Mechanical performance evaluation of the CFETR central solenoid model coil design

Xiaogang Liu†, Zhaoliang Wang, Yong Ren, Junjun Li, Dapeng Yin, Lei Li, Xiang Gao and Yu Wu

Institute of Plasma Physics, Chinese Academy of Sciences, Hefei 230031, People’s Republic of China

E-mail: xgliu@ipp.ac.cn

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Abstract

The Chinese Fusion Engineering Test Reactor (CFETR) Central Solenoid Model Coil is being fabricated by the Institute of Plasma Physics Chinese Academy of Sciences. The Model Coil is comprised of Nb3Sn and NbTi modules held together by a preload structure. It will operate at 4.5 K to produce a peak field of 12 T at 48 kA. In order to investigate the feasibility and integrity of the Model Coil design before its manufacturing, the mechanical performance has been evaluated for the room temperature preload, 4.5 K stand-by and 48 kA operating conditions. A 1/15 3D detailed model that consists of jackets, insulations, bladders, buffers and preload structure, is constructed and simulated using the coupled structural-thermal-electromagnetic solver of ANSYS. In contrary to a smeared winding pack model, our analysis with the detailed model can directly and precisely simulate the differential thermal contraction effect of the preload structure, jacket and insulations, as well as the electromagnetic load acting on the jacket. The detailed deformation and stress behaviors of the Model Coil are illustrated and discussed. The results indicate that the final design of the CFETR Central Solenoid Model Coil is reasonably conservative and satisfy the design criteria.

Keywords: CFETR, central solenoid, model coil, mechanical analysis, preload, thermal contraction, Lorentz force

((Some figures may appear in colour only in the online journal)
Up to now, all the Nb$_3$Sn and NbTi strands for CFETR CS Model Coil have been produced by the Western Superconducting Technologies Co., Ltd, and the acceptance tests have been finished. Parts of the strand cabling for full-length conductors have been completed in ASIPP [6]. The 316LN stainless steel (SS) jackets are in production and the short sample conductors have been tested [7]. The coil winding is already in process.

This paper is organized as follows. First, the final design of the CFETR CS Model Coil is introduced. Next, the electromagnetic analyses including the magnetic field distribution, Lorentz force caused by coil misalignment, and Lorentz load during operating condition are performed. Then, the three-dimensional (3D) finite element model is built, the Material properties, boundary and load conditions are specified. Finally, the models are solved and the analysis results are given.

2. The CFETR CS model coil design

The detailed configuration of the CFETR CS Model Coil is shown in figure 1. It is composed of a Nb$_3$Sn inner module, a Nb$_3$Sn outer module, and three vertically stacked NbTi modules. All these modules are concentrically assembled and connected in series with ‘praying hands’ joints. Every module is pancake wound with a single CICC conductor, which is 642 m for the Nb$_3$Sn inner module, 813 m for the Nb$_3$Sn outer module, and 755 m for a NbTi module. The ends of the conductor are bent with a 0.5 m radius to line up with axis of the CS Model Coil.

The overview structure of the CS Model Coil assembly is shown in figure 2, and the key parameters are listed in table 1. The CFETR CS Model Coil has an inner diameter of 1.5 m, an outer diameter of 4.5 m, and a height of 3.9 m. It is supported by four support posts that support the coil gravity and react seismic loads.

The conductor bends are contained in 0.5 m thick buffer zones at the top and bottom of the coil windings. These buffer zones are made of fiberglass-epoxy (G10) and serve the following functions: (i) filling the spaces between the ends of the coil winding, (ii) supporting the conductor leads, (iii) providing a smooth surface at the coil ends for ground insulation, and (iv) transferring external axial loads into the coil windings.

The turn and ground insulation are 2.6 mm and 3.1 mm respectively, which incorporates Kapton polyimide for electrical insulation and fiberglass epoxy for structural integrity.

The radial clearance between the Nb$_3$Sn inner and outer module is 15 mm, and between the Nb$_3$Sn outer module and NbTi module is 50 mm. These clearances will be filled by bladders during assembly. The NbTi modules are spaced by 50 mm G10 plates.

