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Preliminary design and analysis of the CFQS supporting structure

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Abstract

The Chinese First Quasi-axisymmetric Stellarator (CFQS) is now under design and construction. It will be the first quasi-axisymmetric (QA) configuration device to be operated in the world. The main parameters of the CFQS are as follows: the toroidal periodic number $N_p = 2$, major radius R=1.0 m, aspect ratio A_p=4.0 and magnetic field strength B_t =1.0 T. The low A_p makes it quite challenging to design a supporting structure because of the limited space and strong electromagnetic (EM) force. In this paper, a cage-like supporting structure is proposed for the CFQS modular coil (MC) system to sustain the EM force and the weight of entire device. A finite element analysis is carried out for ensuring the reliability of the supporting structure. The analysis results of the CFQS global model indicate that the cage-like supporting structure can basically satisfy the requirement.

Key words: Stellarator, Quasi-axisymmetric, Modular coils, Finite element analysis.

1. Introduction

Stellarator and tokamak are two major types of magnetic confined fusion devices. The stellarator is potentially a good type of fusion reactor, because it has better property in steady-state operation and magnetohydrodynamic (MHD) stability compared to the tokamak [1]. However, there are also some disadvantages in the stellarator such as high level neoclassical transport and technical complexity, etc.

To improve the confinement properties in stellarators, various optimized stellarator configurations have been proposed in the past few decades, including quasi-helical symmetric, quasi-poloidal symmetric, quasi-axisymmetric (QA) and quasi-isodynamic configurations. These advanced stellarators offer reduced neoclassical transport and stable magnetohydrodynamics (MHD) properties in comparison with conventional stellarators and helical devices. Up to now, only two types of optimized stellarators have been constructed in the world: one is the Helically Symmetric eXperiment (HSX) which is designed as a quasi-helical symmetry device and the other is Wendelstein 7-X (W7-X) which is designed as a quasi-isodynamic device [2-5].

Since the concept of optimized stellarators has many potential merits, fusion scientists in China consider to build an optimized stellarator for promoting research activities in stellarator science. To this end, Southwest Jiaotong University (SWJTU) in China and National Institute for Fusion

Science (NIFS) in Japan reached an agreement to jointly construct a QA device called Chinese First Quasi-axisymmetric Stellarator (CFQS), which is now under construction and would be the first QA experimental device in the world [6-9].

The CFQS is designed based on CHS-qa configuration [10,11]. The major parameters of CFQS are chosen as follows: the major radius is 1 m, the average minor radius is 0.25 m, the aspect ratio (A_p) is ~ 4.0, the magnetic field strength (B_t) can be increased up to 1.0 T and the toroidal periodic number is 2, respectively [12]. The complicate QA magnetic field configuration will be generated by a modular coil (MC) system (16 coils with 4 different shapes), which is depicted in Figure 1.

In order to ensure the reliability of the device, a strong support structure is required for protecting the MC system from displacement and deformation caused by heavy electromagnetic (EM) load. From the engineering point of view, the low-A_p and narrow space between two adjacent coils will increase the difficulty for designing the supporting structure and assembling the device. This paper presents the preliminary design scheme of the supporting structure of the CFQS, and meanwhile, describes several critical issues for designing a low-A_p QA stellarator.

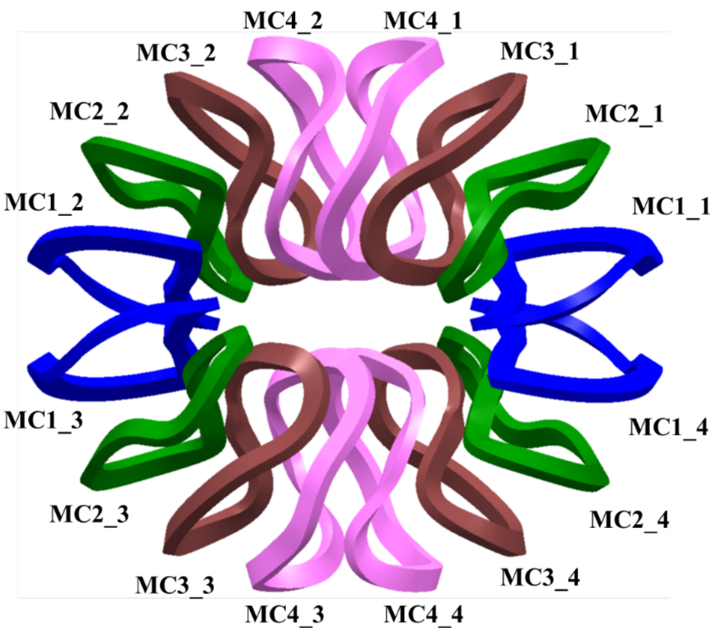


Figure 1. Top view of 16 CFQS MCs.

2. CFQS coil system and electromagnetic force analyses

2.1 CFQS modular coil system

As depicted in Figure 1, there are four different types of MC in CFQS with 4 coils for each type [13]. The detailed parameters of MCs are listed in Table 1.

Figure 2 shows the magnetic field strength on each coil in the operation status. In this figure, the distribution of the magnetic field strength on each coil is not uniform, and the magnetic field strength on the inboard side is larger than on the outboard side. The maximum magnetic strength reaches about 2.2 T, which is located on the inboard side of MC3. It is clearly seen that the distribution of the EM force is irregular on MCs during the machine operation.

Table 1. Parameters of MCs in CFQS.

