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ENGINEERING DESIGN, CONSTRUCTION, AND FLEXIBLE CONTROL OF MAGNETIC FIELD CONFIGURATION OF QUASI-AXISYMMETRIC STELLARATOR CFQS-T

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Abstract

A stellarator having the magnetic symmetry of a tokamak was proposed in the mid 1990s. Subsequently, numerous efforts to design quasi-axisymmetric stellarators, i.e., CHS-qa in Japan, NCSX in U.S.A, and ESTELL in France were intensively made, however, those stellarators were not realized. After a long time, the National Institute for Fusion Science, Japan and Southwest Jiaotong University, China joint project for CFQS quasi-axisymmetric stellarator was initiated in July, 2017. The CFQS is based on the design of CHS-qa. The primary parameters of CFQS are: major radius of 1 m, toroidal periodic

number of 2, and aspect ratio of 4. In CFQS, four different types of 16 modular coils (MCs) are employed to realize a quasi-axisymmetric magnetic field configuration. In addition, to allow flexibility in the magnetic field structure, the CFQS is equipped with 2 pairs of poloidal field coils (PFCs) and 12 toroidal field coils (TFCs). We have successfully achieved the first plasma with the machine having a simplified supporting structure called CFQS-TEST, hereafter CFQS-T by use of a magnetron at the microwave frequency 2.45 GHz in August, 2024. The CFQS-T program was ended in May, 2025 with the intended purpose. The CFQS-T is now being reorganized to be CFQS for 1 T operation. In this paper, the finalized engineering design of the MC system with simplified supporting structures, the established manufacturing method of the MC system for CFQS-T, and flexibility of magnetic field configuration are described.

1. INTRODUCTION

A stellarator embedded with the magnetic symmetry of a tokamak, often called quasi-axisymmetric stellarator (QAS), was proposed in the 1990s [1,2]. Since the QAS provides rotational transform in vacuum in addition to tokamak-like low toroidal viscosity and magnetic well in entire domain of plasma, good plasma performance realized in tokamaks can be expected in QAS with steady-state operation capability and without suffering from major disruption. The CFQS quasi-axisymmetric stellarator project has been undertaken since 2017 as an international joint project between National Institute for Fusion Science (NIFS), Japan and Southwest Jiaotong University (SWJTU), the People's Republic of China [3]. A primary purpose of CFQS is in a proof-of-principle of quasi-axisymmetry (QA) to demonstrate favorable influence of QA on plasma confinement and/or formation of plasma flow structure. The magnetohydrodynamics (MHD) equilibrium of CFQS was designed based on that of the CHS-qa [4, 5]. Because the CFQS is characterized by tight space and strong electromagnetic (EM) force, in particular, at the inboard side of the machine due to its low-aspect-ratio, there have been many challenging issues in the design of supporting structure. We have carefully investigated the supporting structure withstandable against 1 T operation by using ANSYS Maxwell and Mechanical. As a result, we have reached the cage-type supporting structure of which maximum stress is about 100 MPa tolerable to withstand strong EM force during 1 T operation in balance with port arrangement [6]. The CFQS project is divided into the two phases, i.e., the first phase: CFQS-TEST, hereafter called CFQS-T for 0.1 T operation, and the second phase: CFQS for 1 T operation. The construction of CFQS-T was successfully completed in July, 2024. The engineering design and manufacturing of the modular coil (MC) system for CFQS-T are available in Ref. 7. At the beginning, based on mapping experiment strategy carefully drawn up for CFQS [8], we performed magnetic field mapping experiment and obtained good magnetic surfaces with sufficient accuracy as expected [9]. Subsequently, we achieved the first plasma with the help of electron cyclotron resonance wave of which frequency is 2.45 GHz. Many valuable phenomena were observed in the CFQS-T, e.g., an indication of zonal flow, MHD instabilities which seem to be most likely global Alfvén eigenmodes associated with suprathermal electrons [10], etc. Also, CFQS-T played an important role as a platform to develop the heavy ion beam probe in the future [11]. Having fulfilled CFQS-T's intended role, we have stepped into the modification of CFQS-T to realize CFQS capable of 1 T operation.

