Preliminarily Static Analysis of CFETR Central Solenoid Magnet System

Aihua Xu, Jiang Liu, V. A. Anvar, Qi Lin, Xinggang Wang, Houxiang Han, Shi Yi, Jingang Qin, and Yu Wu

***Abstract*—Conceptual design of China Fusion Engineering Test Reactor (CFETR) Central Solenoid (CS) coil had been started in Institute of Plasma Physics, Chinese Academy of Sciences. The highest field of CS coil is 17.2 T when the running current is 60 kA. CS magnet system mainly consists of 8 Nb_3Sn coils compressed with 8 sets of preload structure. The functions of the preload structure are to apply an enough axial compression to the CS coils and to have a mechanical rigidity against the repulsive force between 8 Nb_3Sn coils. This paper describes structural design of CFETR CS magnet system. A global finite element model is created based on the design geometry data to investigate the mechanical property of CFETR CS preload structure and support structure under the different operating conditions. 2D finite element model under electromagnetic is created to calculate the stress on the conductor jacket and turn insulation.**

***Index Terms*—CFETR, central solenoid, structural design, FEA, magnet.**

I. Introduction

CHINA Fusion Engineering Test Reactor (CFETR), a new tokamak device, is under concept design based on the experience of Experimental Advanced Superconducting Tokamak (EAST) and ITER [1], [2]. The highest field of CS coil is 17.2 T when the running current is 60 kA. The Central Solenoid (CS) is one of the sub-systems of the CFETR Magnet System and it contributes to the inductive flux to drive the plasma, to the shaping of the field lines in the diverter region and to vertical stability control. The CS assembly consists of a vertical stack of eight independent coils using a Nb_3Sn cable-in-conduit superconducting conductor (Figure 2), and the stack is supported from the bottom of the TF coils as shown Figure 1. At the top, there is a sliding connection to provide a locating mechanism and support against dynamic horizontal forces. The modules can be energized independently and bus-bars and joints are placed outside the coils, with helium supply and return lines inside the bore. During operation, repelling forces arise between modules as well as net resulting forces. The CS stack is self-supporting against the coil radial forces and most of the vertical forces, with the support to the TF coils reacting only

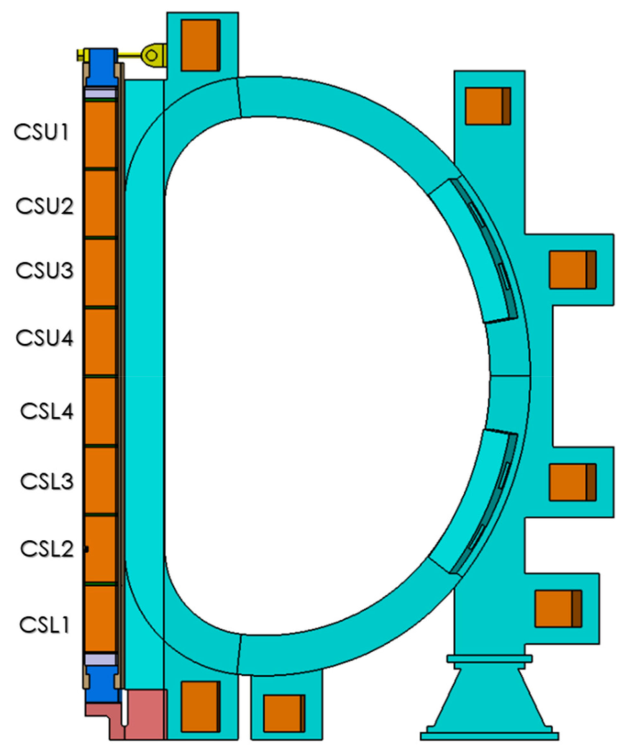


Fig. 1. Overview of part CFETR CS.

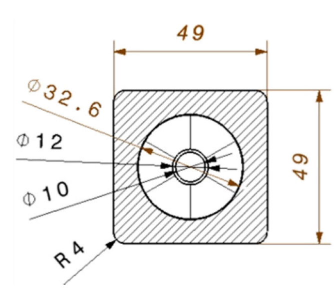


Fig. 2. Section of CS conductor.