Coil type	Amount	Number of conductors	Cross section of conductor (mm^2)	Current density (A/m^2)	One turn current (kA)	Coil current (kAT)	Total current (MAT)
Modular coil	16 in four groups	72 turns in series	58.825	7.378×10^7	4.34	312.5	5

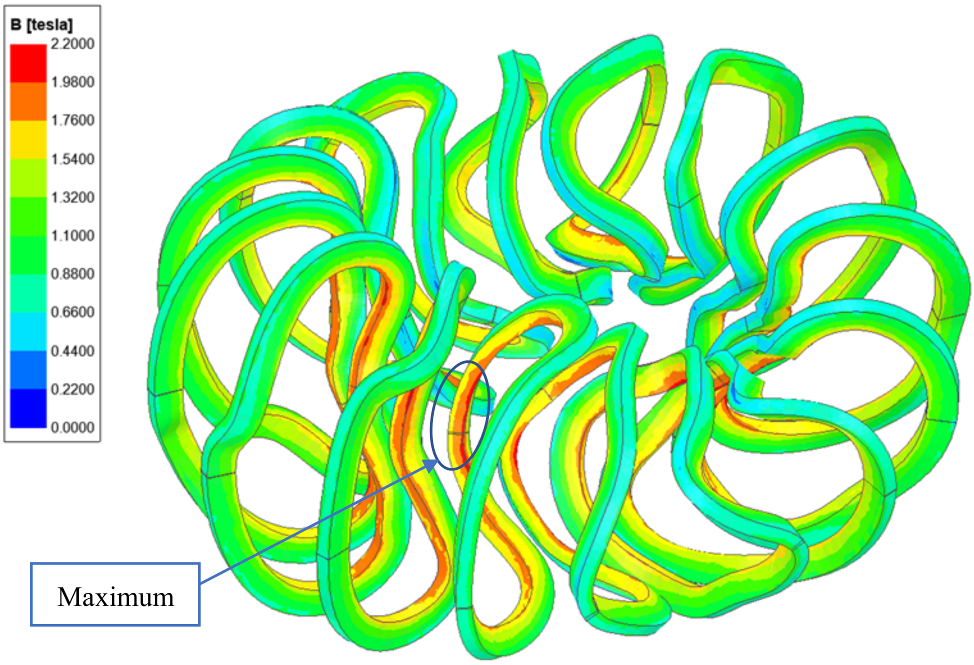


Figure 2. Magnetic field strength on modular coils.

2.2 Electromagnetic force analyses on CFQS MC system

For the design of the supporting structure, the most important issue is to understand the main load applied on the target system. In our case, the main load is the EM force on MCs. Therefore, the evaluation of the EM force is necessary. In this paper, the EM force distributions on the MCs are evaluated by the finite element analysis software ANSYS/Maxwell ™, which is applied in designing work of CFETR and ITER [14,15]. The calculation model is shown in Figure 3(a). In this model, an air box is used for limit the calculation region, and the boundary condition is that the magnetic field strength outside the box is ignored. The EM force distributions on different type of MCs are shown in Figure 3(b). The results indicate that the EM force are larger on the high-field side of the MCs.

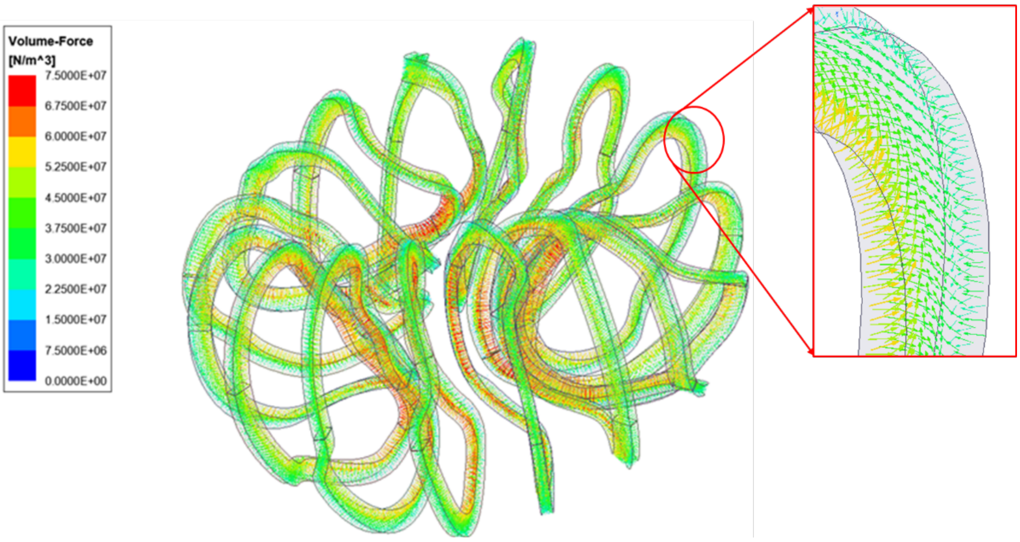


Figure 3. EM force distributions on CFQS MCs.

In order to make it easy for predicting the behavior of coils through the result depicted in Figure 3, the EM forces on MCs are roughly divided into centripetal (radial), toroidal, and vertical components based on a cylindrical coordinate system (see Figure 4). Different force components on the MCs are summarized in Table 2. It can be seen in Table 2 that the centripetal components on MC1, MC2, and MC3 are large and the vertical components are also large on MC2 and MC3, while the toroidal force components are relatively small on all MCs, respectively. Therefore, strong supports are required to resist the centripetal and vertical components, and also, corresponding supports must be adopted for the toroidal components.

