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ORIGINAL RESEARCH

Conceptual Design and Analysis of CFETR TF Coil

X. F. Liu[1] · J. X. Zheng[1] · H. Wu[1] · S. S. Du[1]

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Abstract China Fusion Engineering Test Reactor (CFETR) based on the Tokamak approach with superconducting magnet technology is envisioned to provide 50–200 MW fusion power and operate with a goal of an annual duty factor of 0.3–0.5. The reactor has the equivalent scale compared with ITER. The design of CFETR superconducting magnets is based on the magnet technology of ITER. The TF coils of CFETR are winded with Nb_3Sn cable-in-conduit conductor (CICC). The pure tension theory is used in the design of TF coil. This paper describes the design and presents the critical engineering parameters of CFETR TF coil.

Keywords CFETR · CICC · Superconducting magnet · Pure tension · Nb_3Sn

Introduction

CFETR is the abbreviation of "China Fusion Engineering Test Reactor" which means that the device is used to test and verify the feasibility of engineering and technology in practice for the future fusion reactor [1]. The goal of the design is to try to build the reactor for future energy as early as possible.

The missions of CFETR are as follows [2]:

(a) A good complementary with ITER
(b) Demonstration the fusion energy with a minim Pf = 50–200 MW
(c) Long pulse or steady-state operation with duty cycle time $\geq$0.3–0.5
(d) Demonstration of full cycle of T self-sustain with TBR $\geq$ 1.2
(e) Relay on the existing ITER physical and technical bases
(f) Exploring options for DEMO blanket and divertor with an easy changeable core by remote handling.

The main physics design parameters are listed in Table 1 [3].

CFETR has the comparative scale and the similar structure with ITER device. It is composed of the main components: vacuum vessel, inner thermal shield, toroidal field (TF) coils, central solenoid (CS) coils, poloidal field (PF) coils, outer thermal shield and cryostat. The elevation view of CFETR is shown in Fig. 1.

All the magnets of CFETR are superconductor magnets. The design of superconductor magnets is based on the ITER magnets technology. The magnets of CFETR include16 TF coils, 6 CS coils and 6 PF coils. In addition, there are another two PF coils (DC1 and DC2) at the bottom of the device to produce the snowflake and super-x equilibrium shape.

Pure Tension TF Coil

The instability of a superconducting coil may be interpreted in terms of stresses in the winding. Such instability is a troublesome problem, especially in a superconducting TF coil subject to strong bending moment due to electromagnetic forces. The superconductors with inter-metalic compound, which are particularly sensitive to stress, show instabilities such as current degradation and training effect, and sometimes suffer irreparable stress-cause damage [4].

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Table 1 Main physics parameters of CFETR

Central magnetic field, *Bt* (T)	4.5–5 T
Plasma current, I_p (mA)	8–10 mA
Large radius of plasma, *R* (m)	5.7 m
Minor radius of plasma, *a* (m)	1.6 m
Elongation ratio κ	1.8–2.0
Triangle deformation δ	0.4–0.8
Possible upgrade	R ~ 5.9 m, a ~ 2 m, $B_t = 5$ T, I_p ~ 14 mA