Manuscript received September 22, 2019; accepted January 21, 2020. Date of publication February 3, 2020; date of current version March 3, 2020. This work was supported by the Natural Science Foundation of the Jiangsu Higher Education Institutions of China under Grant 19KJB470011. *(Corresponding author: Jingang Qin.)*

A. Xu is with the Changzhou Vocational Institute of Mechatronic Technology, Changzhou 213164, China, and Institute of Plasma Physics, Chinese Academy of Sciences, Hefei 1126, China (e-mail: xuah@ipp.ac.cn).

J. Liu and X. Wang are with the Changzhou Vocational Institute of Mechatronic Technology, Changzhou 213164, China.

V. A. Anvar is with the University of Twente Energy, Materials and Systems, Faculty of Science and Technology, 7500AE Enschede, Netherlands.

Q. Lin is with the Changzhou Vocational Institute of Engineering, Changzhou 213164, China.

H. Han, S. Yi, J. Qin, and Y. Wu are with the Institute of Plasma Physics, Chinese Academy of Sciences, Hefei 1126, China (e-mail: qinjg@ipp.ac.cn).

Color versions of one or more of the figures in this article are available online at https://ieeexplore.ieee.org.

Digital Object Identifier 10.1109/TASC.2020.2970333

TABLE I
PARAMETERS OF CS MODULE

COILS	R(m)	Z(m)	△R(m)	△Z(m)	TURNS
CS1U	1.70	1.025	1.0	2.05	738
CS2U	1.70	3.075	1.0	2.05	738
CS3U	1.70	5.125	1.0	2.05	738
CS4U	1.70	7.175	1.0	2.05	738
CS4L	1.70	-7.175	1.0	2.05	738
CS3L	1.70	-5.125	1.0	2.05	738
CS2L	1.70	-3.075	1.0	2.05	738
CS1L	1.70	-1.025	1.0	2.05	738

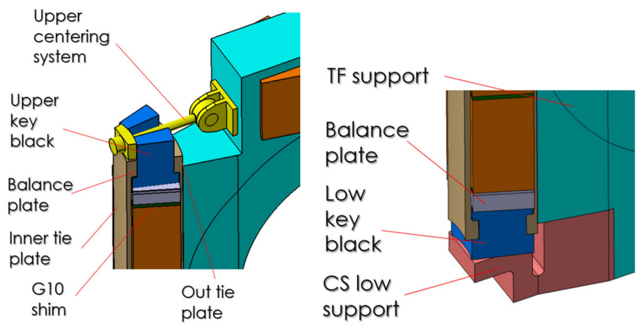


Fig. 3. Local structure of CS system.

the weight and net vertical components resulting from up-down asymmetry of the poloidal field configuration. The CS preload structure provides the vertical pressure on the stack and consists of the 8 set of tie-plates, a Stainless Steel upper and lower key block and G 10 buffer zones. Table I gives the Parameters of CS module.

This paper describes structural design of CFETR CS magnet system. A global 3D FE model and 2D FE model is created based on the design geometry data to investigate the mechanical property of CFETR CS preload structure, support structure under the different operating conditions and the stress on the conductor jacket and turn insulation.

II. Conceptual Design of CFETR CS

Figure 3 gives the preload structure, lower support structure and upper centering system (UCS) of CS assembly. The preload structure is provided to contain forces internal to the CS stack and avoid separation of modules from each other. The CS pre-compression structure is split into a set of 8 identical independent subunits, each one consisting of an inner tie plate, two outer tie plates, balance plates, a lower key block, an upper key block and G10shims. The CS assembly is supported from the bottom of the TF coils by the CS lower support structure. The structure is divided into eight identical, independent subunits, which attach to the lower projection of the TF coil case. The CS assembly must be restrained at the top and bottom to keep it aligned to the axis of the machine. This is accomplished at the top by UCS. The UCS is a set of radial tie rods, which act like spokes to provide a locating mechanism and support against dynamic net horizontal forces. The UCS resists the off-axis displacements and keeps the CS Module Stack aligned to the machine centerline.

