# Mission, physics and engineering designs, and current status of the CFQS quasi-axisymmetric stellarator

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## 1. Introduction

A stellarator embedded with magnetic symmetry of tokamak, often called quasi-axisymmetric stellarator (QAS), was proposed in 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. Numerous efforts to realize QAS had been made in Japan [3,4] and United States of America [5] around 2000, and in France [6] in early 2010s, however, the device has not been realized yet. The attractiveness of QAS is not faded yet because it offers great potential to solve issues and/or drawbacks of existing tokamak and stellarator/heliotron at the same time and opportunity to explore a new regime of magnetic confinement fusion. Because of this reason, National Institute for Fusion Science (NIFS) in Japan and Southwest Jiaotong University (SWJTU) in China concluded an agreement upon execution of CFQS quasi-axisymmetric stellarator program jointly in July, 2017 [7]. After physics and engineering designs for essential parts based on the past work on CHS-qa [3,4] was completed, we began to fabricate, i.e. wind an actual modular coil (MC) of the CFQS in Aug., 2020. In this paper, mission, physics and engineering designs, and current status of the CFQS construction are presented.

## 2. Mission, physics and engineering of CFQS

The CFQS is being constructed as the first QAS in the world. The CFQS will be placed in a campus of SWJTU. Primary device parameters of the CFQS are as follows: major radius of 1 m, number of toroidal periods of 2, aspect ratio ($A_p$) of 4, and maximum toroidal magnetic field strength of 1 T [8]. The outermost magnetic flux surface of the CFQS together with magnetic field strength is shown in Fig. 1. The magnetic field generation coils of CFQS consist of 16 MCs with 4 different types, two pairs of poloidal field coils (PFCs), and 12 toroidal field coils

(TFCs) with 3 different types [9,10] as shown in Fig. 2. The NIFS-SWJTU joint project for CFQS is dedicated to proof-of-principle for intrinsic advantages of QAS. Because quasi-axisymmetry results in significant reduction of neoclassical transport compared with a conventional helical system such as CHS [11], confinement property of CFQS plasmas in low-collisionality regime is examined by use of 2nd harmonic electron cyclotron resonance heating (ECRH). It has been observed that toroidal plasma rotation is significantly suppressed due to helical ripple in conventional helical system [12] while the plasma rotation plays an important role in forming radial electric field closely connected to the transition to the H-mode seen in tokamak. In the CFQS, four individual power supplies will be connected to each set of MC1, MC2, MC3, and MC4. Also, three individual power supplies will be prepared for TFCs as the same manner. Because of this, the CFQS is quite flexible in changing magnetic field topology, toroidal viscosity, resulting plasma flow/rotation, etc. through the change of bumpy ripple component by use of MCs and/or rotational transform by use of TFCs. Therefore, the CFQS can work in an intermediate range widely between axisymmetry limit and non-axisymmetry, contributing to comprehensive understanding of toroidal magnetic confinement fusion. In parallel to the engineering design described later, predictive physics studies on MHD equilibrium [13,14], energetic particles [15,16] and Alfvén eigenmode [17], turbulence-driven transport [18], feasibility of divertor configuration [19], etc. have been intensively carried out.

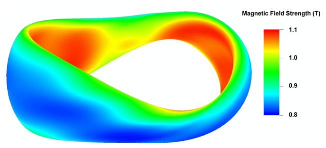

Fig. 1 Outermost magnetic flux surface of the CFQS. The color represents magnetic field strength.

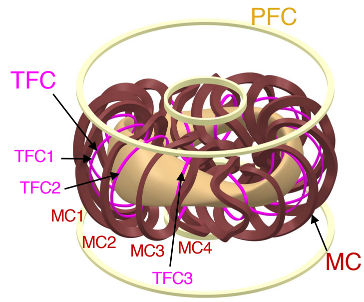


Fig. 2 Magnetic field generation coils of the CFQS.