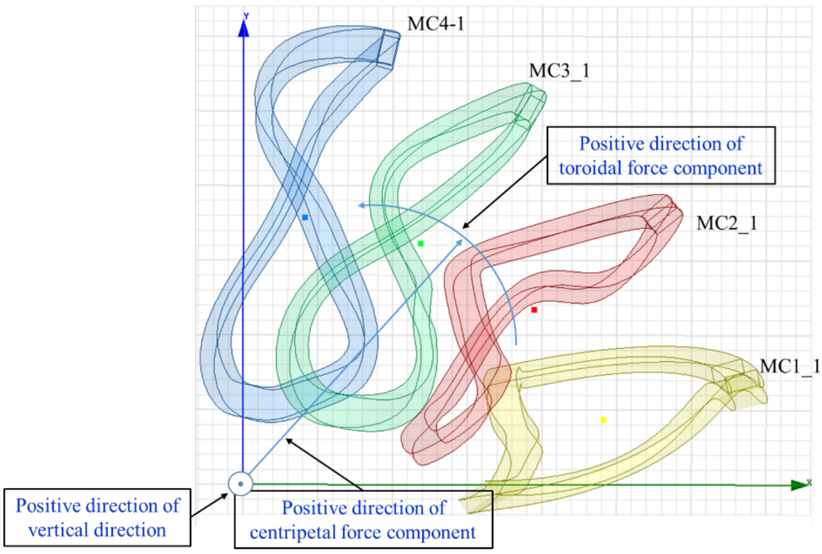


Figure 4. Definition of different EM force components.

Table 2. Different force components on MCs.

Coil name	Centripetal force	Vertical	Toroidal

	(N)	force (N)	force (N)
MC1_1	-167050	-19396	-13066
MC1_2	-167050	19393	13068
MC1_3	-167050	-19408	-13070
MC1_4	-167030	19401	13046
MC2_1	-142390	-60467	-37651
MC2_2	-142390	60463	37657
MC2_3	-142390	-60469	-37687
MC2_4	-142370	60470	37674
MC3_1	-94524	-92567	-37910
MC3_2	-94517	92568	37944
MC3_3	-94495	-92588	-37915
MC3_4	-94490	92559	37925
MC4_1	-39344	-38238	-45916
MC4_2	-39327	38242	45912
MC4_3	-39333	-38232	-45893
MC4_4	-39361	38243	45900

3. Design of the CFQS support structure

There are several issues we should pay attention to in our design work. At first, the center area is rather limited and strong supports are required for resisting the large EM force. Secondly, the minimal gap between two neighboring coils and the gap between coils and the vacuum vessel are quite small. This means that the size and shape of support elements must be appropriate for leaving spaces for future assembling of the device. Thirdly, the working space for installing plasma diagnostics and heating facilities must be spacious enough.

Considering about the above issues, a cage-like supporting structure has been designed with two main components, i.e., the supporting frame and coil supports. An overview of the supporting structure of the CFQS device is shown Figure 5, and the parts of the support structure are listed in Table 3.

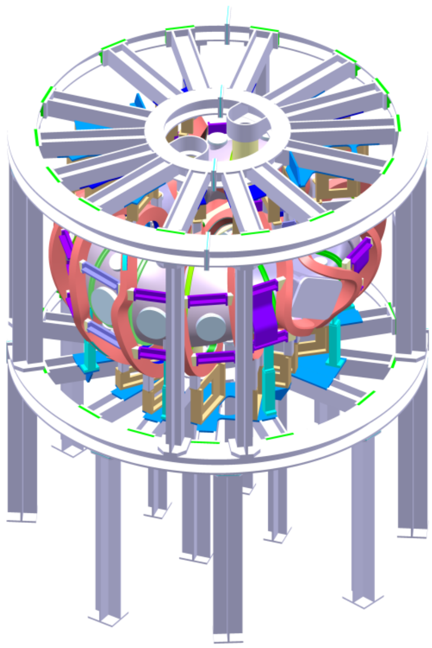


Figure 5. Overview of the supporting structure of CFQS.

Table 3. List of parts in the supporting structure.

Supporting Frame	
Top/Bottom support	2 outer support rings
	2 inner support rings
	14 radial beams
	10 stainless plates
Center support	2 center columns
	10 support elements
	2 H-shape beams
	2 additional MC4 link bars
Outer pillars	8 outer pillars
Base legs	12 base legs
Coil Supports	
Coil cases	16 coil cases (with legs)
Link bars	48 link bars

3.1 Supporting frame

The supporting frame consists of one top support, one bottom support, one center support, twelve base legs and eight outer pillars. The details of the top/bottom support structures are shown in Figure 6.

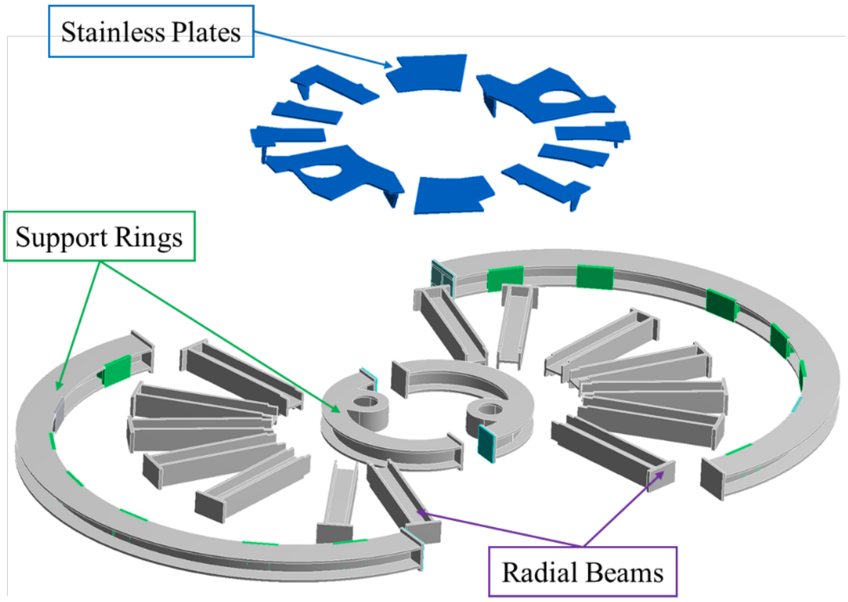


Figure 6. Detailed structure of top/bottom supports.

The top/bottom supports are used to resist the vertical EM force components, and to support the coil cases and the vacuum vessel. These supports consist of fourteen radial beams, four support rings and ten stainless plates. Four support rings and fourteen radial beams form the main body of the top/bottom supports. Ten stainless plates are used to provide required structure for fixing the coil cases on the top and bottom. These stainless plates are cut into special shapes in order to leave space for the installation of diagnostics or other facilities on the vacuum vessel.