The Nb$_3$Sn modules and NbTi modules are mechanically compressed by a preload structure that imposes CS-like axial compression on the modules to ensure the structural performance and react electromagnetic loads. The preload structure consists of 30 load beams (15 upper and 15 lower), 30 tension rods (15 inner and 15 outer), and pressure plates (inner and outer) that are circumferentially segmented to reduce eddy currents. The load beam is 200 mm thick and 400 mm high. The tension rod is 140 mm in diameter and 3.9 m in length. The pressure plate is 100 mm thick. Before cooling to the operation temperature of 4.5 K, each tension rod will be preloaded with 2.5 MN by tensioners at room temperature (RT). The pressure plates locating between the load beams and the buffer zones are utilized to distribute the compression load over the top of the coil modules.

3. Electromagnetic analysis

A self-written Fortran code [5] is used to calculate the magnetic field distribution, and the Lorentz force arising from coil misalignment. The 2D positions and the diameters of the conductor cables are initialized in the Fortran code. A nominal operating current of 48 kA is applied on the series connected Nb$_3$Sn (inner and outer) and NbTi (upper, middle and lower) modules. The calculated field distribution is shown in figure 3. The peak field is 12 T on the Nb$_3$Sn inner module, 8.3 T on the Nb$_3$Sn outer module, and 6.0 T on the NbTi module. The field calculation results are checked with ANSYS, which reveals the deviation is smaller than 0.5%.

3.1. Lorentz force due to misalignment

The case of coil misalignment considered here is that there are a radial $\Delta R$ and an axial $\Delta Z$ misalignment between the Nb$_3$Sn modules and the NbTi modules. The misalignment between the Nb$_3$Sn inner and outer module, and that among the NbTi modules are ignored.

The calculation results show that the radial resultant force $F_R$ experienced by the Nb$_3$Sn inner module is approximately linear with $\Delta R$ at small misalignment, while $F_Z$ is
approximately linear with $\Delta Z$. As listed in tables 2 and 3, the forces for two representative misalignments of 5 mm and 10 mm are shown, which are about a few hundreds of kilo-Newton.

### 3.2. Lorentz load during operating condition

Under the steady state operating condition with a nominal current of 48 kA, the peak field on the Model Coil is 12 T, and the stored magnetic energy is 393 MJ. The Lorentz load is calculated with ANSYS for the convenience of transferring it into the structural analysis. As illustrated in figure 4, the Lorentz forces act to pull the conductors outward in the radial direction, and compress the conductors toward the coil mid-plane in the axial direction. The maximum Lorentz force density is 0.25 N mm$^{-3}$.

### 4. Numerical model

#### 4.1. 3D Finite element model and Meshing

The 3D detailed model based on the CFETR CS Model Coil final design is presented in figure 5. Only 1/15 of the assembly is modeled because it has the cyclic symmetry. The final design geometry of the Model Coil is simplified by (i) removing most of filets from the design to make the analysis more conservative [8], and (ii) removing all the cables of CICC conductors in the Model Coil since they are very ‘soft’ compared to the jacket and so barely affect the structural analysis.

The model is imported into the ANSYS Workbench, and the 3D structural analysis were performed using the coupled mechanical-thermal-electromagnetic solver of ANSYS.

As shown in figure 5, most parts of the model are meshed with hexahedral elements, such as the load beams, tension...
4. rods, nuts, pressure plates, buffer zones, bladders and jackets. Especially for the insulations with a thickness of a few millimeters, sweep method and edges sizing are specified to make sure that the thin insulations are meshed with hexahedral elements. Final mesh contains 0.36 million elements and 2.44 million nodes.

Since all the conductor cables are removed in order to reduce the element number and the computation to a manageable scale, the operating current is applied on the conductor jacket, and accordingly the Lorentz force is loaded on the jacket directly.

The advantage of using the detailed model is that, without using smeared materials for the coil windings, we can directly simulate the differential thermal contraction effect of the jacket, insulation and other structures, and the Lorentz force on the jacket. Therefore we could obtain more accurate simulation results directly on the insulation system and jackets, compared to the combination of global analysis (using smeared material) and local analysis.