TABLE II
MATERIAL PROPERTIES AT 4 K

Properties		G10	316LN	CS Winding pancake
Young's modulus (GPa)	E_x	12	206	57.9
	E_y	20	206	177
	E_z	20	206	57.9
Shear modulus (GPa)	G_{xy}	6	78.8	14.6
	G_{yz}	6	78.8	16.5
	G_{xz}	6	78.8	7.9
Poisson's ratio	ν_{xy}	0.33	0.3	0.205
	ν_{yz}	0.17	0.3	0.358
	ν_{xz}	0.33	0.3	0.205
Thermal contraction (%)	α_x	0.7	0.295	0.312
	α_y	0.246	0.295	0.295
	α_z	0.246	0.295	0.312
Density (kg/m^3)	ρ	1800	7900	7048

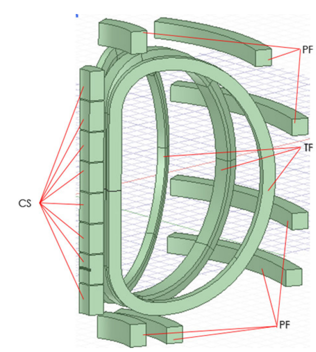


Fig. 4. Maxwell magnet model of CSMC.

III. Finite Element Analysis of CS

A. Material Properties Used in FEA

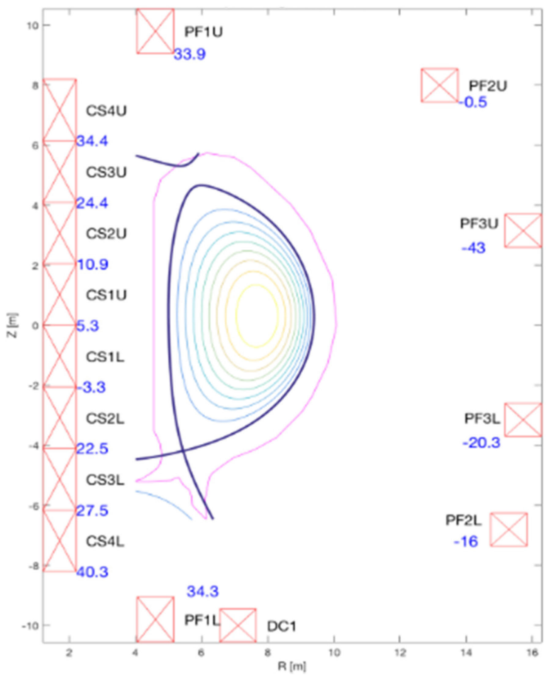
Based on the generalized Hooke's law, orthotropic smeared property used for CS winding pancake are calculated with one so-called 'unit cell' finite element model of the jacket and insulation [3]. Table II gives the material properties used in FEA.

B. Load Condition

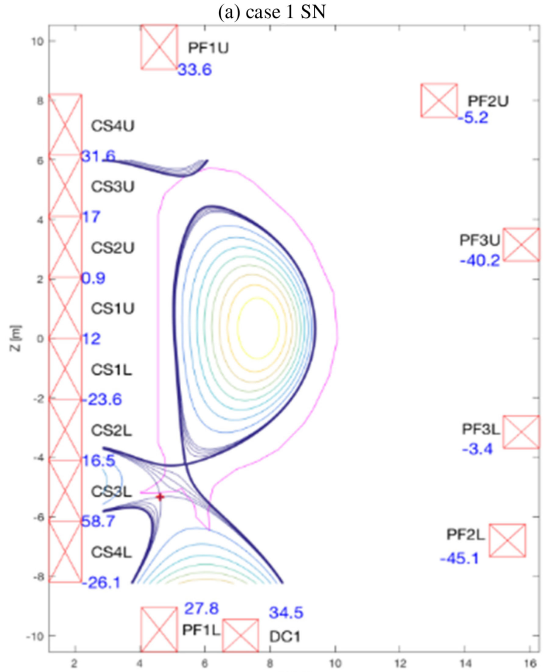
Four load conditions listed below had been considered.

- Weight.
- Initial preload, a total of 180 MN [4].
- Cool-down from RT (293 K) to 4 K.
- Electromagnetic load (SN and SF+).

According to the actual operating condition of the CS, the analysis was performed under three load cases. The first load case (G+P) contains gravity of CS and preload at RT after coil assembly. And then later the coils are cooled down from RT to 4K, so the second load case (G+P+T) contains gravity, preload and thermal load comes from cooling. The last load case contains (G+P+T+E) gravity, preload, thermal load and electromagnetic (EM) load at critical time. The EM load is calculated by the part EM model which consists of 45 °CS, TF and PF coil with Ansoft Maxwell as shown in Fig. 4.



(a) case 1 SN



(b) case 2 SF+

Fig. 5. Plasma equilibrium shape and conductor current (kA).

