Engineering Design of the Chinese First Quasi-Axisymmetric Stellarator (CFQS)*)

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The Chinese First Quasi-Axisymmetric Stellarator (CFQS) is being constructed as an international joint project between the National Institute for Fusion Science in Japan and Southwest Jiaotong University in China. It is being designed as a low-aspect-ratio quasi-axisymmetric stellarator with a modular coil system in a CHS-qa configuration. The physics design is almost finished, and we are now proceeding with the engineering design. Its physical properties are as follows: toroidal periodic number $m = 2$, aspect ratio $A_p = 4$, magnetic field strength $B_t = 1$ T, major radius $R_0 = 1$ m, and typical rotational transform *iota-bar* = 0.4 in the all-radial region. We are currently evaluating the design's technical feasibility and manufacturability using a 3D CAD system, together with structural and electromagnetic analysis software. This paper reports on the CFQS's feasibility from an engineering design viewpoint. We are currently targeting 16 normal conducting modular coils, divided into four types, and a total current of 5 MAT. Each coil has a rectangular cross section of 132×69 mm^2, and is composed of 72 hollow copper conductors with water-cooling holes. These conductors carry currents of 4.3 kA, with a current density of 74 A/mm^2.

Keywords: CFQS, quasi-axisymmetric configuration, engineering, normal conducting coil, stellarator

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1. Introduction

The Chinese First Quasi-Axisymmetric Stellarator (CFQS) project began in July 2017 as a joint international nuclear fusion research project on advanced stellarators, involving the National Institute for Fusion Science in Japan (NIFS) and Southwest Jiaotong University in China (SWJTU) [1].

The CFQS is a low-aspect-ratio quasi-axisymmetric stellarator, based on a CHS-qa configuration, which aims to improve neoclassical transport and explore high-β configurations by combining the best features of advanced tokamaks and optimized stellarators [2]. It is expected to be stable in magneto-hydrodynamic (MHD) without a conducting structure, require no current drive at high β, give good orbit confinement, and provide neoclassical confinement equivalent to that of a tokamak. In addition, achieving a low-aspect-ratio in a quasi-axisymmetric configuration is an attractive way to minimize the costs of near-term experiments and the capital costs of possible future power plants. The physics design is almost finished and has previously been reported [1, 3]. In this paper, we discuss the feasibility of the CFQS's design from an engineering viewpoint.

2. Physical Specifications

Figure 1 shows three poloidal cross sections of the equilibrium magnetic surfaces without the plasma pressure effect. The CFQS design reduces the major radius, increases the aspect ratio, and reduces the magnetic field slightly in order to reduce costs and make it easier to manufacture by using the 2b32 CHS-qa configuration [2].

The CFQS's main parameters are as follows: toroidal

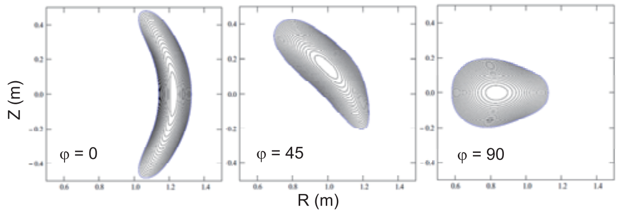

Fig. 1 Shape of the equilibrium magnetic flux surfaces for $\beta = 0$.

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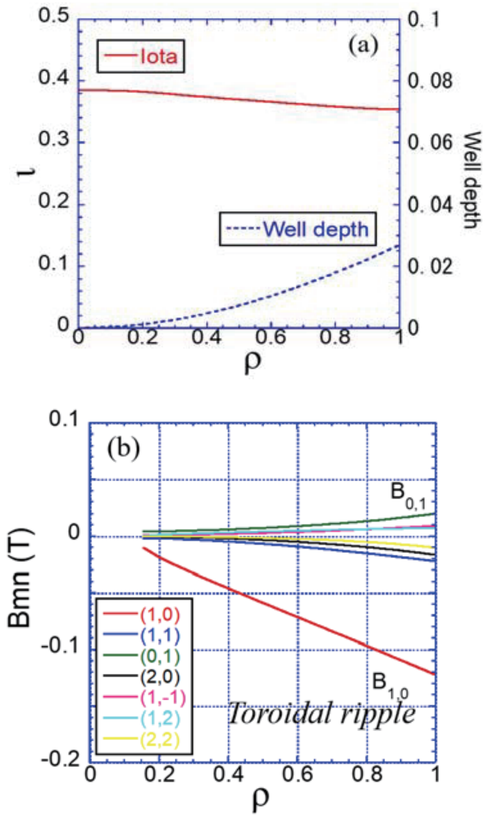

