Conceptual design of the CFETR TF coil with rectangular conductors

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1. Abstract

A Comprehensive Research Facility project was approved in Dec. 2018 with a funding of 345 million EUR, to support R&D of the China Fusion Engineering Test Reactor (CFETR). As part of this project, a full-size CFETR TF coil will be designed, manufactured and tested in the Institute of Plasma Physics Chinese Academy of Sciences. Two options are being explored in parallel, using either circle-in-square or rectangular CICC conductors. The rectangular conductors have been reported to have some merits for a DEMO TF coil, as considered by the EU-DEMO and K-DEMO. The TF coil is one of the most important coils, which defines the shape of tokamak, the major radius and the toroidal field. According to the most recent single-null configuration and radial build of CFETR, a conceptual design of the TF coil with graded rectangular CICC conductors has been presented. Electromagnetic analyses are performed to give the magnetic field distributions, toroidal field ripple, the in-plane and out-of-plane Lorentz loads. Following this, a 3D global and a 2D local mechanical analyses are conducted, which show the stresses and displacements of the TF coil are acceptable by referring to the ITER criteria. Our analyses have given valuable insight into the mechanical behavior of the CFETR TF coil system. The TF coil design will be updated in the future according to progress in the detailed design of the rectangular conductors.

2. WP design

The cross section of the WP and the magnetic field on cables are shown in Figure 1. The main parameters are listed in Table 1. The total number of turns is 154, the peak field is 14.7 T with a conductor current of 95.6 kA at 4.5 K.

In the high-field (14.7 T) and low-stress layers (L1 to L3), high-performance Nb3Sn CICC with a jacket thickness of 7 mm is employed. In the middle-field (10.8 T) layers (L4 to L8), ITER-like Nb3Sn CICC is used. In the low-field (5.3 T) and high-stress layers (L9 to L12), NbTi CICC with a 13 mm thick jacket is used.

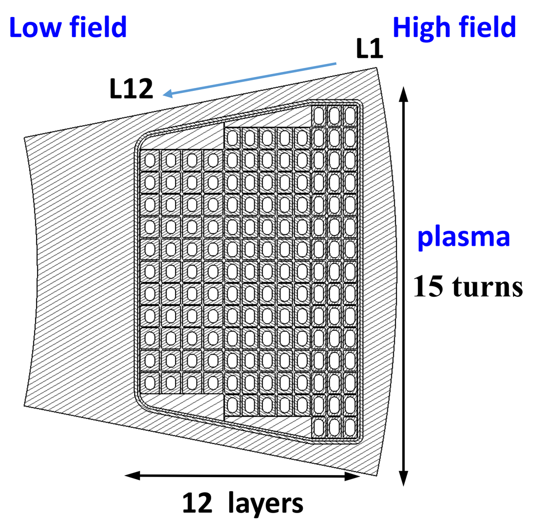

Figure 1. CFETR TF WP design

Table 1. CFETR TF WP design with graded rectangular conductors.

WP parameters	Grade-1 High-Perf. Nb_3Sn			Grade-2 ITER-like Nb_3Sn					Grade-3 NbTi			
Layer	L1	L2	L3	L4	L5	L6	L7	L8	L9	L10	L11	L12
Peak field (T)	14.7	13.4	12.1	10.8	9.8	8.8	7.8	6.5	5.3	4.3	3.3	2.2
No. of turns	15	15	15	13	13	13	13	13	11	11	11	11
Turn length (m)	43.3	43.7	44.0	44.3	44.7	45.1	45.4	45.8	46.2	46.6	47.0	47.4
Jacket ext. (mm)		46 × 70				52 × 70				58 × 70		
Jacket thk. (mm)		7				10				13		

3. Numerical model

The finite element EM analysis on a 2D / 3D model is performed with ANSYS. A 16-fold cyclic symmetry is applied in the analysis. Non-linear contact is considered between the coil case and insulations with a frictional factor of 0.3.