2. ENGINEERING DESIGN OF CFQS-T

Figure 1 shows the CFQS-T main body. It mainly consists of a magnetic field coil system, a vacuum vessel (VV), a cage-type support structure, and water cooling pipes [12, 13]. The cage-type structure is designed to be sufficiently robust against complex EM forces on the magnetic field coil system, low-cost, and good assemblability/disassemblability for upgrade. While this cage-type structure will be used even for the second experimental phase with 1 T pulse operation, numerous additional support structures reinforcing the MCs against complex and massive electromagnetic forces are planned to be installed [6, 14, 15]. Figure 2 represents the schematic drawing of the CFQS-T coil system. It employs 16 MCs of 4 different types in shape for generation of

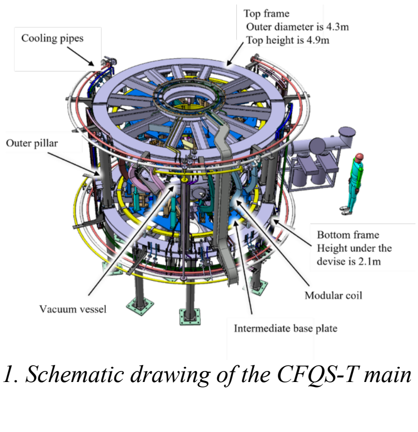

FIG. 1. Schematic drawing of the CFQS-T main body.

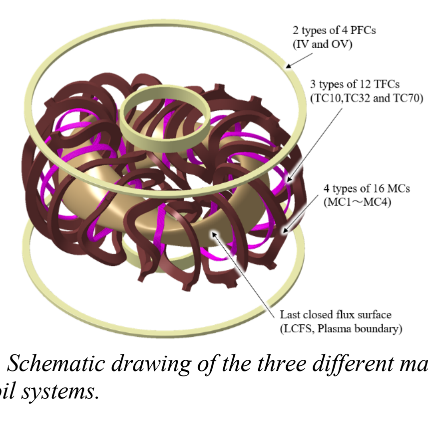

FIG. 2. Schematic drawing of the three different magnetic field coil systems.

the QA magnetic configuration [16-18]. In addition, 2 pairs of poloidal field coils (PFCs) for control of the magnetic axis position, and 12 toroidal field coils (TFCs) for rotational transform control are employed. The coils are connected in series for each type, and each coil current is independently controlled to realize the experiment with various magnetic field configurations, e.g., an island bundle divertor configuration [19]. The coil power supply (PS) employs an energy storage station with 750 kWh in order to supply these with a large amount of power, equivalent to 700 kW during the plasma experiment. The maximum pulse duration for 0.1 T operation is limited to 269 s due to coil temperature rise [7]. The discharge interval of 10 mins was determined by the MC cooling down time. MC is composed of water-cooled 12×6 oxygen-free copper hollow conductors. The winding method is a double pancake with three simultaneous windings to suppress the water pressure loss up to 1 MPa. Although basic geometry of MCs is defined by the center trajectory of the MC, a so-called filament coil calculated with the NESCOIL code [20], three-dimensional (3D) MC structure is adjusted in terms of manufacturability, including the gap between MCs or an individual MC and other components, as well as the curvature of the 3D surface [7, 18, 21]. Figure 3 shows a partial clamping structure consisting of coil clamps and coil legs for MC winding packs support. They will be reinforced for the 2nd experimental phase as the CFQS for 1 T operation. This support structure is low-cost and easy to assemble/disassemble with MC winding packs. The validity of the MC winding pack support system was ensured by stress analysis using an analysis software based on the finite element method ANSYS/Mechanical and Maxwell [7]. PFCs are also composed of the same water-cooled oxygen-free copper hollow conductors. The winding method is four solenoids winding for the inner vertical (IV) coils and two double pancakes with winding parallel simultaneously for the outer vertical (OV) coils. The number of turns is 64 with 16 turns and four layers for the IV and 32 with eight turns and four layers for the OV. TFCs are designed to be wound insulated cables so called crosslinked polyethylene insulated vinyl sheath (CV) cables on the VV. The CV cables are cooled by natural air flow. Although a choice of water-cooled conductors like MCs and PFCs is desirable to realize long time, short interval operation, it was necessary to increase the cross-sectional area of TFCs, which makes winding work quite challenging, and interference between TFCs and the MCs was concerned. A winding test using solid copper conductor was carried out to confirm the manufacturability as shown in Fig. 4. It was revealed that an unacceptable gap came out between conductors and VV surface due to the hardness of the conductor and 3D large torsion of TFCs. Based on the above test results, we made a decision to use a flexible air-cooled circular CV cable. The VV consists of four sections in the toroidal direction: two Type-A and two Type-B as shown in Fig. 5. It has 3 dimensionally twisted structure with 46 ports and 12 TFCs. Two 340×580 mm large rectangular ports installed on VV type-A will be used for the neutral beam injection (NBI) heating system [22] and the Thomson scattering diagnostic system. Sheathed heaters for baking are divided into 14 systems around the entire VV and controlled by different PSs to achieve a homogeneous VV temperature distribution. The VV is supported by eight leaf-type