Up till now, two cases of CFETR is determined and the plasma equilibrium shape and coil current is shown in Figure 5. Two cases are used as the load to the EM model. Plasma current is not considered in the EM model.

C. FEA Model

To obtain the mechanical behavior for static assessment the global model has been created based on ANSYS as shown in Fig. 7. This global model consists of 8 CS modules (45 degrees), 7 PF modules (22.5 degrees), one TF module and a set of CS preload system. CS, TF and PF modules are modeled as smeared monoliths with orthotropic material properties. The node at the bottom surface of TF support has the prescribed displacement Ux = Uy = free and Uz = 0. The cyclic symmetry boundary conditions are applied at the surface of 0°, 22.5° and 45° plane. Sliding between insulating layers between modules has a friction coefficient of 0.3 [5]. The frictional contact type is used to contact surface in FEA. Pre-compression elements are used on the three tie plates.

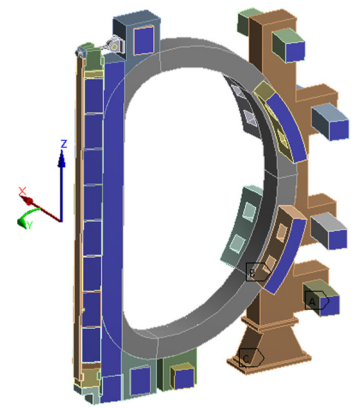
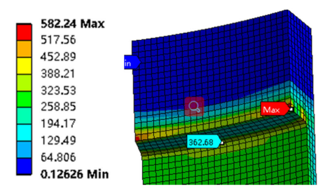
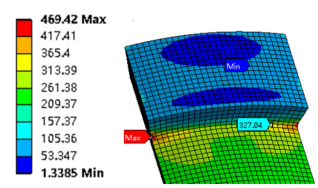


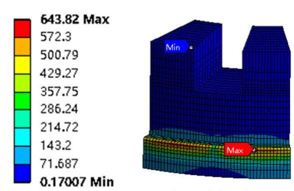
Fig. 6. Global FEA model.



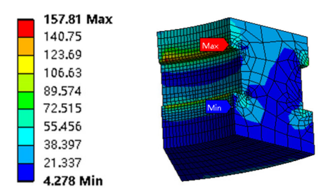
(a) Outer tie plate



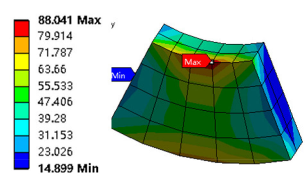
(b) inner tie plate



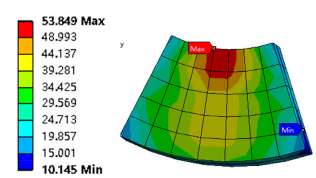
(c) Upper key block



(d) Lower key block



(e) Upper balance plate



(f) Lower balance plate

Fig. 7. Tresca stress of preload structure at G+P+T+SF+ / MPa.

IV. Result of 3D FEA

A. Design Code and Allowable Values

The allowable stresses according to CFETR CSMC design requirement within the construction are: Pm ⩽ 2/3*Sy, Pm+Pb ⩽ Sy, P+Q ⩽ Sy. Sy is yield strength at 4 K or RT, Pm is primary

TABLE III
ALLOWABLE VALUE OF SS 316LN AND 316L/MPa [6]

Item	SS 316LN	SS 316L
Sy at RT	600	170
Pm	400	113
Pm+Pb	600	170
P+Q	600	170
Sy at 4K	900	431
Pm	600	287
Pm+Pb	900	431
P+Q	900	431

TABLE IV
TRESCA STRESS ON THE PRELOAD STRUCTURE/MPa

Component/state	G+P	G+P+T	G+P+T+ SF+	G+P+T+ SN
Outer tie plate	450.4	298.8	582.2	294.7
Inner tie plate	443.2	357.5	379.9	379.9
Upper key block	494.5	328	643.8	325.8
Lower key block	127.3	95.1	157.8	95.7
Upper balance plate	58.6	54.8	88	53.9
Lower balance plate	63.2	38.9	53.8	38.9

membrane stress, Pb is bending stress and P+Q is the sum of primary stress and secondary stress. For the SS 316LN and SS 316L, the allowable values are shown in Table III. For G10, the allowable shear strength at 4 K is 40 MPa [7].