Material properties where 316 LN stainless steel for the coil case, support structures, conductor jackets, and G10 for insulations are defined. The calculated smeared properties of the WP are listed in Table 2.

For the structural behavior analyses the following load conditions are defined: (i) cool-down from room temperature to 4 K, (ii) energization of TF coil (TF-Only), (iii) middle of flattop (MOF)

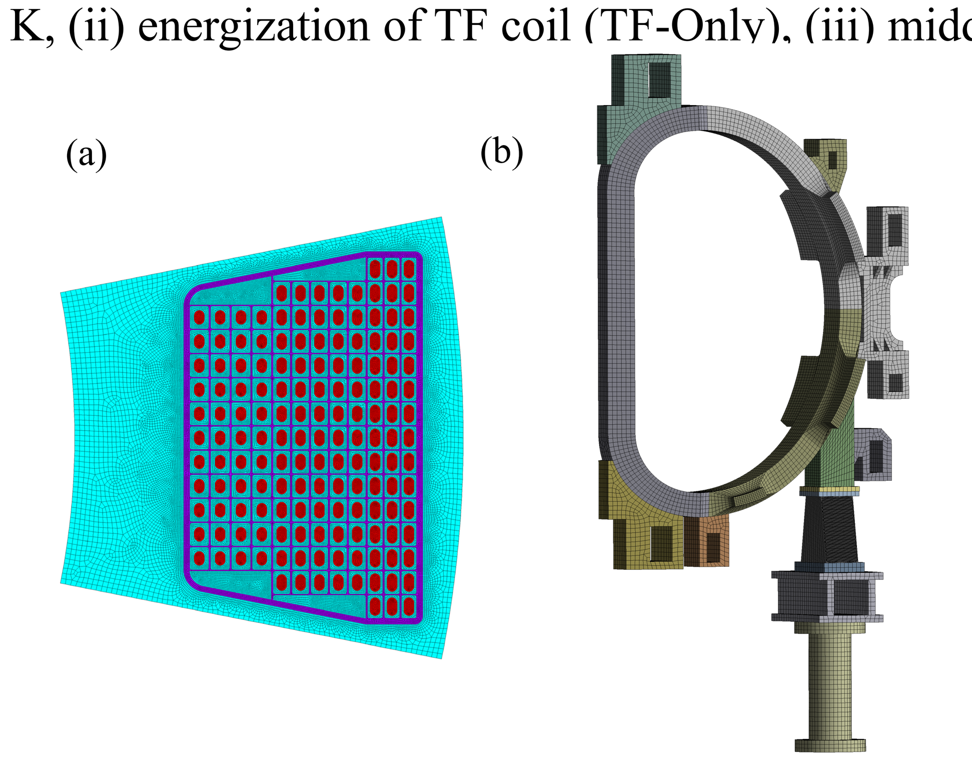

Figure 2. CFETR TF mesh: (a) 2D mesh and (b) 3D mesh.

Table 2. Calculated smeared properties of the TF WP.

Properties	High-field part	Mid-field part	Low-field part
E_x (GPa)	27.4	38.2	50.0
E_y (GPa)	89.9	110.0	126.3
E_z (GPa)	48.4	58.7	67.9
ν_{xy}	0.090	0.103	0.118
ν_{yz}	0.296	0.296	0.296
ν_{xz}	0.216	0.226	0.232
G_{xy} (GPa)	14.6	17.8	20.9
G_{yz} (GPa)	14.1	17.3	20.0
G_{xz} (GPa)	3.0	4.8	7.2
CTE_x (%)	0.339	0.335	0.330
CTE_y (%)	0.294	0.294	0.294
CTE_z (%)	0.316	0.316	0.316

4. Electromagnetic analyses

The magnetic field distribution computed with 3D global model is illustrated in Figure 9, where the peak field in the TF WP is 14.6 T compared to the 14.7 T obtained with 2D model. The resultant centering force is 1090 MN.