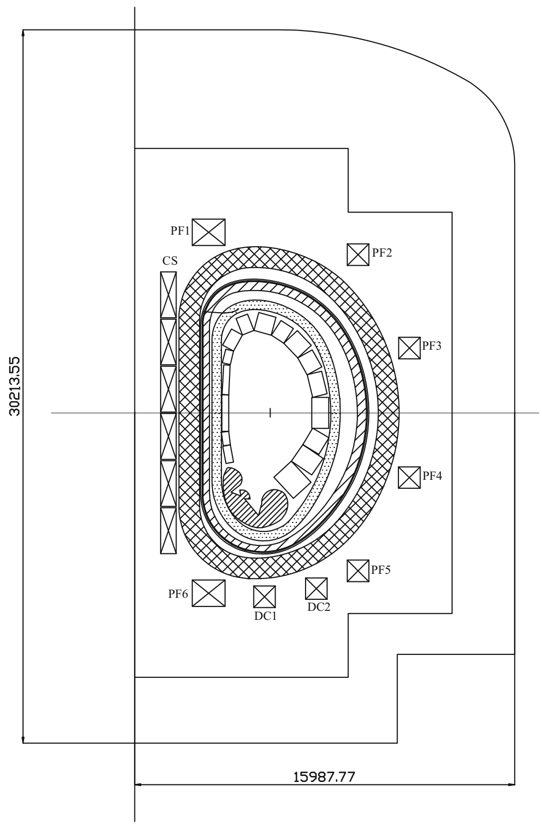


Fig. 1 The elevation view of CFETR

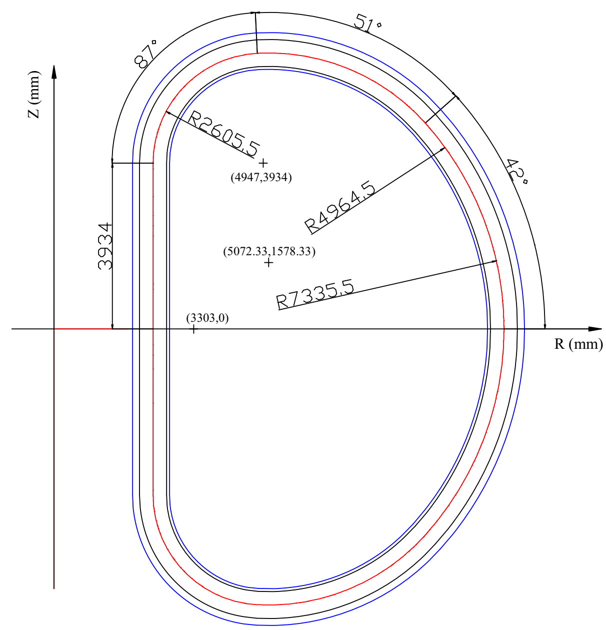


Fig. 2 The skeleton map of CFETR TF coil

So the reduction of stresses in a superconducting coil is very important.

File proposed that the shearing-force and bending-moment inside the coil can be zero (neglect the coil weight) if the shape of coil is reasonable. The curve of pure tension is derived from Eq. (1):

$$r\left(d_2r/dz^2\right) = \pm 1/k\left[1+(dr/dz)^2\right]^{3/2} \tag{1}$$

The curve generated by Eq. (1) describes the shape of a conductor lying in a TF which inversely with the radius from the axis of the torus. In order to have the 1/r field distribution, the torus shall be continual that there must be small gaps or none at all between coils. But in practical coil system must necessarily be made up of a number of discrete coil segments for access to the useful volume, as well as for ease of manufacture. So the Eq. (1) shall be modified.

Boris and Kuckes have derived the expressions of toroidal magnetic field for a system composed of n coils. At $\theta = 0$, The B_θ is [5]:

$$B_\theta = 1/kr\left\{1 - \frac{\left[(r_1/r)^{2n} - (r_1/r)^n\right]}{\left[1-2(r_1/r)^n + (r_1/r)^{2n}\right]} - \frac{\left[(r/r_2)^{2n} - (r/r_2)^n\right]}{\left[1-2(r/r_2)^n + (r/r_2)^{2n}\right]}\right\} \tag{2}$$

File modified the Eq. (1) based the Eq. (2):