Because the CFQS is characterized by narrow space and strong electromagnetic (EM) force in particular in the inboard side of the machine due to its low-$A_p$, there has 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-like 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. As for the vacuum vessel (VV), the SUS316L with thickness of 6 mm will be used. The inner wall of VV will be conditioned by baking at the temperature of 130~150 ℃ with sheath heaters. We have performed FEM analysis with ANSYS Mechanical to make sure the reliability of VV, considering together with atmospheric pressure and self-weight in addition to the baking temperature. The analysis tells us that the maximum of Von Mises stress and deformation are 126 MPa and 3 mm respectively, which are below tolerable value [20]. Also, eddy current generated on VV has been of our great concern since the CFQS is the pulse operation machine and the eddy current may give an unfavorable effect on plasma performance. The analysis indicates that the influence of the eddy current on a plasma discharge is negligible [21]. The port design is steadily ongoing. The VV and latest design of port arrangement are depicted in Fig. 3. The CFQS is equipped with two large tilted rectangular ports for neutral beam injection heating and Thomson scattering diagnostic. In addition, middle and small size ports of 44 will be prepared for ECRH, plasma diagnostics, etc. Results for the CFQS engineering are well summarized in Ref. 9.

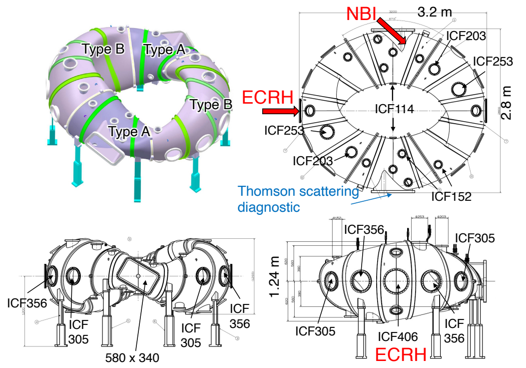


Fig. 3. CFQS vacuum vessel and port arrangement.

## 3. Current status of CFQS construction

Because the MCs of CFQS are intrinsically three-dimensional, manufacturability and achievability of manufacturing accuracy of MC have been of our great concern. Therefore, we started from winding of MC4 mockup which is the most complicated in shape in May, 2019 [10]. After we made sure the manufacturability and the achievability of manufacturing accuracy for MC4 through several measurements and tests for MC4 mockup, we initiated to fabricate actual MCs and VV in Sep., 2020. Casting for MC winding moulds and recent status of MC manufacturing are shown in Fig. 4 in time series. In parallel to MC4, manufacture of MC1 will be initiated soon to accelerate the rate of MC production. As for VV, manufacture of the type-A seen in Fig. 3 has begun. The CFQS VV having complicated geometry in shape is manufactured by press work. In the viewpoint of manufacturability, the type-A, i.e., 1/4 section in toroidal direction is divided into the 2 parts, and furthermore the 2 parts, actually 1/8 section in toroidal direction are divided into the 4 parts. Because we have experienced significant spring back in the press work, hot pressing method is adopted to manufacture VV. After all of 4 parts of SUS316L plates are shaped by the press work, they will be welded into 1/8 toroidal section of VV. Next, two 1/8 sections will be connected by welding into a 1/4 section. Subsequently, holes for ports will be made by cutting VV, and then short pipes and vacuum flanges will be assembled by welding on VV.

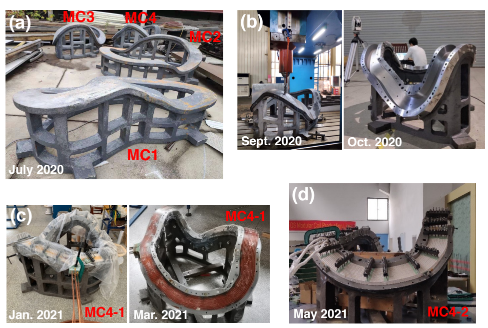


Fig. 4. a) Casting for four different MC winding moulds, b) Manufacture of MC4 winding mould, c) Copper conductor winding and status right after 1st vacuum pressure impregnation for MC4-1, d) Copper conductor winding for MC4-2.

## 4. Summary

After biding our time for 20 years, the world's first QAS named CFQS is now being realized. Broad policy of physics strategy, efforts on engineering, and current construction status of the CFQS are described. The project is dedicated to demonstrate superiority of quasi-axisymmetry concept where advantages of both tokamak and helical/stellarator are embedded at the same time. Since the CFQS is designed to be operated from the vicinity of axisymmetric limit to non-axisymmetry dominated by bumpy ripple, the CFQS can contribute to comprehensive understanding of physics of toroidal fusion plasmas. The construction of CFQS is steadily ongoing as a result of tight coupling of NIFS-SWJTU-Hefei Keye Electro Physical Equipment Manufacturing Co., Ltd. The first plasma of CFQS will be ignited at $B_t$ of 0.1 T. After integrity of the machine and fundamental property of QAS, e.g. characteristics of plasma flow due to low toroidal viscosity are examined, we will switch to 1 T operation.


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