

Consideration of the Influence of Coil Misalignment on the Chinese First Quasi-Axisymmetric Stellarator Magnetic Configuration^{*)}

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The effects of misalignment of modular coils on various physical properties in the Chinese first quasi-axisymmetric Stellarator (CFQS) are discussed in this study. To estimate the effects quantitatively, simple assumptions are made regarding the structure of coil displacement. We consider the following three cases: displacement in radial direction (Case A), displacement in the vertical direction (Case B), and displacement by tilting (Case C). In all cases, we assume that the displacement structure has a stellarator symmetry. These assumptions are employed to calculate the change in the magnetic surfaces, rotational transform profile, magnetic well depth profile, and the effective helical ripple. Calculation results show that if the magnitude of displacement is less than 10 mm, the effects on these physical properties are small, and the good neoclassical transport property is retained.

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1. Introduction

Helical devices are advantageous over tokamak in terms of steady state operation as a future nuclear fusion reactor because their magnetic configurations are produced by external magnetic field coils, thus, no inductive plasma current is required. Recently, plasma experiments conducted by large-sized helical devices, e.g. the large helical device (LHD) [1] and Wendelstein 7-X (W7-X) [2], presented remarkable results, by which the possibilities of a future helical reactor can be anticipated. The neoclassical transport of a helical device was considered to be not good basically in the collisionless regime, so called in the $1/\nu$ regime (ν is the collision frequency). In recent decades, various optimized stellarator configurations, which have improved the neoclassical transport property, have been proposed and experimental devices have been constructed. A quasi-axisymmetric stellarator (QAS) is one of those stellarators, of which magnetic configuration is axisymmetric in magnetic coordinates, i.e., the Boozer

coordinates [3, 4]. The neoclassical transport property of QAS is similar to that of tokamak; however, the current drive is not required and the advantage of the steady state operation capability is retained. The Chinese first quasi-axisymmetric stellarator (CFQS) is the first experimental device of the QAS, which will be constructed in China, under the international joint project of National Institute for Fusion Science (NIFS) in Japan and Southwest Jiaotong University (SWJTU) in China [5–7]. The physical design for the CFQS is almost complete, and the engineering design is underway.

This paper discussed the effects of coil misalignment on the magnetic field configuration. Estimating these effects is important for determining the tolerance error in construction and assembling the modular coil system. Additionally, the quantitative estimation of tolerance is essential to verify the feasibility of the machine construction. Moreover, we are interested in the sensitivity of the displacement of magnetic field coils to the configuration as the large electromagnetic force deforms the coils during machine operation. For example, in W7-X, a large deformation of 20~30 cm in modular coils is caused by the electromagnetic force during the machine operation [8].

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Although the deformation by the electromagnetic force is large, the main deformation has stellarator symmetry, because all the components e. g., modular coils and the supporting structure, generally have stellarator symmetry. The sensitivity of this deformation to the magnetic field configuration should be considered in the design process. Herein, although limited cases are considered, in which the displacement structure of modular coil system has stellarator symmetry, it is helpful to quantitatively understand the effects of misalignment on various physical parameters.

2. Assumption of Coil Misalignment

The main parameters of the CFQS are as follows: the major radius is 1 m, the magnetic field strength is 1 T, and the aspect ratio is 4 [5–7]. The modular coil system of the CFQS was designed by the NESCOIL code [9]. The total number of modular coils was chosen to be 16 with four types of coils. This number is determined to achieve enough space between two neighboring coils and the small curvature of modular coils [5].

To consider the effects of misalignment of modular coils, the following three cases are considered: Case A, where the coils move to radial direction; Case B, where the coils move to the vertical (Z) direction; and Case C, where the coils tilt around the cylindrical R coordinate. Assumptions of these three cases are shown in Fig. 1. The displacement structure has stellarator symmetry for the simplicity of calculation. Herein, stellarator symmetry means that for the radial deformation, $\Delta R(\varphi, \theta) = \Delta R(-\varphi, -\theta)$, and for the vertical deformation, $\Delta Z(\varphi, \theta) = -\Delta Z(-\varphi, -\theta)$ are considered. Here, φ and θ are the toroidal and poloidal angles, respectively. Moreover, a toroidal periodicity of two is assumed. Hence, in Case A, eight modular coils move to

the radially outward direction and another eight modular coils move to the radially inward direction. The situation in Cases B and C is similar to this. Therefore, eight modular coils move in the same direction. For the deformation, the toroidal mode number of eight is considered to investigate the effect of main highest mode. The low mode will be included in future analyses for a more comprehensive understanding of the deformation effect on magnetic field properties.

3. Calculation Results

Magnetic surfaces are considered for these three types of displacements, as shown in Fig. 2. The displacement magnitudes are illustrated as follows: Fig. 2(a) depicts magnetic surfaces for the case where no displacement is considered. Figure 2(b) is for $\Delta R = 10$ mm in Case A, Fig. 2(c) is for $\Delta Z = 10$ mm in Case B and Fig. 2(d) is for $\Delta\theta = 0.6$ degrees in Case C. The red line depicts the originally designed plasma boundary surface of the CFQS. Magnetic surfaces exist outside the red line, so that the limiter in the actual experiment will determine the outermost magnetic surface. Generally, good magnetic surfaces are maintained in all cases of displacement are considered. We checked the good magnetic surfaces up to the displacement of $\Delta R = 50$ mm, $\Delta Z = 50$ mm, and $\Delta\theta = 3.0$ degrees. Therefore, magnetic surfaces are very robust.