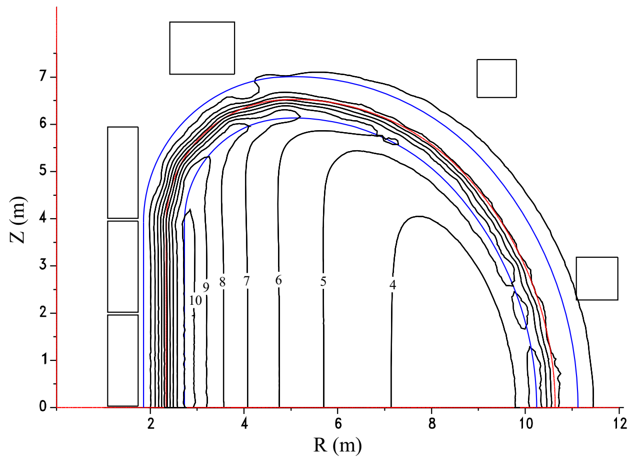


Fig. 3 The magnetic field distribution of TF coil

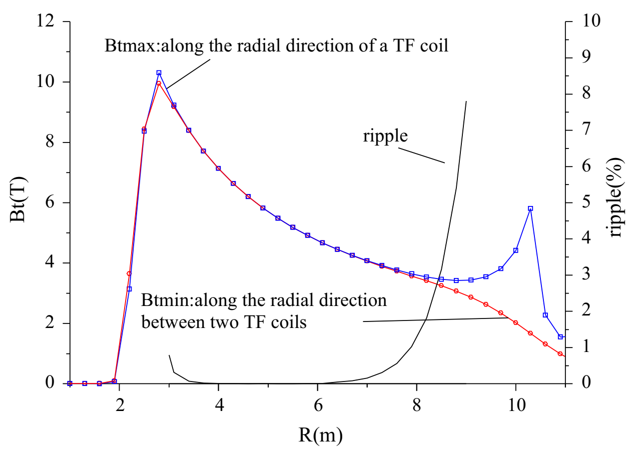


Fig. 4 Magnetic field and ripple distribution along radius in middle plane

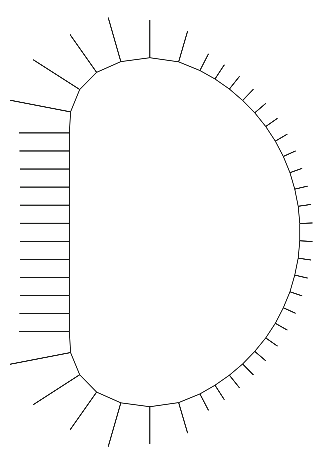


Fig. 5 Certral force distribution of TF coil

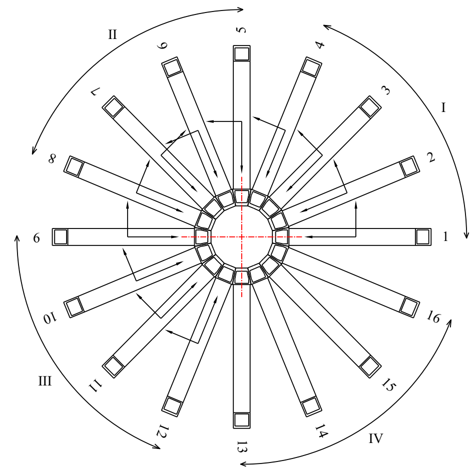


Fig. 6 The group number of TF coils

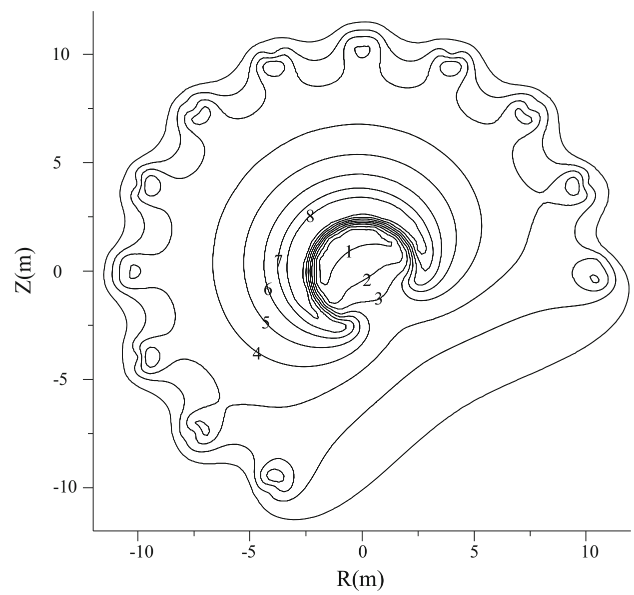


Fig. 7 Magnetic field distribution in the abnormal operation

$$r\left(d_2r/dz^2\right) = \pm 1/k\left[1 + (dr/dz)^2\right]^{3/2} \left\{1 - \frac{\left[(r_1/r)^{2n} - (r_1/r)^n\right]}{\left[1 - 2(r_1/r)^n + (r_1/r)^{2n}\right]} - \frac{\left[(r/r_2)^{2n} - (r/r_2)^n\right]}{\left[1 - 2(r/r_2)^n + (r/r_2)^{2n}\right]}\right\} \quad (3)$$

Numerical solution of Eq. (3) by computer codes can generate the curve. For CFETR TF system, $r_1 = 2.34$ m, $r_2 = 10.64$ m, n = 16. For manufacture easy, the pure tension curve should be fit by arc and straight line. The fitted curve of TF coil is shown in Fig. 2.