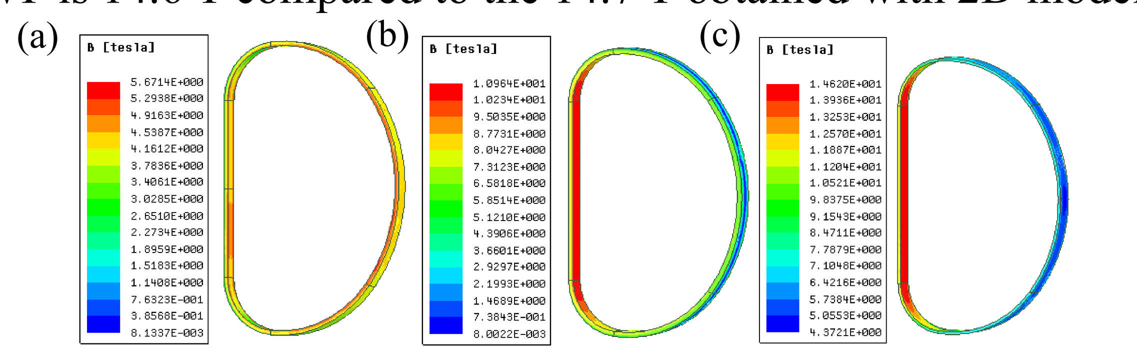

Figure 3. 3D Magnetic field at TF-Only: (a) Low-field WP B_{max} = 5.6 T, (b) Mid-field WP B_{max} = 10.9 T, and (c) High-field WP B_{max} = 14.6 T

Table 3. Field distribution on cables for 2D model.

Rectangular conductor WP_154	High-Perf. Nb3Sn			ITER-like Nb3Sn					NbTi			
	L1	L2	L3	L4	L5	L6	L7	L8	L9	L10	L11	L12
No. of turns	15	15	15	13	13	13	13	13	11	11	11	11
Peak field (T)	14.7	13.4	12.1	10.8	9.8	8.8	7.8	6.5	5.3	4.3	3.3	2.2

Table 4. Coils current at MOF

Coil	CS4U	CS3U	CS2U	CS1U	CS1L	CS2L	CS3L	CS4L
MA	11.548	8.807	1.155	-5.551	-10.56	-0.412	16.455	15.792
kA/Turn	15.648	11.933	1.565	-7.521	-14.309	-0.558	22.297	21.399
Coil	PF1U	PF2U	PF3U	PF3L	PF2L	PF1L	DC1	TF
MA	10.655	-1.373	-7.952	-2.152	-7.638	17.968	4.062	14.722
kA/Turn	27.747	-19.076	-36.145	-17.934	-38.192	46.792	18.466	95.6

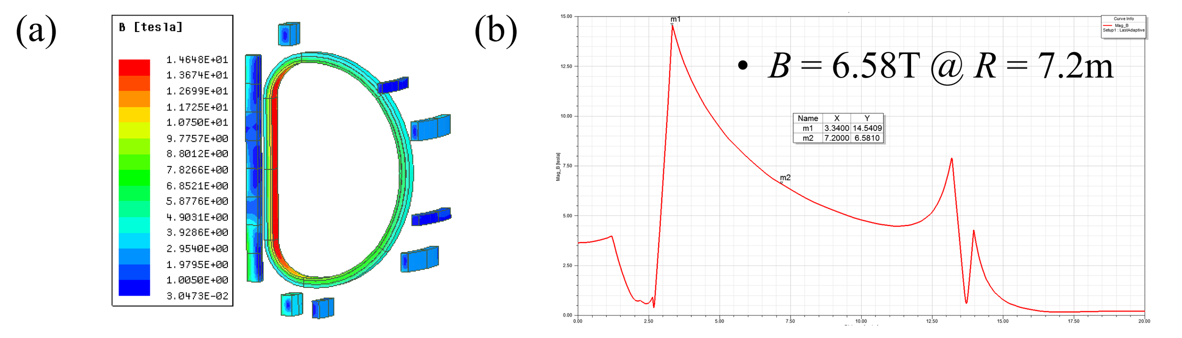

Figure 4. 3D Magnetic field at MOF: (a) B_{max} = 14.6 T at TF and (b) B_t =6.58T at R = 7.2 m.