4.2. Material properties

Material properties at 4.5 K used for analysis are listed in table 4, which were retrieved from the ITER data base [9]. The 316 LN SS material is utilized for the load beams, pressure plates, tension rods and nuts.

Orthotropic epoxy glass fiber G10 material properties [8–12] are utilized for the buffer zones, insulation system and bladders. For these materials, x is through the thickness direction (perpendicular to the layer) with a Co efficient of thermal

| $\Delta R$ | $\Delta Z$ | 0 mm  | 5 mm  | 10 mm |
|-----------|-----------|-------|-------|-------|
| 0 mm      | $F_R$ (kN)| 0     | 0     | 0     |
| 5 mm      | $F_R$ (kN)| 129.402 | 129.396 | 129.379 |
| 10 mm     | $F_R$ (kN)  | 258.813 | 258.801 | 258.766 |

Noted that $\Delta R$ and $\Delta Z$ are the radial and axial misalignments between the Nb$_3$Sn and NbTi modules, respectively.

| $\Delta R$ | $\Delta Z$ | 0 mm  | 5 mm  | 10 mm |
|-----------|-----------|-------|-------|-------|
| 0 mm      | $F_Z$ (kN)| 0     | 258.798 | 517.572 |
| 5 mm      | $F_Z$ (kN)| 0     | 258.803 | 517.584 |
| 10 mm     | $F_Z$ (kN)  | 0     | 258.821 | 517.619 |

Table 2. Radial resultant force acting on the Nb$_3$Sn inner module arising from coil misalignment.

Table 3. Axial resultant force acting on the Nb$_3$Sn inner module arising from coil misalignment.

Figure 3. Magnetic field distribution of the CFETR CS model coil with a peak field of 12 T at 48 kA.

Figure 4. Cross-section view of the Lorentz force density on the CFETR CS model coil at 48 kA with a peak field of 12 T.
expansion (CTE) of $-0.7\%$, while $y$ and $z$ are along the layer direction with a CTE of $-0.25\%$.

For the mechanical analysis at RT, the elastic modulus of 316LN SS is 192 GPa. While for G10, because we cannot find the suitable mechanical properties at RT, we use the properties at 4.5 K for RT analysis in this paper. The Young’s modulus of G10 at RT may be smaller than that at 4.5 K by about 22% [13].

4.3. Boundary conditions

Non-linear contact are considered between the following contacting parts: (i) the load beams and the nuts, (ii) the load beams and the tension rods, (iii) the load beams and the pressure plates, (iv) the pressure plates and the buffer zones, and (v) the buffer zones and the insulation. All layers of turn insulation are considered to be fully bonded to the conductor jackets.

At the bottom surface of the lower load beam, displacement in the axial direction is fixed, while displacement in the radial direction is free. Therefore, the model coil is supported at this surface in the axial direction, and free to shrink in the radial direction during cool-down.

4.4. Load conditions

The mechanical analysis is performed for each of three load conditions that are representative of particular states in the operating cycle of the CFETR CS Model Coil. These three conditions are:

(i) RT preload condition. A temperature of 293 K is set to all parts of the Model Coil, and a 75 MN pre-compression load is applied to the model by applying 2.5 MN axial force on each of the upper and lower nut.

(ii) 4.5 K stand-by condition. A thermal cool-down load is applied during the Model Coil is cooled from 293 K to 4.5 K. For the buffer zones and insulation system, the lower thermal contraction direction is oriented in the axial direction, to prevent preload loss during cool-down. Meanwhile, the higher thermal contraction in the radial direction causes a radial mismatch with respect to the preload structure and jackets, which shrink less than the buffer zones and insulations.

(iii) 48 kA operating condition. The Lorentz load on the conductor jackets of the Model Coil is simulated using the ANSYS Maxwell, then it is transferred into the ANSYS Workbench and applied to the detailed model as body force density.

The gravity and the electromagnetic misalignment load are not considered in our analysis, because they are both much smaller than the preload or the Lorentz load.

5. Mechanical analysis

The assessment of the CFETR CS Model Coil design mainly refers to the ITER Magnet Structural Design Criteria Part 2 and Part 3 [14, 15].