Fig. 2 Equilibrium parameter profile, showing (a) the rotational transform and well depth and (b) the Fourier spectrum of the magnetic field strength.

periodic number $m = 2$, aspect ratio $A_p = 4$, magnetic field strength $B_t = 1$ T, and major radius $R_0 = 1$ m. Figure 2 (a) shows the typical rotational transform and magnetic well profile. We are able to achieve low magnetic shear and a shallow well structure throughout the entire region. Figure 2 (b) shows Fourier spectra of the magnetic field strength in Boozer coordinates. Here, the dominant ripple is the toroidal mode $B_{1,0}$, which indicates a tokamak-like or quasi-axisymmetric configuration. The CFQS project aims to confirm the effectiveness of this equilibrium.

3. Overall Structure

Figure 3 shows a schematic of the CFQS, which is approximately 2790 mm high and has an outer diameter of 4300 mm. The electromagnetic force applied to the modular coils is supported by a cage-type support structure, with diagonal beams to absorb the overturning force and two central pillars to absorb the centripetal force.

These devices are installed in a 15 × 45 m torus hall with power supplies for plasma heating, as shown in Fig. 4. The plasma heating apparatus is intended to provide for tangential neutral beam injection (NBI) of 40 kV and 1 MW and electron cyclotron resonance heating of 54.5 GHz and 450 kW. For plasma diagnostics, we will use

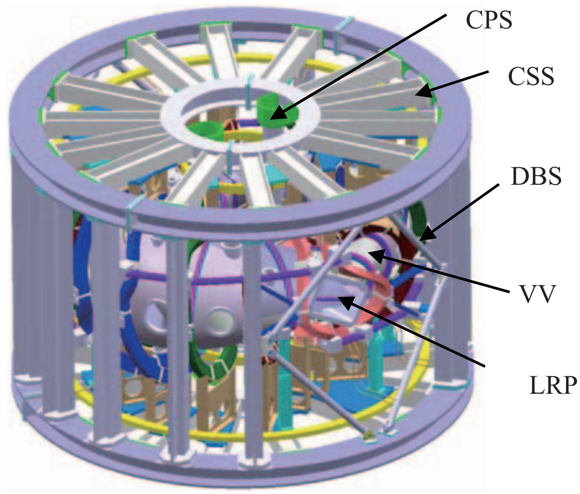

Fig. 3 Schematic of the CFQS. CSS: Cage-type support structure. CPS: Central pillars. DBS: Diagonal beams. VV: Vacuum vessel. LRP: Large rectangular port.

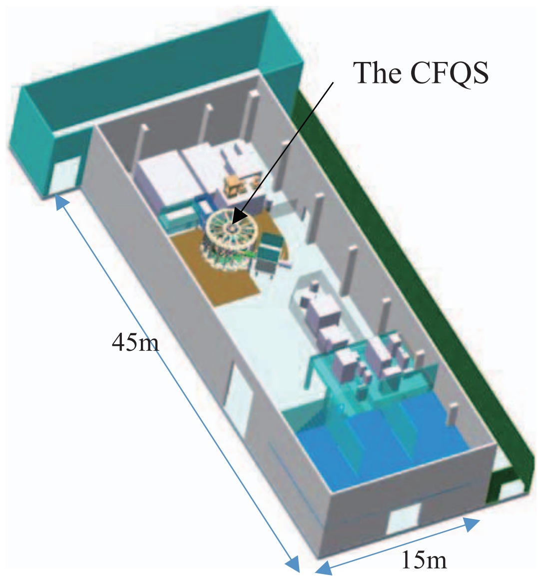

Fig. 4 Torus hall for the CFQS.

a Thomson scattering system, a microwave interferometer, a charge exchange system, a heavy ion beam probe, and magnetic measurements, among others.