The center support plays a key role in supporting centripetal EM force components. Here, the center support is formed by two solid columns, two connecting beams and several other support elements. All winding packs (with coil cases) will be connected to the center column through other support elements and two H-shape beams are set between the columns in order to strengthen them. In the design of the center support, a special structure is created for MC4s. Due to the complicate shape of MC4s, it is not sufficiently strong to support the MC4s by only connecting them on the center column. Therefore, two additional link bars are added to connect two MC4s together so as to partially cancel the centripetal force components. The center support is shown in Figure 7. In this figure, the relationship among the center support, coil cases and the bottom support are also illustrated. In addition, a special design for assembling the center support will be discussed in section 3.3.

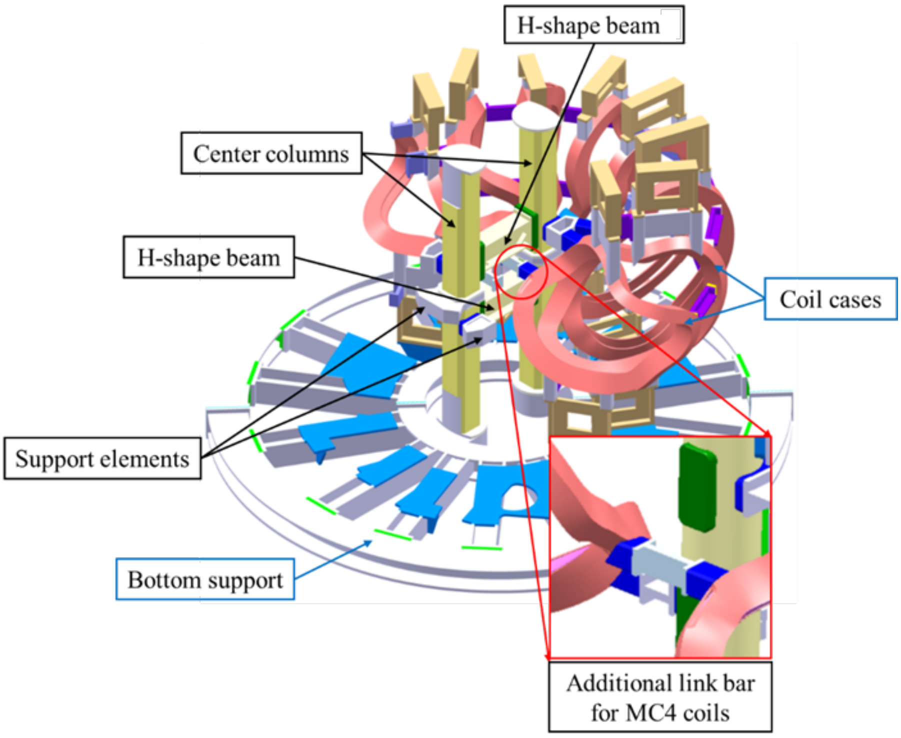


Figure 7. The central supporting structure of the cage-like support.

As for the eight outer pillars and twelve base legs, they are set for the connection of top/bottom support, and to fasten the device on the ground of experiment hall.

3.2 Coil supports

In CFQS, since the shapes of MCs are complicated and the space for the supports is quite limited, the use of the coil cases and 48 link bars to support MCs appears to be necessary. In our case, a 'U' shape coil case is designed for satisfying the assembly process, and for simplifying the manufacturing process. The cross section of the 'U' shape coil case is shown in Figure 8.

The coil cases will be fabricated by welding one 'L' shape shell and one lid, whose size is slightly larger than the cross section of the MCs. The thickness of the coil case is 10 mm for MC1, MC2 and MC3 coils. For MC4 coils, the thickness is increased to 13 mm to avoid large deformation. Besides, some Fiber Reinforce Plastic (FRP) spacer should be inserted into the case to fill and adjust the gap between winding packs and coil cases. The length of the gap is currently set as 5 mm to meet the future assembly process.

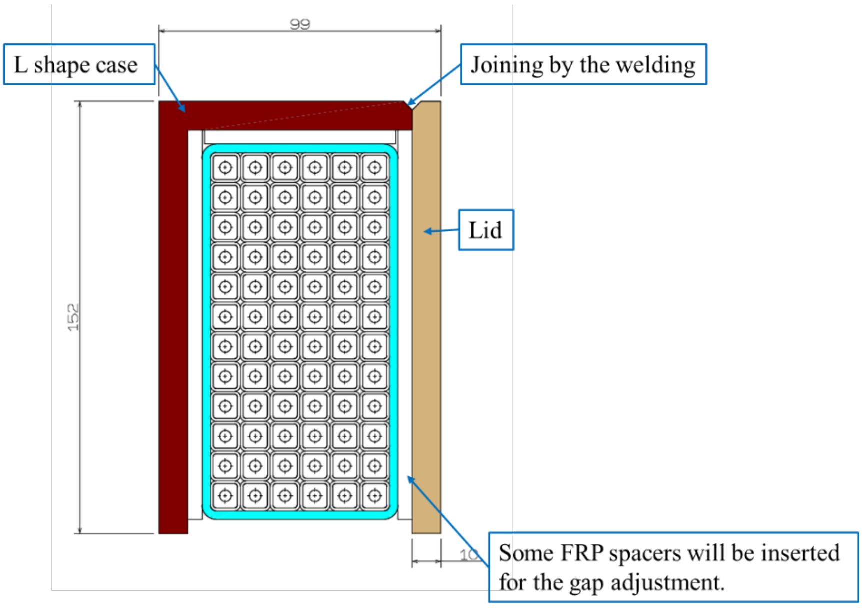


Figure 8. Design of the ‘U’ shape coil case.

