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

[1,2]A. SHIMIZU, [1,2]M. ISOBE, [1]S. OKAMURA, [1,2]K. OGAWA, [1,2]H. TAKAHASHI, [1,2]H. YAMAGUCHI, [1,2]M. SHOJI, [1,2]M. OSAKABE, [2]L. YANG, [1]T. MURASE, [1]S. NAKAGAWA, [1]H. TANOUE, [3]Y. XU, [3]H.F. LIU, [3]H. LIU, [3]J. CHENG, [3]X. ZHANG, [3]J. HUANG, [3]X. WANG, [3]J.F. Shen, [3]H. Lan, [4]C. TANG, [5]D. YIN

[1]National Institute for Fusion Science, National Institutes of Natural Sciences, Toki, Japan
[2]The Graduate University for Advanced Studies, SOKENDAI, Toki, Japan
[3]Institute of Fusion Science, School of Physical Science and Technology, Southwest Jiaotong University, Chengdu, China
[4]Physics Department, Sichuan University, Chengdu, China
[5]Hefei Keye Electro Physical Equipment Manufacturing Co., Ltd, Hefei, China

Email: shimizu.akihiro@nifs.ac.jp

CFQS quasi-axisymmetric stellarator has been developed as a joint project of National Institute for Fusion Science, Japan and Southwest Jiaotong University, China. The quasi-axisymmetric stellarator (QAS) offers good plasma confinement properties with low aspect ratio, giving a prospect to explore further advanced option in fusion research development. MHD equilibrium of the CFQS was designed based on that of the CHS-qa [1,2]. Purpose of CFQS is proof-of-principle experiment to prove effect of QAS on confinement. CFQS project is performed as two steps, 1st phase: CFQS-T for 0.1 T operation, and 2nd phase: CFQS for 1 T operation. Construction of CFQS-T was completed in July, 2024, and 1st phase of experimental campaign started. In assembling process of magnetic field coils of CFQS-T, required accuracy was achieved, and good magnetic configuration of QAS was successfully realized. In this presentation, we report the engineering design, construction of CFQS-T, and flexible control of its magnetic field configuration.

A QAS has an axisymmetric magnetic field configuration in the magnetic flux coordinates, *i.e.*, Boozer coordinates. The neoclassical transport of the QAS can be reduced to a similar level to tokamak. Further, QAS does not essentially require net plasma current, with retaining the advantage of the steady-state operation capability, and not suffer from major disruption. Moreover, due to its low toroidal viscosity property, large plasma rotation is expected, by which we can expect the transition to high confinement status, like the H-mode in tokamaks, in which shear flow can suppress the turbulence and improve the confinement.

Fig. 1 A photo of CFQS-T quasi-axisymmetric stellarator in the experiment hall in Jiuli campus of SWJTU.

The CFQS [3-5] is the first QAS medium-sized experiment device in the world. The major/minor radius are 1 m / 0.25 m, respectively. Toroidal periodic number is 2. The CFQS project is performed in two steps, 1st phase: CFQS-T for 0.1 T operation, and 2nd phase: CFQS for 1 T operation. CFQS-T construction was completed in July, 2024. Photos of CFQS-T is shown in Fig.1.

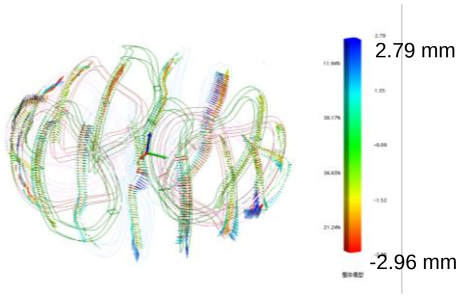

Fig. 2 Error of MC position measured by laser tracker.

Main magnetic field is produced by 16 modular coils (MCs) in 4 different shapes. For flexibility, 12 toroidal field coils (TFCs) and 2 pairs of poloidal field coils (PFCs) are designed. For MCs, copper conductors with square cross section of 8.5 mm × 8.5 mm, having ϕ 4 mm water cooling channel, were wound, and total turn number is 72. For PFCs, same copper conductors were used, however, for TFCs, cabtyre cable was directly wound on vacuum vessel (VV) to simplify its design and manufacturing process.