4. Coil and Support Structure

Table 1 gives technical data for the coil system, which is illustrated in Fig. 5. A basic quasi-axisymmetric configuration can be produced by four types of modular coils (for a total of 16), whose shapes are shown in Fig. 6. However, in order to allow for flexible configuration, we have also installed four poloidal field coils (to move the magnetic axis horizontally) and eight toroidal field coils (to change the rotational transform). The coil currents are driven by four power supplies for the modular coils, two for the poloidal field coils, and one for the toroidal field coils.

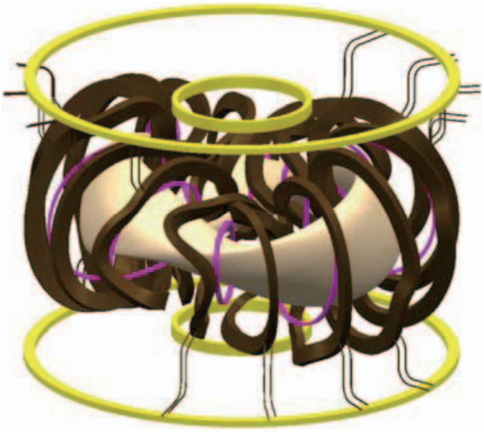

Fig. 5 Schematic of the coil system, showing 16 modular coils (brown), 4 poloidal field coils (yellow), and 8 toroidal coils (pink). The outermost magnetic flux surface is shown in beige.

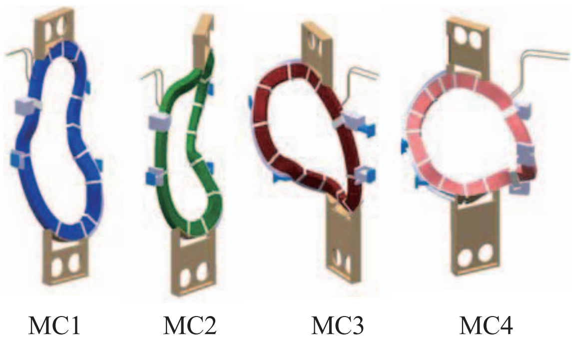

Fig. 6 Modular coils, showing the legs and supports.

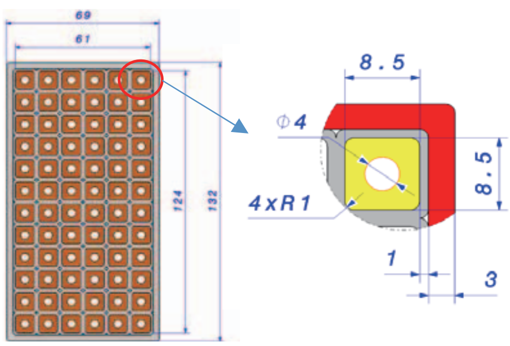

Fig. 7 Cross section of a modular coil, which is composed of 72 hollow conductors.

Table 1 Technical data for the coil system.

Common	
Conductor cross section (mm^2)	**8.5x8.5**
Cooling medium	**H_2O**
Nominal current *I* (kA)	**4.34**
Current density (A/mm^2)	**74**
Pulse length (s)	**0.6**
Adiabatic temperature rise (°C)	**20**
Pulse interval (min)	**5**
Modular coil system	
Number of types	**4**
Number of coils	**16**
Number of turns per coil	**72**
Nominal total current (MAT)	**5**
Overall cross section (mm^2)	**132 x 69**
Number of power supplies	**4**
Nominal voltage (kV)	**2.4**
Poloidal field coil system	
Number of types	**2**
Number of coils	**4**
Number of turns per coil	**32**
Nominal total current (MAT)	**0.556**
Overall cross section (mm^2)	**90 x 48**
Number of power supplies	**2**
Nominal voltage (kV)	**1.5**
Toroidal field coil system	
Winding on the vacuum vessel	**-**
Number of types	**2**
Number of coils	**8**
Number of turns per coil	**8**
Nominal total current (MAT)	**0.28**
Overall cross section (mm^2)	**40 x 20**
Number of power supplies	**1**
Nominal voltage (kV)	**0.43**

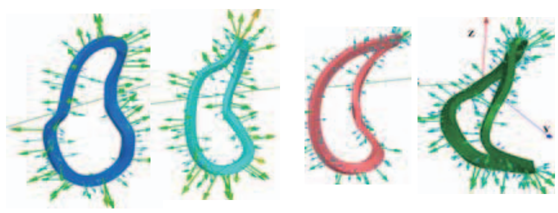

Fig. 8 Electromagnetic force profiles. Here, vector diagrams show the forces applied to the four types of modular coils.