The detailed design of coil supports is shown in Figure 9. Because of the irregular shapes of coil cases, it is almost impossible to directly connect them onto the supporting frame. Thus, some auxiliary parts are added on coil cases, such as coil legs and central/side connection elements. The coil legs are used to fasten coil cases on the top/bottom plates, in addition, some holes are cut on coil legs and coil cases for setting diagnostics cables and power leads. Connection elements can provide flat regions for connecting the coil cases on the supporting frame via link bars and support elements, then the whole device can be formed as a ‘cage’.

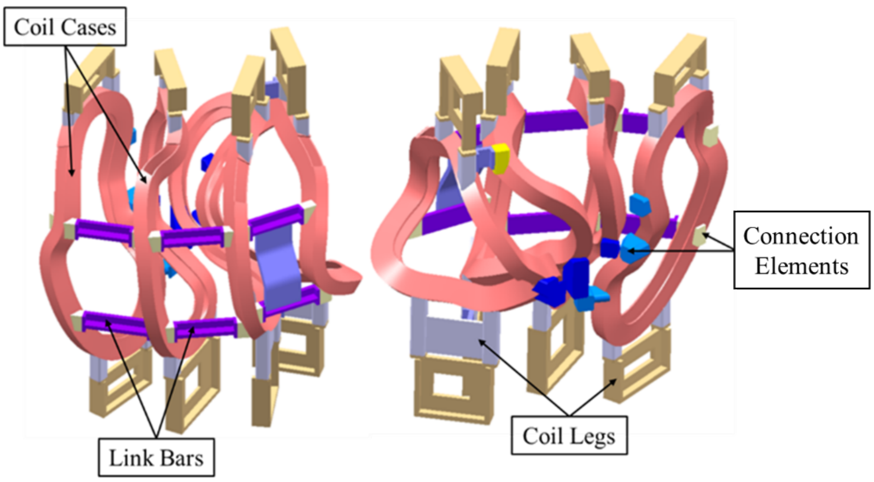


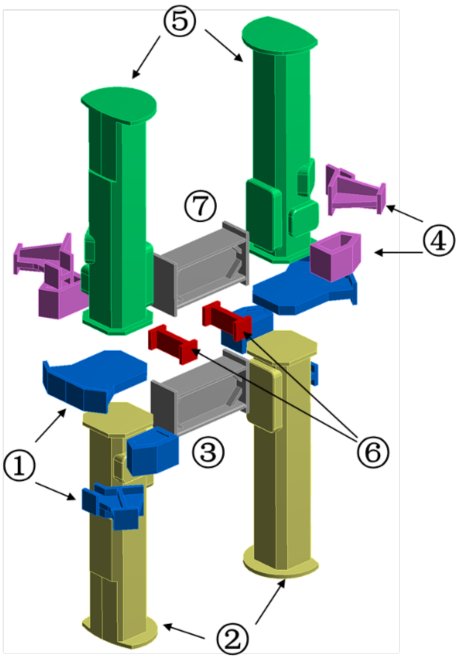
Figure 9. Detailed structure of coil supports.

The link bars can help MCs to resist the EM force and reduce deformation of MCs with their ‘I’ or ‘T’ shape cross-section. To avoid interference between the link bars and large diagnostic ports, the positions of the link bars are selected far away from the mid-plane of the vacuum vessel. Since there is no diagnostic port near that area, four additional support plates will be added to reinforce the structure to decrease the maximum deformation on the coil cases of MC4.

3.3 Detailed design of the center support

For the design of the supporting structure, assembly work is one of the most important issues. In our case, due to the low aspect ratio, the space for assembly work is quite limited, especially for the center support. Thus, a special structure design is carried out for future assembly work.

The process of assembly work contains three main steps. First, set up the base legs and the bottom plate. Secondly, install MCs with coil cases, the vacuum vessel and center supports. Finally, assemble the outer pillars and the top plate. In the second step, after we install MCs and the vacuum vessel, the working space will be insufficient for inserting the whole center support directly. Since the center supports must be assembled after vacuum vessel and MCs (to keep necessary space for welding vacuum vessel), we decide to separate the center column into upper part and lower part instead of reducing its size. The design of the center supports and its assembly process is displayed in Figure 10.



① Add some support elements (blue) on lower part of center column (yellow).
② Install the assembled lower part of center column.
③ Insert one H-shape beam
④ Add remain support elements on upper part of center column.
⑤ Install the assembled upper part of center column.
⑥ Connect MC4 coils with two additional link bars.
⑦ Insert another H-shape beam.

Figure 10. Structures and assembly process of the center support.

4. Finite element analysis on the supporting structure

The finite element analysis has been widely used for structural analysis in many fusion devices [16-18]. Usually, the analysis result is considered as a reference in order to estimate the quality of the supporting structure design and help designers to make optimization. In this paper, a finite element analysis for the CFQS global model is carried out by ANSYS/Mechanical APDL^{TM}, by evaluating results of deformation, von-Mise stress and the elastic strain. As a result, we can estimate the property of the CFQS supporting structure.