For CFQS-T and CFQS, all coil conductors are the same, however, supporting structure is different. For CFQS, strong electromagnetic force, which acts on MCs during 1 T operation, is supported by cage like support structure, which consist of coil cases, center pole, and pillars between adjacent coils. Analysis based on the finite element method was performed by ANSYS/Mechanical to check the von-Mises stress, deformation, and elastic strain. These results show that this support system is sufficiently robust for 1 T operation [6]. After the assembling of all components, MCs, PFCs, TFCs and VV in CFQS-T, error of MC position was measured by laser tracker, as shown in Fig.2. Maximum error of MC position is about ±3 mm. We analysed effects of MC position error on the magnetic configuration properties, such as shape of magnetic surface, rotational transform, neoclassical transport, and changes in them are not significant if the error level is less than 5 mm [7,8].

The flexibility of magnetic configuration is very valuable to perform experiments to study various physics research topics. With TFCs, the rotational transform can be easily controlled, by which the divertor configuration can be produced with 2/5 islands structure in the peripheral region. Quasi-axisymmetry is slightly deteriorated by this control, however, effective helical ripple is kept lower level than that of W7-X. By using PFCs, position of magnetic axis can be shifted. This control can be utilized to suppress the Shafranov shift in high beta operation. By adjusting the current ratio of inner vertical (IV) PFC to outer-vertical (OV) PFC, rotational transform also can be changed. In Fig.3, the controllability of magnetic axis position and rotational transform by PFCs are shown. Low mode islands are produced by this control, and those islands can be utilized effectively to evaluate error field in mapping magnetic field experiments [9]. Since islands width are very sensitive to the error field, accurate evaluation of coil misalignment magnitude is possible.

Magnetic field mapping experiment was performed by installing fluorescent mesh in the VV. One example of obtained image is shown in Fig.4. Results support good accuracy of MC positions, because good magnetic surfaces without islands were obtained in the standard configuration, and measured ones coincided with simulation results well. This is consistent with the error level in the modular coil position, measured with laser tracker in Fig.2, and good quasi-axisymmetric magnetic configuration is successfully produced in CFQS-T.

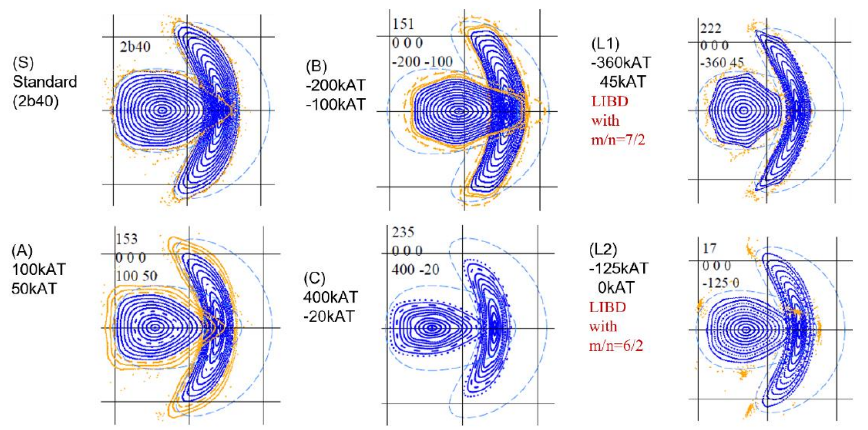

Fig. 3 Magnetic surfaces obtained by control with PFCs. Magnetic surfaces, at the toroidal angle ϕ of 0 and 90 degrees are shown. (S) is the standard configuration. (A), (B) are magnetic axis position control, inward and outward shifts, respectively. (C), (L1), (L2) are the control of rotational transform. In (L1) and (L2), island divertor configuration of m/n = 7/2 and 6/2 are produced.

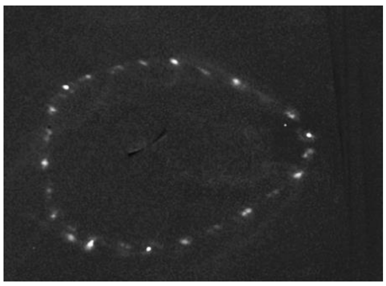

Fig. 4 Mapping magnetic field experiment result of standard configuration. Fluorescent mesh is installed at the triangular cross section (ϕ = 90 degree). Shape of magnetic surface coincides well with that of Fig. 3(S).

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