Figure 7 shows the cross section of a modular coil. Since the current density is very high, the conductor temperature rises by about 20° per second of operation. In order to absorb this heat before the next shot, the coils are cooled by pure water.

Figure 8 shows the electric magnetic force profiles applied to the four types of modular coil. The forces' magnitudes and directions are very complicated, and their characteristics are not easy to describe. They are similar to those of a tokamak's toroidal field coil (TFC) but, since it is necessary to reveal even the components that are negligible for tokamaks, analyzing the modular coils is more difficult. Their characteristics include vertical forces and vertically asymmetric overturning moments, and the generation of forces in the toroidal direction that cause attraction between adjacent coils. Naturally, as with tokamaks, we also need to consider large centripetal and expansion force components, and we need a support structure that can withstand such complex forces.

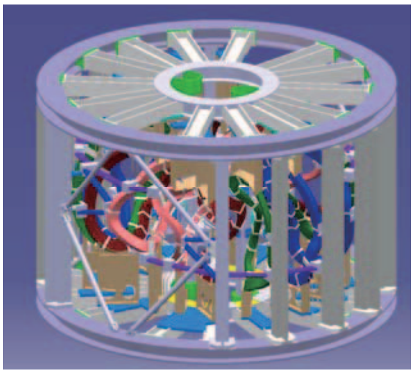

Fig. 9 (a) Cage-type structure. Outer pillars and diagonal beams prevent the overturning forces rolling the coils over. Due to the use of tangential NBI, it is not possible to install pillars around the large rectangular port, so we instead use diagonal beams.

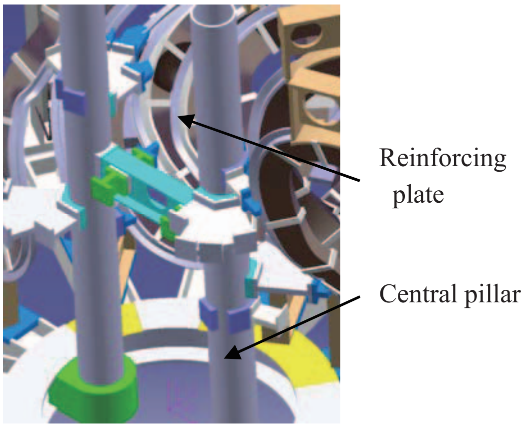

Fig. 9 (b) Absorbing centripetal forces. Since it is not possible to realize the wedge structure used in tokamaks, partial reinforcing plates and two central pillars absorb the central forces.

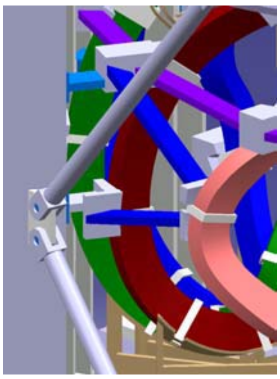

Fig. 9 (c) Absorbing expansion and toroidal forces. Beams between the coils are used to cancel out the toroidal force imbalance and the outer pillars absorb the coils' expansion forces.