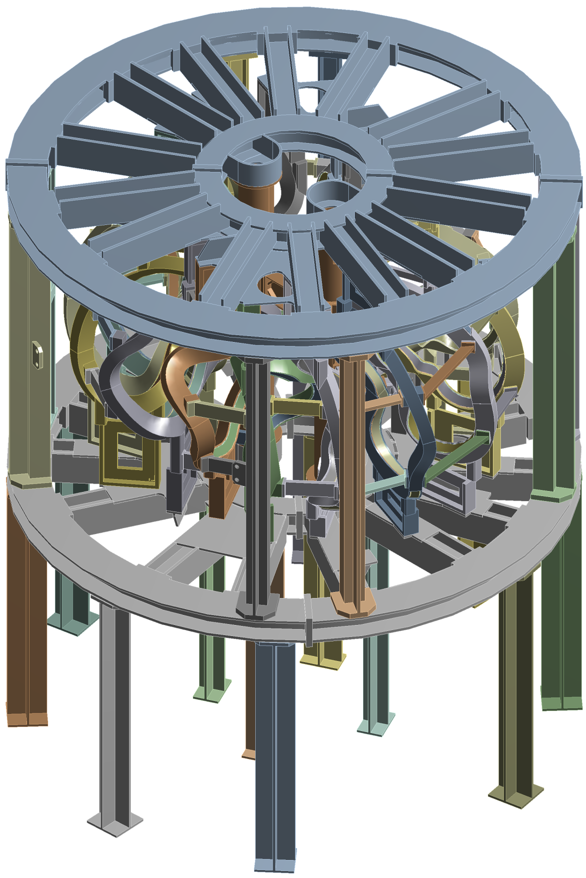
4.1 Calculation model

In this paper, all design values are decided following the material properties. For the supporting structure, the material properties are the same as SUS316/304. For winding packs, since there is no clear criterion, the design stress is depended on oxygen-free copper (OFC), and the strain should be restricted for protecting the insulation layers. The maximum deformation is currently set to be 2 mm to ensure the deformation of MCs will not cause any interaction between two coil cases, neither affect the magnetic configuration significantly [19]. The allowable stress for typical materials in CFQS was assumed in Table 4.

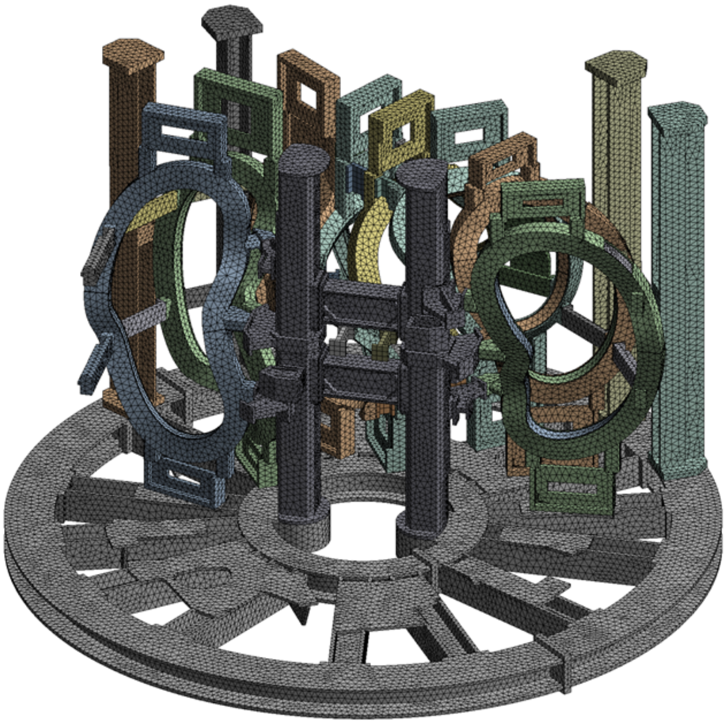
Table 4. Design guideline of typical materials.

Material			Supporting structure	Winding pack (MC)	FRP
Young's Modulus	(GPa)	E	197	100	100
Design Stress	(MPa)	S_m	137	90	50
Design Strain		ε		＜0.1％	
Poisson's ratio		ν	0.3	0.34	0.3
Deformation				< 2 mm	

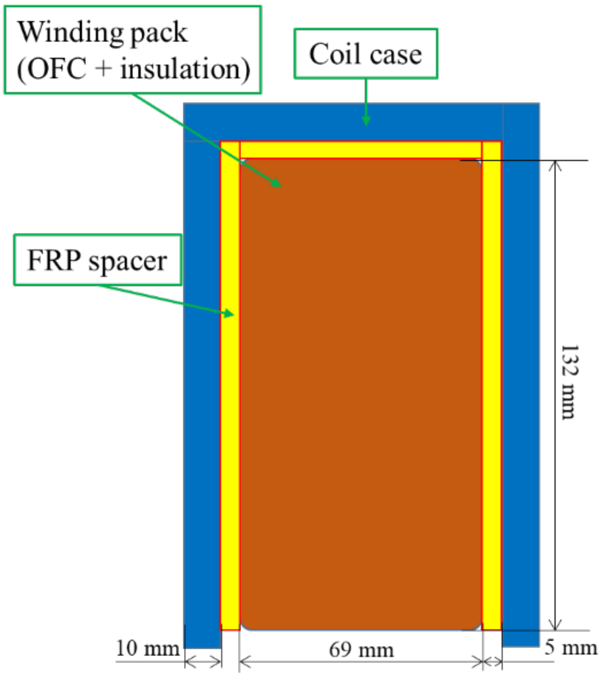
Figure 11(a) shows the three-dimensional global model of the CFQS, and figure 11(b) shows the distribution of the mesh on the main part of the model. In this model, the vacuum vessel is not included in calculation. Figure 11(b) shows the simplified cross-section of the winding packs. In simulation, the bottom surface of twelve base legs is set as fixed boundary, and all parts are bonded together except for the coil case, FRPs and winding packs, since the coil case is not a closed one. In the real situation, the contact areas of winding packs and FRPs are frictional. But in our simulation, we set the contact condition as frictionless (the winding pack is not well supported and the relative move could be large) as we want to know the property of the supporting structure in the worst situation. For the contact areas between coil cases and FRPs, we assume no separation (no relative move on perpendicular direction) because the FRPs should fulfill the initial gap between the coil case and winding packs. The load condition includes the deadweight of the device and EM forces applied on MCs.