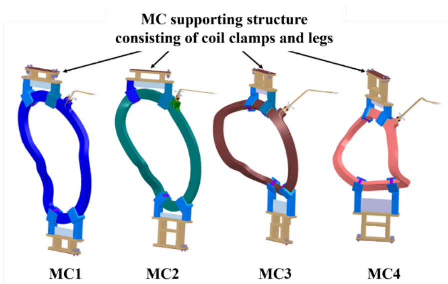

FIG. 3. Modular coil support structure with simplified partial clamps and legs.

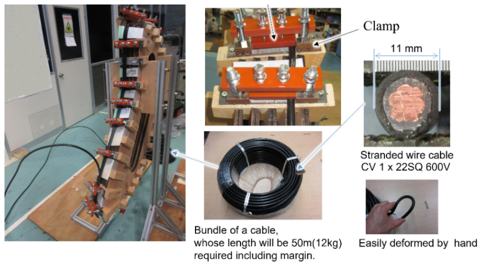

FIG. 4. Photographs of toroidal field coil winding test on a wooden vacuum vessel part.

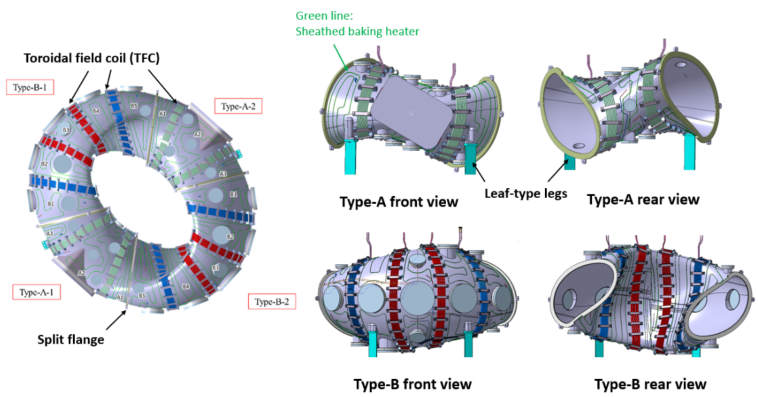

FIG. 5. Configuration of the CFQS-T vacuum vessel consisting of two pairs of vacuum vessel type A and type B. Sheathed baking heaters and TFCs are wound on it.

legs, which can deform to absorb the VV's thermal expansion during baking with around 130 degrees Celsius. The maximum stress and deformation of the VV during vacuum condition were analyzed by ANSYS/Mechanical [23]. The EM force due to eddy currents derived from rapid coil excitation was also evaluated by ANSYS/Mechanical and Maxwell [24]. It was ensured that these factors were within an acceptable range.