Figure 9 shows the support structures used. Figure 9 (a) shows a cage-type structure with diagonal beams that prevents deformation by the overturning moments or

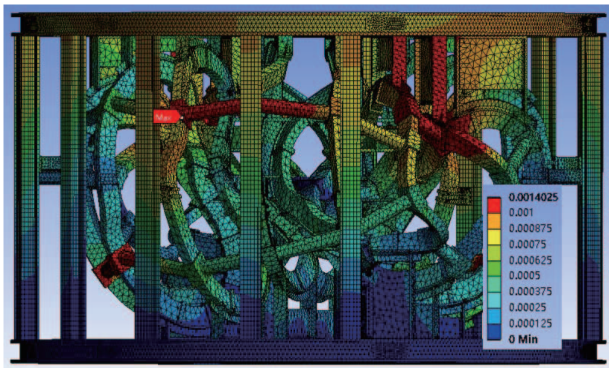

Fig. 10 Preliminary structural analysis based on the applied electromagnetic forces. The estimated maximum deformation is 1.4 mm.

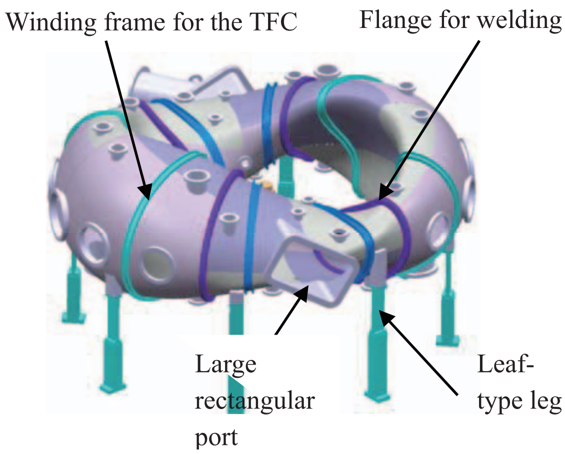

Fig. 11 Schematic of the vacuum vessel, which will be manufactured by welding together four sections in the toroidal direction and supported by eight leaf-type legs. The flanges for welding are shown in purple. The vessel has eight winding frames for the TFC (shown in blue).

vertical forces and handles the entire load. It also has, among other components, a vacuum vessel, other coils, and a diagnostic system attached to it. For use in future NBI experiments, we adopted a design that does not have pillars around the large rectangular port, instead surrounding it with diagonal beams.

Large tokamaks are typically designed with TFC wedges to support the centripetal forces. Since the CFQS cannot take this approach due to shape constraints, it instead absorbs the centripetal forces with two central pillars, as shown in Fig. 9 (b). The attractive forces between adjacent coils are canceled out by beams sandwiched between the coils, as shown in Fig. 9 (c). For parts that experience substantial coil deformation due to expansion forces, these forces are absorbed by the outer pillars.

Figure 10 shows the results of a preliminary structural analysis in terms of the electromagnetic forces, which indicate that the estimated maximum displacement is 1.4 mm.

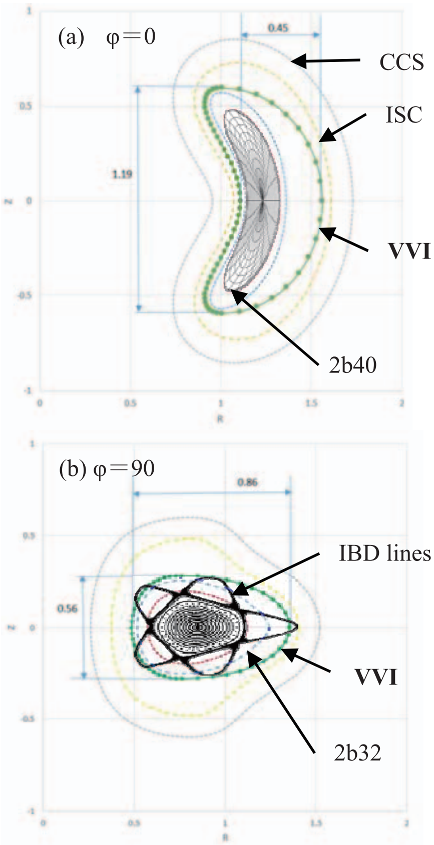

Fig. 12 Vacuum vessel cross section, showing the shapes of the plasmas for the (a) standard 2b40 equilibrium configuration (aspect ratio: 4.0) and (b) 2b32 island bundle diverter configuration (aspect ratio: 3.2). VVI: Inner vacuum vessel surface. CCS: Current carrying surface, on which the center of the modular coil is placed. ISC: Innermost peripheral surface of the modular coil. IBD: Island bundle diverter.