The radial and axial deformation of the Model Coil under the RT preload, 4.5 K stand-by and 48 kA operating conditions are shown in figures 6 and 7, respectively. Compressed by the 75 MN pre-tension load, the tension rods bend by 0.8 mm (the outer tension rods bend inward and the inner tension rods bend outward) in the radial direction, and contract by 1.52 mm in the axial direction. After cool-down to 4.5 K, the preload structure contract 7.23 mm radially and 11.74 mm axially. Finally the Lorentz load causes a 0.35 mm radial expansion and a 0.74 mm additional axial contraction. The analysis results show that no loss of contact occurs in the Model Coil under all the three load conditions.

The equivalent (von-Mises) stress distribution under the three load conditions are displayed in figure 8. The detailed
Figure 6. Radial deformation distribution under the (a) RT preload, (b) 4.5 K stand-by, and (c) 48 kA operating condition.

Figure 7. Axial deformation distribution under the (a) RT preload, (b) 4.5 K stand-by and (c) 48 kA operating condition.

Figure 8. Equivalent (von-Mises) stress distribution under the (a) RT preload, (b) 4.5 K stand-by and (c) 48 kA operating condition.
maximum equivalent stresses on parts of the CFETR CS Model Coil assembly are tabulated in table 5. In figures 8(a) and (b), the maximum equivalent stress occurs on the outer Nuts, which amounts to 124.2 MPa and 131.6 MPa respectively. In figure 8(c), the maximum equivalent stress occurs on the conductor jacket of the innermost mid-plane turn due to the application of huge Lorentz load, which amounts to 261.8 MPa. This peak stress is still well below the allowable limits of the 316LN SS.

Noted that we use the 4.5 K material properties of G10 for the RT preload analysis. Therefore for the insulations and buffer zones under the RT preload condition, the actual strains should be larger than our analysis results, and the actual stresses should have deviations to our results. However, the analysis results of the jackets and preload structure at RT should be intact, due to the fact that SS is much ‘harder’ than G10. In addition, it should be noted that for the insulations and buffer zones at RT, the maximum principal strain is very small (6.3 × 10^{-4} mm/mm), the maximum normal stress is 16.7 MPa, and the maximum shear stress is only 2.8 MPa. At RT, for the strain and stress results of the insulations and buffer zones, the deviations should be small and acceptable. Therefore, for the RT preload condition, our analysis results of the insulations and buffer zones should have enough margins and are acceptable.

Table 5. Maximum equivalent (von-Mises) stresses on the jackets and preload structure.

| CFETR CS model coil parts | Max equivalent stress (MPa) |
|---------------------------|-----------------------------|
|                           | RT preload | 4.5 K stand-by | 48 kA operating |
| Jackets                   | 49.0       | 96.8           | 261.8           |
| Nuts                      | 124.2      | 131.6          | 105.6           |
| Load beams                | 120.5      | 128.7          | 101.4           |
| Inner tension rods        | 113.1      | 116.2          | 90.9            |
| Outer tension rods        | 110.4      | 114.4          | 99.1            |
| Inner pressure plates     | 36.4       | 39.0           | 19.7            |
| Outer pressure plates     | 62.7       | 61.3           | 51.4            |

5.1. Coil winding

Figure 9 shows the equivalent stress distribution on the conductor jackets.

First, the RT preload is applied. The maximum equivalent stress on the jackets is 49.0 MPa.

Second, the coil is cooled down to 4.5 K. On one hand the pre-compression load is increased due to the axial contraction mismatch between the tension rods and the coil.

On the other hand radial mismatches occurs between the buffer zones, turn insulations and the jackets. These mismatches give rise to stress enhancement on the jackets, and the peak von-Mises stress increases to 96.8 MPa.

At last, the Lorentz load during operation is applied. A bending of the jackets could be observed in figure 9(c), the maximum equivalent stress on the jackets increases to 261.8 MPa, the predominant stress on the jackets is the hoop stress, which is 224.3 MPa on the conduit of the innermost mid-plane turn.