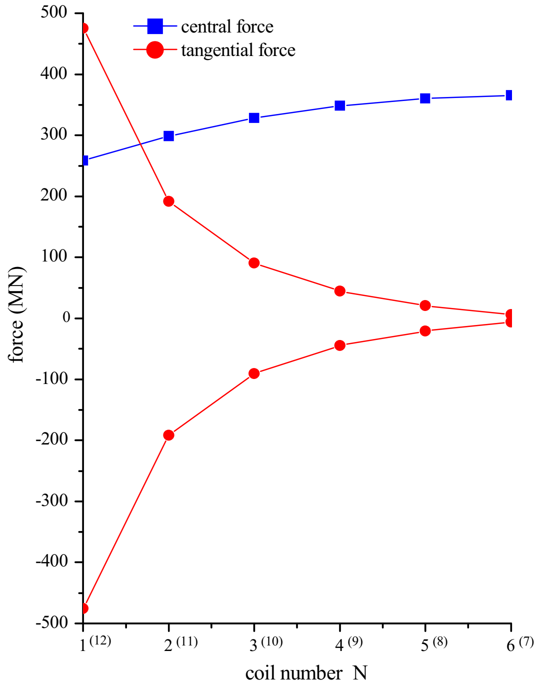


Fig. 8 Central force and tangential force varies with the fault group amount

Table 2 The maximum central force and maximum tangential force with different fault group amount

Total number fault group amount	Maximum central force (MN)	Maximum tangential force (MN)
0	417	0
1	366	475
2	292	496
3	159	451

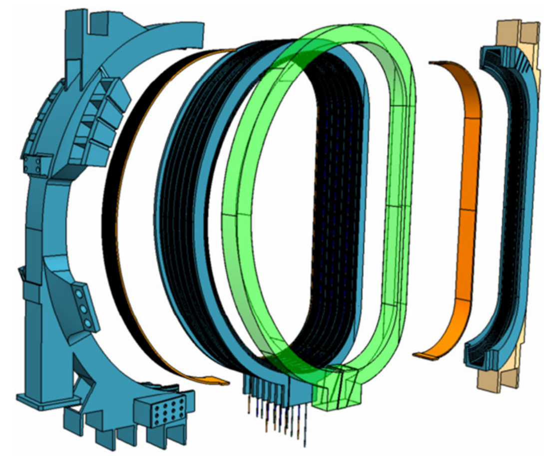


Fig. 10 The structure of CFETR TF coil

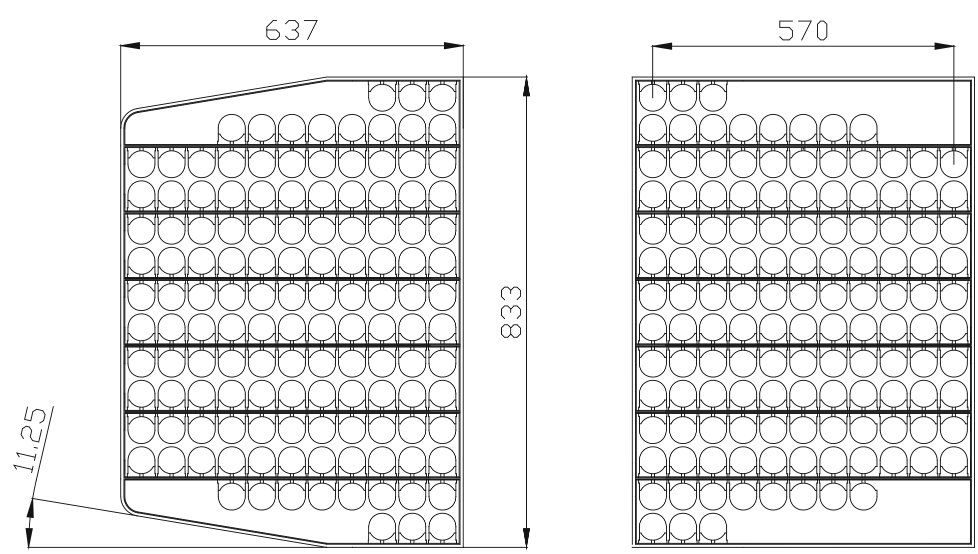
Electromagnetic Analysis of TF Coil

The toroidal magnetic field is produced by a set of 16 D-shaped Nb_3Sn superconducting coil, and each coil consists of 132 turns cable-in-conduit conductor (CICC). The physics design requires that the TF coil can provide 5.0 T at the center of plasma and the ripple of plasma area is limited within 0.5 %. Magnetic field map of the TF coil based on the operating current of 67.5 kA is shown in Fig. 3, where the maximum field in TF coil is about 10.4 T. The distribution of ripple and magnetic field along radial direction in the middle-plane are shown in Fig. 4 that the maximum ripple is about 0.3 % at the boundary of plasma.

The total inductance of TF system in CFETR is 15.75 Henry, so the total stored energy of TF system is 35.88 GJ.

