up.

II. CICC CONDUCTOR DESIGN AND MANUFACTURE

A. Nb$_3$Sn Strand

Fig. 1(a) shows the cross-sectional view of Nb$_3$Sn 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.

Critical current density ($J_c$) of Nb$_3$Sn 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>
<thead>
<tr>
<th>Parameter</th>
<th>Unit</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$C_{1}$</td>
<td></td>
<td>19948.5</td>
</tr>
<tr>
<td>$P$</td>
<td></td>
<td>0.57</td>
</tr>
<tr>
<td>$Q$</td>
<td></td>
<td>2.0</td>
</tr>
</tbody>
</table>

B. Nb$_3$Sn CICC

For Nb$_3$Sn 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 Nb₃Sn CICC of CFETR-CSMC which originates from ITER CS Nb₃Sn 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 Nb₃Sn CICCs [10]-[12]. The detail structure parameters of Nb₃Sn 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 Nb₃Sn strand and CIC conductor.

Besides, the application of Cr coating with 2 um thickness on the surface of Nb₃Sn 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

<table>
<thead>
<tr>
<th>Property</th>
<th>Unit</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cabling layout</td>
<td></td>
<td>(2SC+1Cu)×3×4×4×6</td>
</tr>
<tr>
<td>Final outer diameter</td>
<td>mm</td>
<td>32.6</td>
</tr>
<tr>
<td>Void fraction</td>
<td></td>
<td>32.7%</td>
</tr>
<tr>
<td>Twist pitch sequence mm</td>
<td></td>
<td>24/49/89/160/450</td>
</tr>
<tr>
<td>Petal stainless steel wrap</td>
<td></td>
<td>70% overlap</td>
</tr>
<tr>
<td>Cable stainless steel wrap</td>
<td></td>
<td>overlapped</td>
</tr>
<tr>
<td># of SC strand</td>
<td></td>
<td>576</td>
</tr>
<tr>
<td># of copper wires</td>
<td></td>
<td>288</td>
</tr>
<tr>
<td>Heat treatment schedule °C/h</td>
<td></td>
<td>210/50+340/25+450/25+575/100+650/100</td>
</tr>
</tbody>
</table>

#### III. Basic Structure Design of CFETR-CSMC

### A. CSMC Coil

CFETR-CSMC coil is mainly composed of the internal high magnetic field Nb₃Sn 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](image)

In order to optimize the cost of coil manufacture, the CICC with Nb₃Sn strand is used for the high magnetic field region where the maximum field is 12 T; another NbTi strand is used for the low magnetic field region where the field is less than 6.1 T. The model of the CFETR-CSMC 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

<table>
<thead>
<tr>
<th>Component/state</th>
<th>P</th>
<th>P+T</th>
<th>P+T+E</th>
</tr>
</thead>
<tbody>
<tr>
<td>Upper beam (MPa)</td>
<td>189.8</td>
<td>359.7</td>
<td>378.0</td>
</tr>
<tr>
<td>Low beam (MPa)</td>
<td>160.7</td>
<td>357.5</td>
<td>379.9</td>
</tr>
<tr>
<td>Out rod (MPa)</td>
<td>149.2</td>
<td>119.7</td>
<td>142.3</td>
</tr>
<tr>
<td>Inner rod (MPa)</td>
<td>143.1</td>
<td>121.1</td>
<td>170.3</td>
</tr>
<tr>
<td>Upper support plate (MPa)</td>
<td>283.9</td>
<td>393.6</td>
<td>423.6</td>
</tr>
<tr>
<td>Lower support plate (MPa)</td>
<td>207.3</td>
<td>377.1</td>
<td>402.4</td>
</tr>
</tbody>
</table>

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 47.65 KA (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; (2) CS2M&CS1U joint; (3) CS1I&CS2I joint_1; (4) CS1U&CS2I joint_1; (5) CS1U&CS2I joint_2; (6) CS1I&CS2I joint_2; (7) CS1I lead; (8) CS3L lead. (1)- (6) are joints and (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 5 nΩ. The prototype joint is now being developed in ASIPP.

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;

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.

### IV. MEASUREMENT RESULTS OF CONDUCTOR SAMPLE

Full-sizes Nb3Sn 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 Nb3Sn CICCs sample [13-14]. Current sharing temperature ($T_{cs}$) and coupling loss measurements are the main assessment performance for the Nb3Sn 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.

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 Nb3Sn 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.

The coupling losses measurement results of Nb3Sn 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/cm³ 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 Nb3Sn CICC sample, as the most important stage assessment, are performed in SUTLAN test facility. The measurement results show that the performance of Nb3Sn CICC meets the design requirement.

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