The maximum compression stress and maximum shear stresses on the insulations are summarized in table 6. The maximum compression stress in the axial direction is 12.6 MPa under the RT preload condition. After cool-down to 4.5 K, it increases to 79.3 MPa, and further increases to 88.1 MPa after energizing of the model coil.

The shear stress on the insulations mainly exists on the RZ plane, due to the thermal strain difference between the preload structure and the coil, together with the asymmetry of the coil geometry with respect to the inner and outer tension rods. As shown in figure 10, the Lorentz load reduce the peak shear stress on RZ plane from 35.0 MPa to 30.9 MPa, by radially expanding the coil a little bit to compensate the asymmetry. The peak shear stress on the insulations satisfies the ITER design criteria. However, it is above the test results (~30 MPa at 77 K) of the designed insulation for the CFETR CS Model Coil [17], therefore the design of insulation need to be optimized.

5.2. Preload structure and buffer zone

The von-Mises stress evolution on the preload structure is shown in table 5. At RT, through the preload structure an axial compression load is applied to the Nb3Sn and NbTi modules. After cool-down this axial load is increased. In consequence, the maximum equivalent stresses on the nuts, load beams and pressure plates increase. During 48 kA operation, the Lorentz forces help the preload structure compress the coil winding, which reduce the peak equivalent stresses on the nuts, load beams and pressure plates.

By using the axial normal stresses at the mid-plane of the tension rods, the axial tension forces could be calculated, and thus the preloading force variation after cool-down and energizing could be evaluated. As listed in table 7, at RT, a preloading force of 2.5 MN is applied to the inner and outer tension rods. After cool-down to 4.5 K, the axial tension force increases to 2.58 MN for the inner rod and 2.63 MN for the outer rod. This additional axial loading is caused by the thermal contraction differences between the coil modules and the tension rods. Then after energizing to 48 kA, the axial tension force is reduced by the application of the electromagnetic load. It decreases to 1.81 MN for the inner rod and 2.22 MN for the outer rod. We noted that the variation tendency of our results is consistent with that measured on the ITER CS Model Coil [18].

For the buffer zones of the Nb3Sn inner and outer module, the peak compressive stresses increase from 13.9 MPa and 10.0 MPa to 15.4 MPa and 12.9 MPa during cool-down, then decreases to 7.7 MPa and 12.2 MPa after the Lorentz load is applied. Different from this, the peak compressive stress on the NbTi buffer zone decreases from 16.7 MPa to 15.8 MPa during...
cool-down, and decreases further to 14.9 MPa during operation. The reason is that the NbTi modules have a more thickness of buffer zone than that of Nb3Sn inner and outer modules. It is obvious that the inner and outer pressure plates are thick enough to adequately spread the axial loads into the coil buffers. Besides, it should be note that the maximum axial compressive stress on the coil modules is 16.7 MPa, which is a little smaller than the design requirement of the preload (23 MPa) for the ITER CS [19].

**Table 7.** Axial tension forces on the tension rods.

| Tension rods   | Axial tension forces (MN) |
|----------------|--------------------------|
|                | RT preload condition     | 4.5 K stand-by condition | 48 kA operating condition |
| Inner tension rod | 2.5                      | 2.58                     | 1.81                      |
| Outer tension rod  | 2.5                      | 2.63                     | 2.22                      |
6. Conclusions

The electromagnetic and mechanical analyses of the CFETR CS Model Coil are presented in this paper. Using a 1/15 3D detailed model, the mechanical behavior under the RT axial pre-compression load, the thermal load caused by differential thermal contraction during cool-down, and the electromagnetic load under 48 kA steady-state operating condition are evaluated. The deformation and stress level of the components of the Model Coil are below the allowable limits. Our simulation results indicate that the final design of the CFETR CS Model Coil is relatively conservative.

After the Model Coil is cooled down to 4.5 K, the peak shear stress occurs on the insulations is 35.0 MPa, which is above the test result of the preliminary designed insulation for the CFETR CS Model Coil. Therefore the insulation design should be optimized.

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ORCID iDs

Xiaogang Liu  https://orcid.org/0000-0002-1702-5154

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