B. Preload Structure

The preload structure consists of outer tie plate, inner tie plate, upper key block, lower key block, upper balance plate, and lower balance plate. The stress intensity history of preload structure can be seen in Table IV and Fig. 7.

The maximum stress intensity at RT is 494.5 MPa and occurs in upper key block. P_m is 153.2 MPa, P_m+P_b is 339.4 MPa and P+Q is 494.5 MPa. Stress linearization shows that the stress level is below the criteria values for 316LN. The maximum stress occurs at last load case G+P+T+E and amounts to 643.8 MPa in the upper key block as shown in Fig. 7c. $P_m = 206.4$ MPa, P_m+P_b is 451 MPa and P+Q is 643.8 MPa.

According to the linearization stress analysis, SS 316L is suitable for balance plate and lower key plate. For tie plate and upper key block, SS 316LN is a viable option.

C. Support Structure

The stress intensity at 4 load case is 16.3 MPa, 16.7 MPa, 70.9 MPa and 16.4 MPa as shown in Fig. 8. The maximum stress intensity at RT is 16.3 MPa and occurs in bottom of trench. P_m is 11.7 MPa, P_m+P_b is 15.1 MPa and P+Q is 16.3 MPa. Stress linearization shows that the stress level is below the criteria values for 316L.

D. UCS

This connection allows relative vertical displacements and toroidal rotation between the CS and the TF coils by deformation of the tie rods while it keeps the assembly centered to avoid contact between the CS pre-compression structure and the TF coils.

The maximum stress intensity at G+P+T+SN is 219.3 MPa and occurs in the rod as shown in Fig. 9. P_m is 77.1 MPa, P_m+P_b is 189.2 MPa and P+Q is 219.3 MPa. The maximum stress intensity at RT is 211.7 MPa and occurs in the rod. P_m is 75 MPa, P_m+P_b is 182.7 MPa and P+Q is 211.7 MPa. Stress linearization shows that the stress level is below the criteria values for 316LN. SS 316L is suitable for the base according to the analysis result.

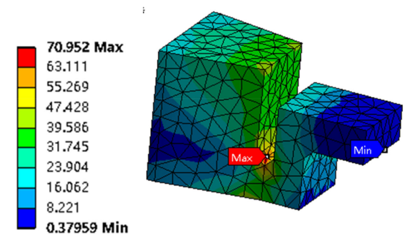
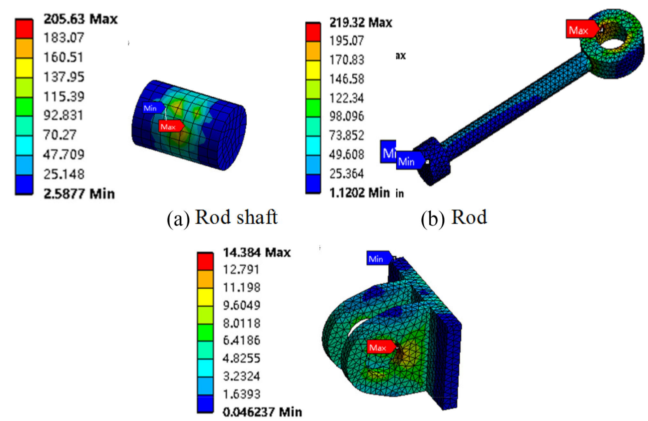


Fig. 8. Tresca stress of CS lower support at G+P+T+SF+ / MPa.



(a) Rod shaft (b) Rod

(c) Base

Fig. 9. Tresca stress of UCS at G+P+T+SN / MPa.

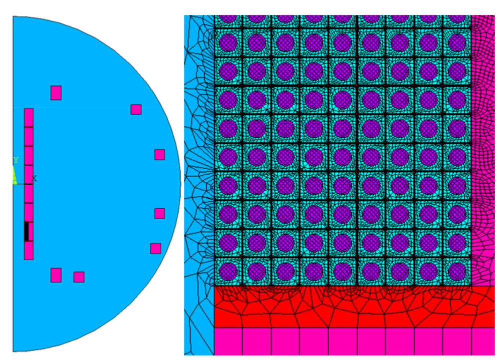


Fig. 10. 2D model with conductor in the CS2L.

V. CONDUCTOR STRESS ASSESSMENT

To get the stress on the conductor and insulation, a 2D FE model is established base on ANSYS as shown in Figure 10.