(a) Simplified CFQS global model



(b) Distribution of the mesh on main parts of the model



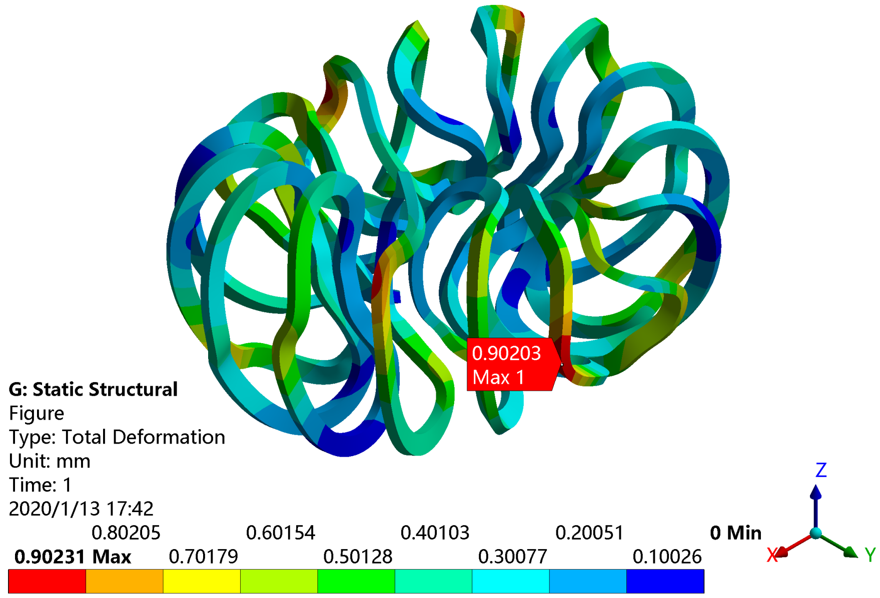
(c) Simplified cross-section of the winding pack

Figure 11. Simplified model of the supporting structure and modular coils.

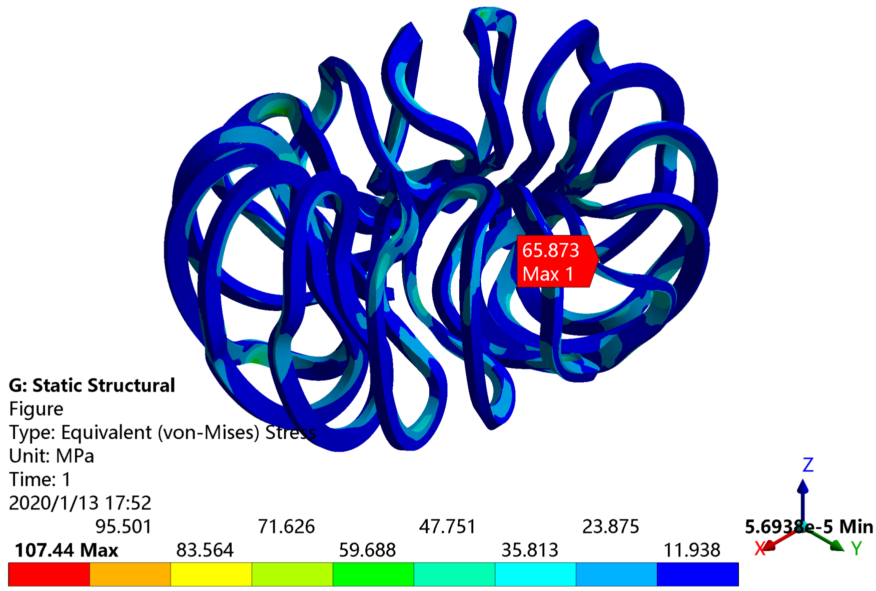
4.2 Simulation result

In Figure 12, three contour plots show the relevant result. The distribution of deformation on winding pack indicates that the maximum deformation is about 0.902 mm, which occurs on MC4. Therefore, we consider that the deformation will not affect the property of the entire MC system significantly. The maximum von-Mise stress and elastic strain on the winding pack is about 66 MPa and 0.06%, respectively. These maximum values of von-Mise stress and elastic strain are also located on MC4, and both are less than our design values.

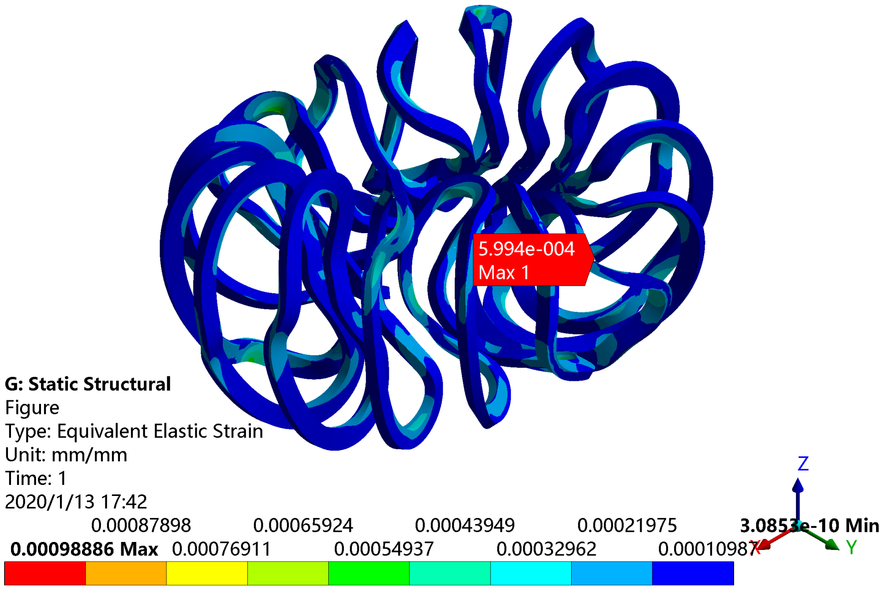
In the winding pack, the coils are formed by two parts, i. e., OFC and resin insulation. But in this simulation the coils are replaced by one composite material. Therefore, both design values for von-Mise stress and elastic strain should be satisfied. The distribution of the von-Mise stress and elastic stress on coils is shown in Figure 12(b) and (c). The results indicate that both stress and strain are in the tolerable range.