3. CONSTRUCTION OF CFQS-T

Figure 6 shows the established major manufacturing procedures of MCs. Before actual MC manufacturing, a prototype MC was fabricated to investigate its manufacturability and the validity of its performance [12]. The distinctive point of MC manufacturing is to adopt vacuum pressure impregnation (VPI) in two steps to maintain the shape of MC winding packs during ground insulation taping without the winding mould [11]. All MCs have passed quality inspections, including dimension measurement by a laser tracker, voltage proof tests, an impulse test, resistance and inductance measurement, and a water flow test. They have been manufactured with less than 2 mm dimensional deviation [9]. This order of dimensional deviation does not significantly influence the magnetic flux surfaces [25, 26]. PFCs have been manufactured with only one VPI and passed all inspections as well. Manufacturing process of the VV sections is shown in Fig. 7. SUS316L plates of 6 mm thickness were formed by hot press processing to reduce spring-back deformation to less than 5 mm. Because the VV Type-A and Type-B are divided by taking advantage of their rotational symmetricity, several pressing dies can be reused. The plates were welded on a mould and shaped by hammering. The mould can be disassembled when it is pulled out from a VV section after welding. TFCs were wound on each VV section after clamping bases to fix CV cables were installed by positioning with a paper pattern as shown in Fig. 7 procedure No. 3. Baking heaters were installed on the surface of VV sections by point welding. The wiring route was studied on a 3D printer model in advance so that a heater density should be homogeneous. 3D measurement of the SUS316L plate surface, port flange was taken place using a laser tracker. The maximum deviation of the SUS316L plate surface was around 4.7 mm and the horizontal port flange surface was around 4.3 mm. This deviation did not affect assembling significantly because the gap between VV and MC is larger than that of deviation. A brief assembly process is depicted in Fig. 8. Four VV sections with MCs have been carefully and precisely installed and welded together one by one. Although the designed minimum gap between MC and VV is only 15 mm, the main body been assembled in the factory by a few fully skilled mechanics without any specialized assembly tools. After the assembling of all components, error of MC position was measured by a laser tracker. The maximum error of MC position is about 3 mm [9]. We analyzed effects of MC position error on the magnetic configuration properties, such as shape of magnetic flux surfaces, rotational transform, and neoclassical transport properties, and changes in them are not significant if the error level is less than 5 mm [25, 26]. The CFQS-T was installed in the SWJTU Jiuli campus at July 31th, 2024. An overview picture of CFQS-T can be seen in Fig. 9.

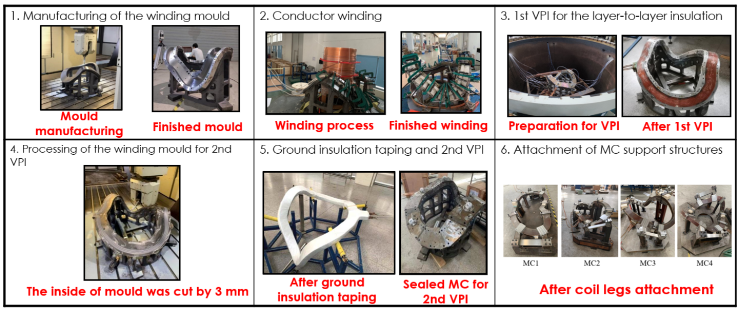

FIG. 6 Established manufacturing process of modular coils.

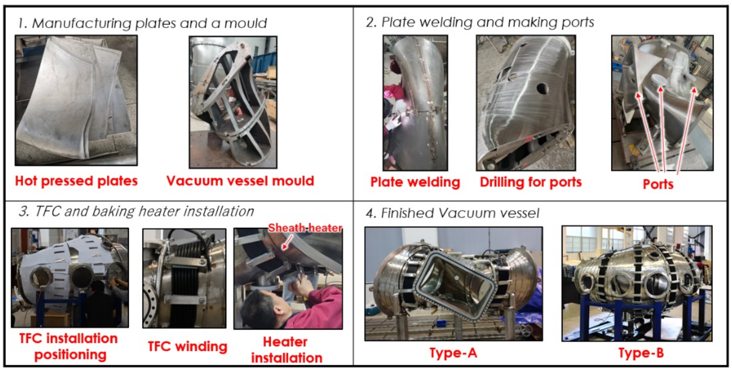

FIG. 7 Established manufacturing process of vacuum vessel sections.