5. 3D and 2D mechanical analyses

After cool-down from room temperature to 4 K, the maximum radial and axial displacement are -48.2 mm and -63.3 mm, corresponding to a 16.3 m radius and 21.7 m height of the TF coil system.

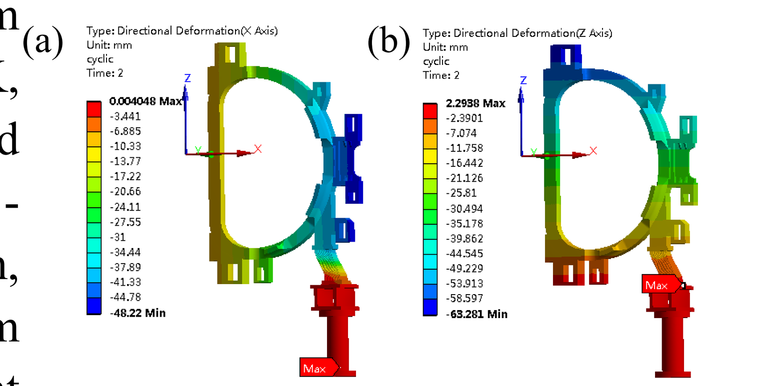

Figure 5. Displacement under cool down condition: (a) max radial displacement, (b) max axial displacement

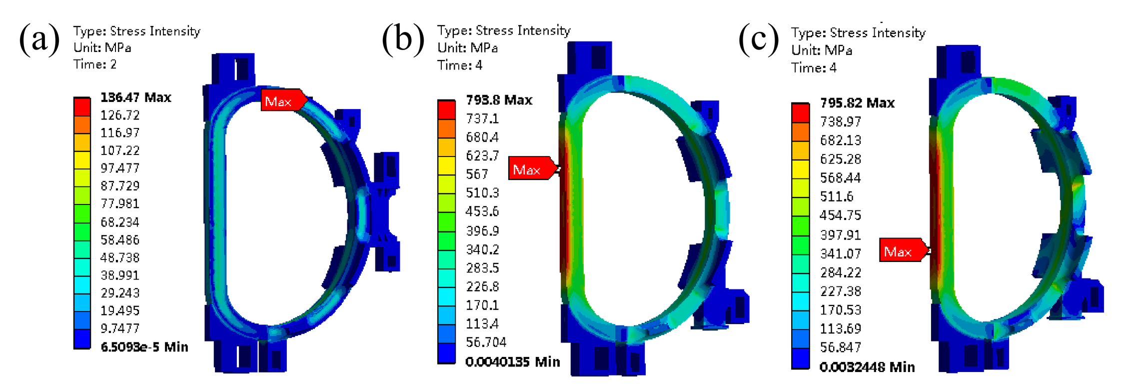

Figure 6. Stress intensity (MPa) distribution under the (a) cool down, (b) cool down + TF-Only , and (c) cool down +TF-Only + MOF.