Under the normal operation, the electromagnetic load in the 16 TF coils is same. Each TF coil has vertical force and no tangential force (not considering the magnetic field

Fig. 9 The cross section of CFETR TF coil



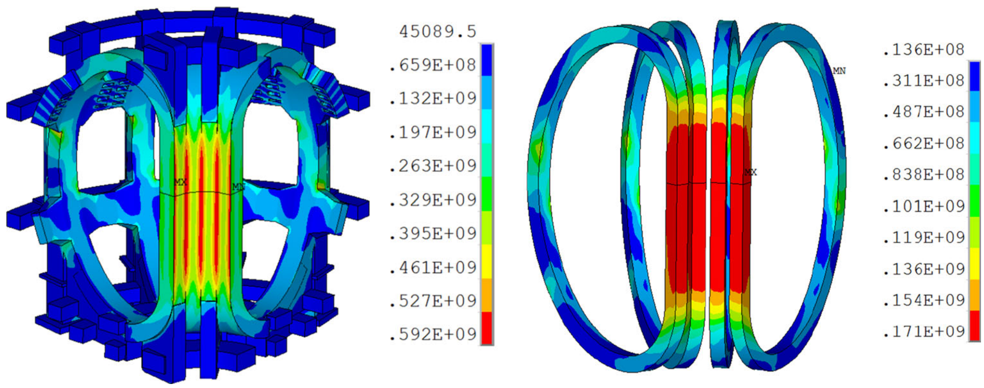


Fig. 11 Von-Mises stress distribution of TF system

produced by PF coil and plasma), just shown in Fig. 5. And the integration force is central force about 417 MN.

But under the abnormal operation, the symmetrical force system is become unbalance [6]. The tangential force will appear. Considering the operation safe and maintenance facility, the 16 TF coils are divided as 4 groups with each group has the 4 coils in series, just shown in Fig. 6.

Assume that one group (for example group IV) has fault with no current and the other three groups has normal operation with the current is 67.5 kA. The distribution of magnetic field is not symmetric which is shown in Fig. 7. The magnetic field at the center of plasma is uneven with the value from 1.8 to 4.6 T. And the maximum magnetic field in the coil is about 10 T.

When a group of coils has fault, the rest of coils with large tangential force extrude each other make that the coil adjacent the fault coil has the largest tangential force and the coil far away the fault coil has the smallest tangential force. The distribution of central force is just the opposite. The tangential force and central force of different coil is shown in Figs. 6 and 8.

Table 2 gives the maximum central force and tangential force with different fault group amount. The maximum central force decreases with the increases of fault group amount while the maximum tangential force depends on the distance between the two coils at the edge. The longer the distance, the larger the tangential force.

Structure Analysis

The structure of CFETR TF coil is similar to the ITER's structure. Figure 9 shows the cross section of CFETR TF coil.

The structure of TF coil is shown in Fig. 10. The obvious difference with ITER is that the middle-top part of TF case is block structure not the wing-type structure of ITER. The reason is that the top port of vacuum vessel is larger than ITER, so the support between two TF coils should be reinforced.

The result of structure analysis with coupling the gravity load, electromagnetic load and other loads is shown in Fig. 11. The maximum Von-Mises stress on TF case and winding are 592 and 171 MPa, respectively. The results show that the design of TF coil is safe.

Conclusions

The conceptual design and analysis of CFETR TF system is agoing. The physics aim for TF system is that it should provides 5.0 T magnetic field at the center of plasma with the ripple is <0.3 %.

The design of CFETR TF coil is based on the ITER superconducting magnet technology. The TF system is composed of 16 identical D-shape coils with Nb_3Sn superconductor and 4.5 K operation temperature.

Pure tension theory is applied to the design of TF skeleton map. For manufacture convenience, arc and straight lines are used to fit the pure tension curve.

Electromagnetic analysis of normal operation shows that the TF coils can generate the 5.0 T magnetic field at the center of plasma with the operation current is 67.4 kA. The maximum ripple at the edge of plasma is about 0.3 %, which meets the physics design requirement. In the abnormal operation, the tangential force in TF coil appears. The analysis result shows that the maximum central force decreases with the increases of fault group amount while the maximum tangential force depends on the distance between the two coils at the edge. The longer the distance, the larger the tangential force.

The results of structure analysis show that the maximum Von-Mises stress on TF case and winding are 592 and 171 MPa, respectively.

All the results in this paper are the preliminary analysis results and should be adjusted with the further development of TF system design.

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