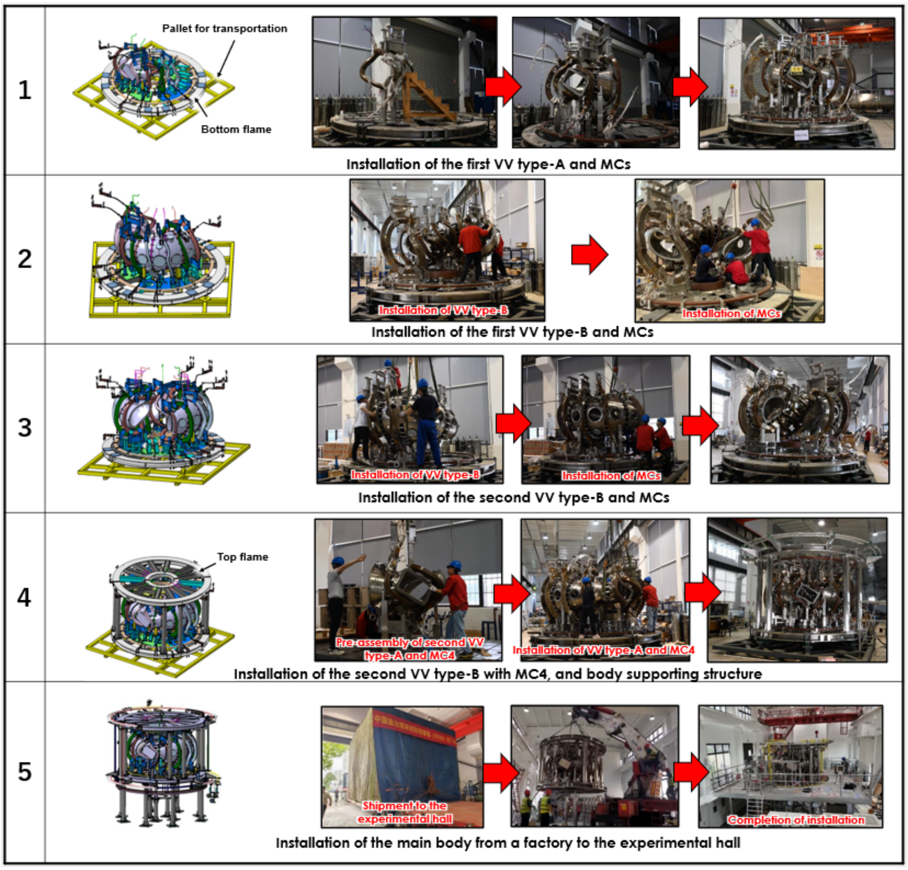

FIG. 8 Assembly process of the CFQS-T main body.

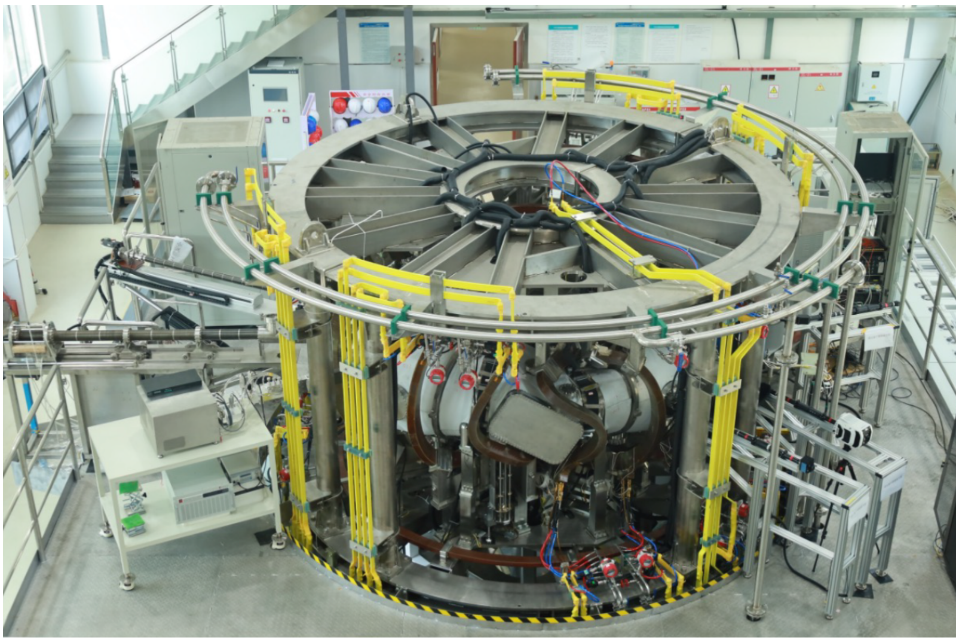

FIG. 9 Overview of CFQS-T.