5. Vacuum Vessel

Figure 11 shows a schematic of the vacuum vessel, which will be manufactured by welding together four sections in the toroidal direction. The flanges used for welding are shown in purple. Since the electromagnetic forces on the vacuum vessel are expected to be small, it will be fabricated from SUS316L with relatively thin walls (6 mm). As a result, the one-turn resistance is roughly 0.3 mΩ which we believe to be sufficiently large while not producing significant Joule heating. The walls will be conditioned by baking them at 130 - 150° via induction heating at about 500 Hz.

The vacuum vessel is fixed to the cage-type support structure shown in Fig. 3 by eight leaf-type legs, added to allow for the vacuum vessel's thermal expansion during baking. Winding frames have also been included on the vessel in order to wind the TFCs. More than 40 large ports, with a diameter of at least 114 mm, will be provided for heating and measurement.

The vacuum vessel will be assembled as follows.

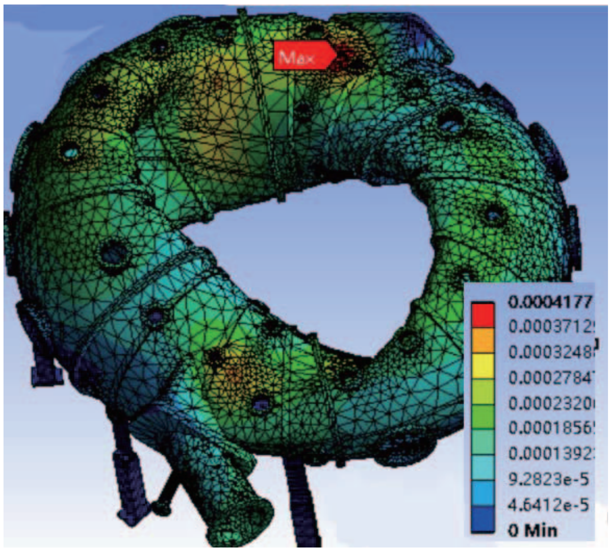

Fig. 13 Preliminary structural analysis in terms of the applied atmospheric pressure. The estimated maximum deformation will be 0.4 mm.

(1) Manufacture the four sections with port flanges.
(2) Perform a vacuum leak test by temporarily connecting the sections with rubber O rings.
(3) Insert the vacuum vessel sections into the modular coils.
(4) Weld the four sections together from the inside.

We have drawn up a design plan in order to carry out this process and conduct various equilibrium experiments.

Figure 12 shows a cross section of the vacuum vessel. The inner surface cross section (VVI) is much larger than that of the 2b32 reference surface defined for the island bundle diverter experiment [4], with the minimum gap between the 2b32 plane and the VVI surface being 30 mm. The outermost magnetic surface of the standard 2b40 equilibrium configuration is narrower than the 2b32 surface. The width and height of the VVI are both at least 450 mm, which is sufficient for people to work inside. Using such a large vacuum vessel also helps to make the experiment more flexible. Two large rectangular ports are also included, both for workers to enter and for use in NBI and Thomson scattering.

Figure 13 shows the results of a structural analysis based on the applied atmospheric pressure. Here, the estimated maximum displacement is 0.4 mm, which is within an acceptable range.

6. Next, Steps

The engineering designs for the modular coils and vacuum vessel are complete, and the detailed design processes have begun. We are also producing a mockup coil to confirm the modular coil design's effectiveness and manufacturability.

Work has also begun on the conceptual design of the power supplies and water-cooling systems. Shortly, we will begin the detailed design process for the torus hall and examination of the diagnostic system.

7. Summary

The CFQS is being constructed as an international joint project between the NIFS and SWJTU, and will produce several quasi-axisymmetric stellarator configurations. The physics design is almost finished, and now we are discussing the project's feasibility from an engineering viewpoint. An overall structure and layout has also been proposed for the CFQS's torus hall.

In addition, the engineering design processes have been completed for the modular coils (and their support structures) and the vacuum vessel, and analyses conducted to preliminarily confirm their effectiveness.

The vacuum vessel design takes both the assembly procedure and the need to conduct experiments with varying plasma configurations into account.

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