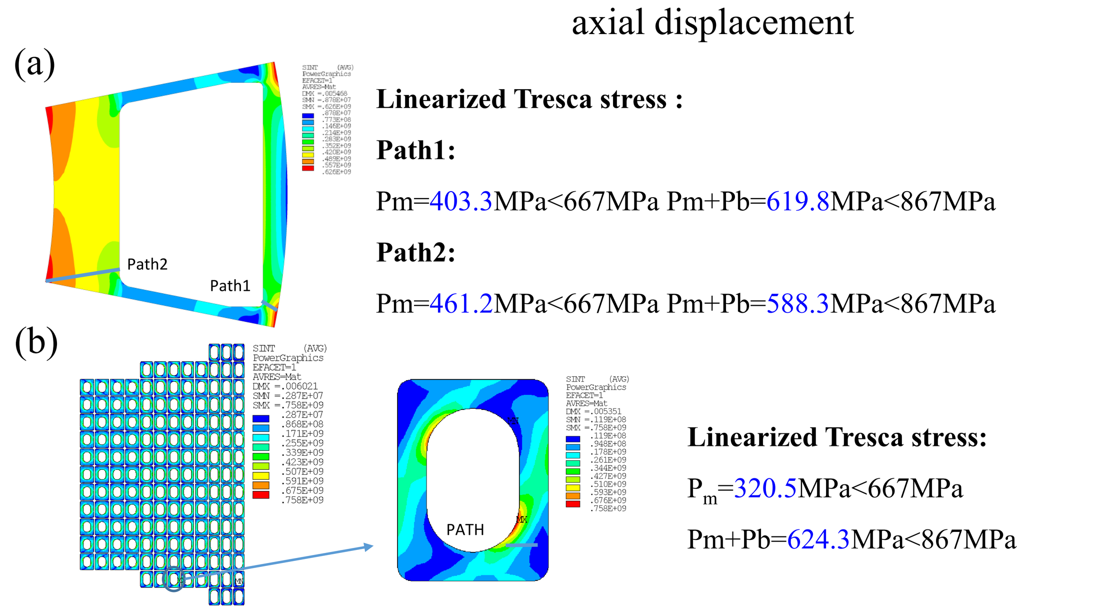

Figure 7. Linearized tresca stress: (a) TF case, (b) Conductor jacket

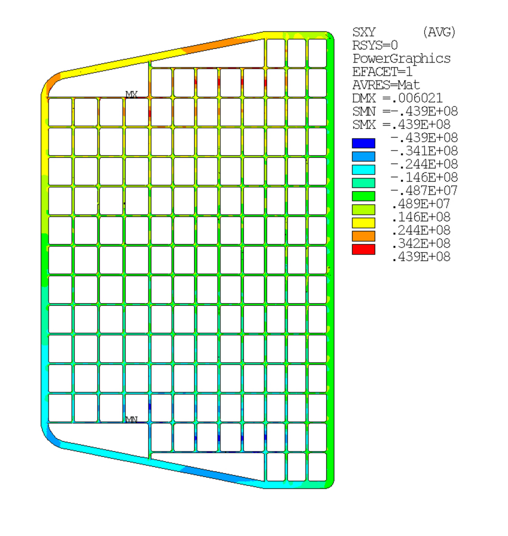

Figure 8. Shear stress on Insulations

In order to obtain information on the mechanical behavior of the TF conductor and insulations, a detailed 2D local mechanical analyses at TF-Only for the TFC inboard leg cross-section have been performed.

6. Conclusion

According to the updated design (R=7.2m, B_t=6.5 T, N=16) and radial build of CFETR, the conceptual design of the TF coil with graded rectangular conductors is conducted.

- Electromagnetic analyses show that the inductance is 34.9 H (2 times of ITER) and the stored energy is 159.6 GJ (4 times of ITER). The resultant centering force is 1090 MN/coil (2.7 times of ITER).
- The 3D global and 2D local mechanical analyses have been performed, the high stress regions have been identified as the inboard straight leg of the TF coil case and the lower curved region of the OIS structures.
- The mechanical behavior and the stress levels of the TF coil satisfy the ITER design criteria. Our structural assessment has given valuable insight into the mechanical behavior of the TF coil. However, the present design of CFETR TF coil still needs to be updated according to the detailed design of the rectangular conductors.