(a) Deformation distribution on the winding packs (MC).



(b) Stress distribution on winding packs (MC)

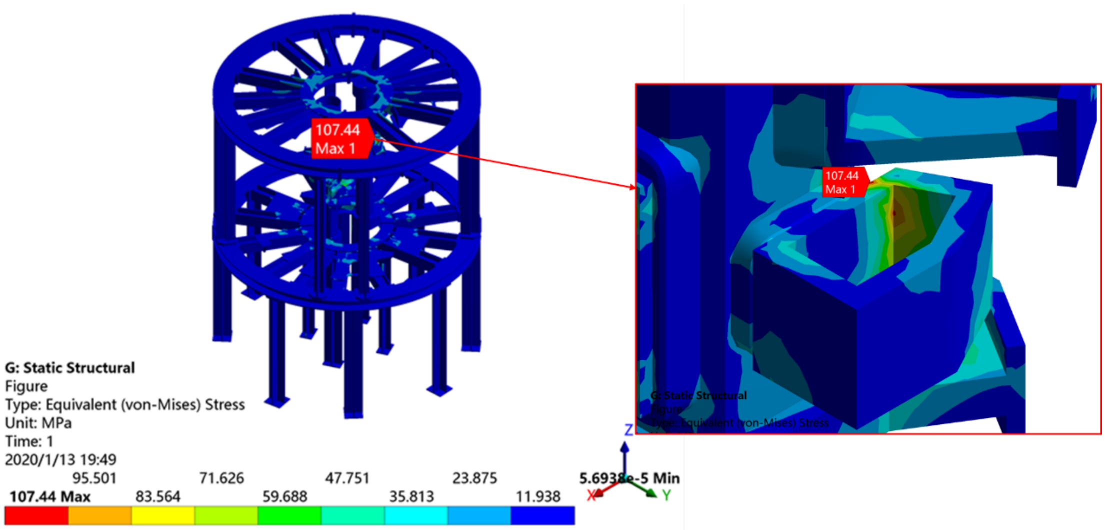


(c) Elastic strain distribution on winding packs (MC)

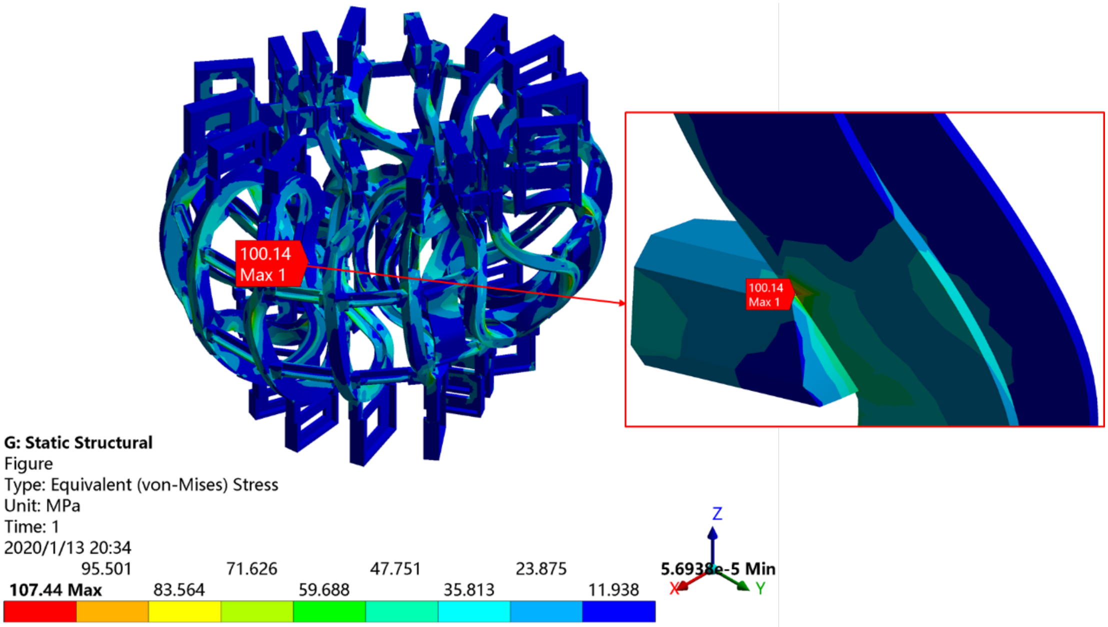
Figure 12. Finite analysis result on winding packs (MC).

Figure 13 shows the stress distribution on the supporting frame and coil cases. It is obvious that the maximum stress on the supporting structure is 107.44 MPa. The maximum stress on the supporting frame and coil cases is located on the center support element and connection elements on MC1, respectively. The results indicate that the property of the supporting structure satisfies our design guideline.

We need further simulation with detailed model which includes connection condition (bolt preload, welding deformation, thermal stress, etc.). The sub-model analysis, which is applied in designing work of W7-X, may be a good choice for our future work [20].



(a) Stress distribution on supporting frame



(b) Stress distribution on coil supports

Figure 13. Stress distribution on supporting structure.

5. Summary

In this paper, the distributions of the EM force on MCs are evaluated by finite element analysis to roughly predict the coil's behaviors. Based on different EM force components, a cage-like supporting structure is designed to support the modular coil system. The whole structure contains two main components, i.e. the supporting frame and the coil supports. These components are set up to prevent deformation and to decrease large stress on MCs caused by EM forces. A finite element analysis on the supporting structure is carried out for ensuring the property of the design. The results of finite element analysis on the CFQS global model show that the stress, elastic strain, deformation on MCs and designed supporting structures is less than we expected. Therefore, the cage-like supporting structure is basically strong enough to protect the MCs. To further confirm the property of this design, some detailed conditions, such as bolt preload, thermal stress in operation regime, welding deformation, etc, should be considered in our future analysis.

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