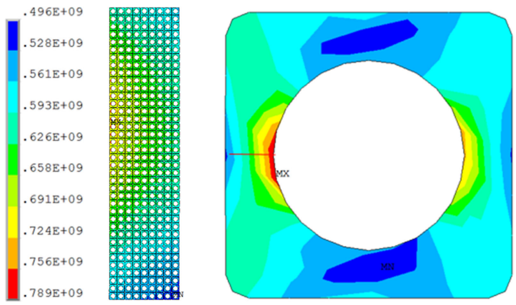


Fig. 11. Tresca stress on the Jacket under electromagnetic load / Pa.

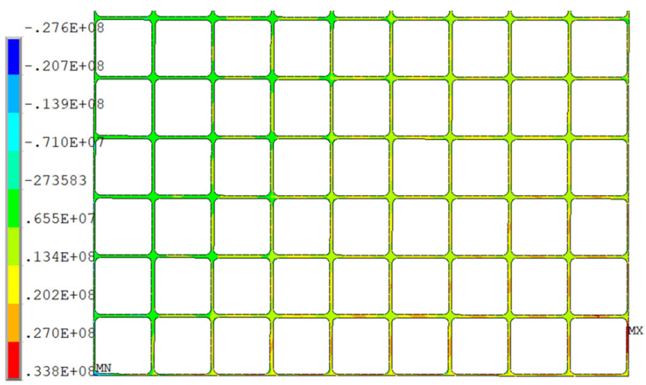


Fig. 12. Shear stress on turn insulation under electromagnetic load / Pa.

The model includes 8 CS coil and 7 PF coil. In the inner CSL2 module, the detailed winding model included jacket, insulation and cable are built by plane 53. Plane 53, which has 8 nodes, is usually used for magnetism-stress coupling analysis. Far field boundary condition is applied on the curve sided of air field. Average current of case 2 (SF+) is loaded in cable and winding pancake.

Max stress of jacket is 789 MPa as shown in Fig. 11. Stress linearization shows the Pm is 588 MPa and Pm+Pb is 769 MPa, and P+Q is 789 MPa. 316LN can meet allowable value but safety margin is small.

Figure 12 gives the shear stress of turn insulation and the maximum value is 33.8 MPa. So the turn insulation of conductor is safe.

VI. Conclusion

To investigate the structure safety and mechanical property of CFETR CS, a global 3D FEA model of the CFETR CS model coil under different load conditions which includes CS, PF, TF, preload structure, lower support of CS and UCS. Stresses in preload structure, UCS and CS lower support are acceptable based on statics analysis.

A 2D model is built to assess the conductor and insulation. The results show stresses in the jacket located in the peak magnetic field are acceptable. Shear stress in turn insulation located in the peak magnetic field are acceptable.

Structural assessment of CFETR includes the 4 types of analyses: static, fatigue S-N and/or LEFM, fast fracture, structural stability. After determining the number of plasma pulse operation cycle, other analysis of CFETR CS such as fatigue analysis will be carried out in detail in future work.

References

[1] K. Tomabechi, J. R. Gilleland, and Y. A. Sokolov, "ITER conceptual design," *Nucl. Fusion*, vol. 31, no. 6, pp. 1135–1224, Jun. 1991.

[2] Y. Wan, "Mission of CFETR," presented at the ITER Train. Forum 2nd Workshop MFE Develop. Strategy, Hefei, China, Sep. 2012.

[3] A. Xu, "Structural stress analysis of the CFETR central solenoid model coil," *IEEE Trans. Plasma Sci.*, vol. 46, no. 5, pp. 1512–1516, May 2018.

[4] K. D. Freudenberg, "ITER CS support structure analysis," *Fusion Eng.*, pp. SP2–38, 2011.

[5] R. Leonard Myatt, "ITER CS intermodule support structure," *Fusion Eng.*, pp. SP2–35, 2011.

[6] A. Xu, "Development of the helium inlet and outlet for the CFETR central solenoid model coil," *IEEE Trans. Appl. Supercond.*, vol. 28, no. 4, May 2018, Art. no. 4205705.

[7] H. Jin, "Mechanical properties of preliminary designed insulation for CFETR CSMC," *IEEE Trans. Appl. Supercond.*, vol. 26, no. 4, Jun. 2016, Art. no. 9001604.