4. FLEXIBILITY OF CFQS MAGNETIC CONFIGURATION

The flexibility of magnetic configuration is essential to investigate various physics research topics. With TFCs, the rotational transform can be easily controlled, by which the divertor configuration can be produced with m/n = 2/5 islands structure in the peripheral region. Although the QA-ness is slightly deteriorated by this control, effective helical ripple can be kept lower level than that of Wendelstein 7-X. By using PFCs, position of the magnetic axis can be shifted. This control can be utilized to suppress the Shafranov shift in high-β operation. By adjusting the current ratio of IV coil to OV coil, rotational transform also can be controlled. In Fig. 9, the controllability of magnetic axis position and rotational transform by PFCs is shown. Low mode magnetic islands are produced by this control, and those islands can be utilized effectively to evaluate the error field in mapping magnetic field experiments [8]. Because the width of magnetic islands is sensitive to the error field, accurate evaluation of coil misalignment magnitude is feasible.

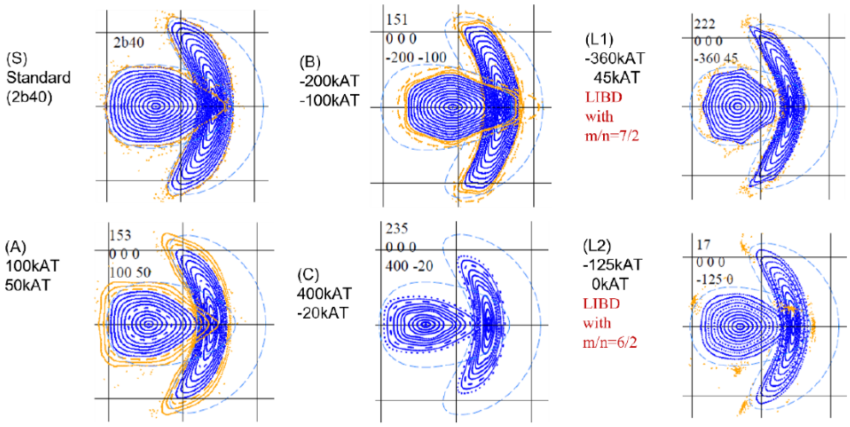

FIG. 9 Magnetic surfaces obtained by control with poloidal field coils. Magnetic surfaces, at the toroidal angle ϕ of 0 and 90 degrees are shown. (S) is the standard configuration. (A) and (B) are magnetic axis position control, inward and outward shifts, respectively. (C), (L1), (L2) are the control of rotational transform. In (L1) and (L2), island divertor configuration of m/n = 7/2 and 6/2 are produced.

5. SUMMARY

In summary, the construction of the CFQS-T was completed in July, 2024 with numerous efforts to overcome engineering challenges due to its low aspect ratio. The first plasma of CFQS-T was successfully generated in the end of August, 2024. The main components, the magnetic field coil system, and the vacuum vessel having complex geometry were manufactured without any significant engineering issues based on several research and development including an analysis by the ANSYS/Mechanical and Maxwell. In the MC manufacturing phase, we carefully measured the accuracy of manufactured MCs in shape from the 3D CAD model, indicating that the deviation of the manufactured MC was within an acceptable level. As a result, the magnetic field mapping experiments with the fluorescent fine mesh and electron gun showed good agreement with magnetic flux surfaces predicted by magnetic field calculation [13]. The CFQS-T were transferred by land to the factory in Hefei, People's Republic of China right after the first phase CFQS-T program was ended in May, 2025. The CFQS-T is now being reorganized to make 1 T operation possible and will be referred to as the original name CFQS. The CFQS will be installed in the new Tianfu district and we are going to initiate the first plasma at toroidal magnetic field of 1 T in January, 2027.

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