Figure 3 shows changes in the radial profile of rotational transform in Case A, B, and C. ΔR and ΔZ are scanned from 5 to 50 mm, and $\Delta\theta$ is scanned from 0.3 to 3.0 degrees (these values of $\Delta\theta$ correspond to the change in the maximum displacement of coil position from 5 to 50 mm). As shown in these figures, the effect of the misalignment on the rotational transform is small; therefore, islands caused by the low mode rational surface do not appear in the magnetic field configuration. Figure 4 shows the change in the radial profile of the magnetic well depth. In all cases, the magnitude of change is very small.

The effects of the displacement of coils on Fourier components B_{mn} in Boozer coordinates are shown in Fig. 5. The magnetic field, B , is decomposed to cosine terms only because stellarator symmetry is assumed. In these figures, mode numbers (m, n) are annotated. Here, m is the poloidal mode number, and n is the toroidal mode number, which is normalized by the toroidal periodic number, 2. Therefore, the magnetic field B is expressed as $B = \sum B_{mn} \cos(m\eta + nN_p\zeta)$. Here, η and ζ are poloidal and toroidal angles, respectively, and N_p is 2 for the CFQS. Figure 5(a) shows the radial profile of B_{mn} from the free boundary VMEC [10] calculation result in the case where no displacement is considered. Figure 5(b) shows B_{mn} with a displacement of $\Delta R = 10$ mm in Case A. Figure 5(c) shows for $\Delta Z = 10$ mm in Case B, and Fig. 5(d) shows for $\Delta\theta = 0.6$ degree in Case C. In all cases, the dominant component is $B_{1,0}$, which corresponds to the toroidal ripple (axisymmetric) component. Other components are

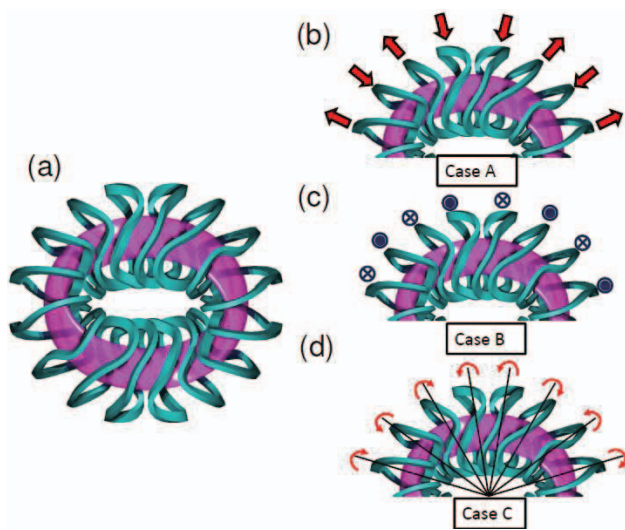


Fig. 1 (a) the top view of modular coil system of the CFQS. (b) assumed coil displacement of Case A, with coils moved to the radial direction. (c) Case B, with coils moved to the vertical direction, and (d) Case C, with coils tilting around the cylindrical R coordinates.

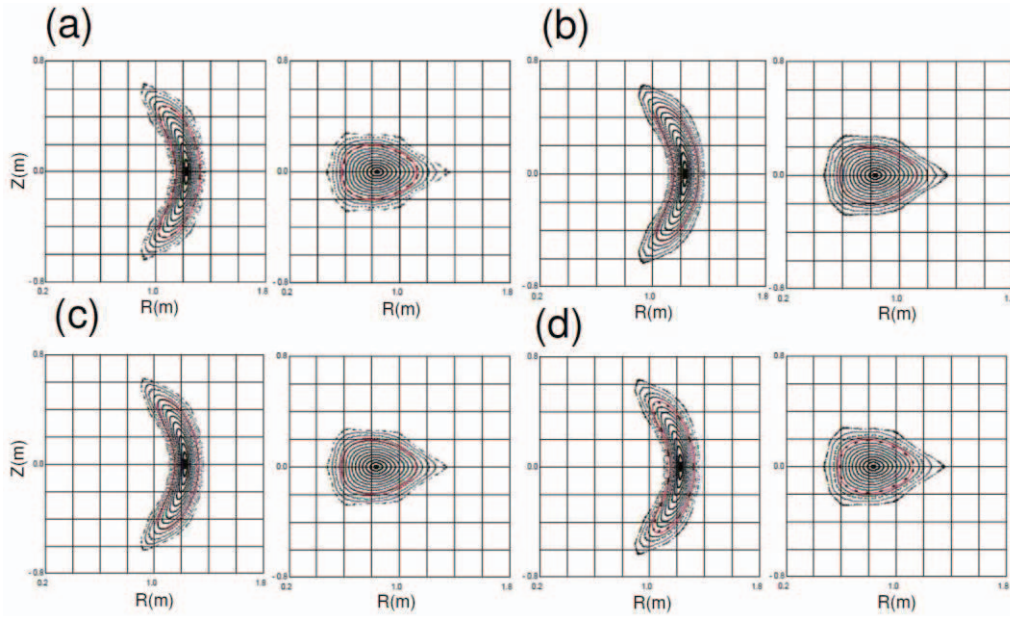


Fig. 2 Poincare plots with (a) no displacement of coils, (b) $\Delta R = 10$ mm displacement in Case A, (c) $\Delta Z = 10$ mm in Case B, and (d) $\Delta\theta = 0.6$ degree in Case C.

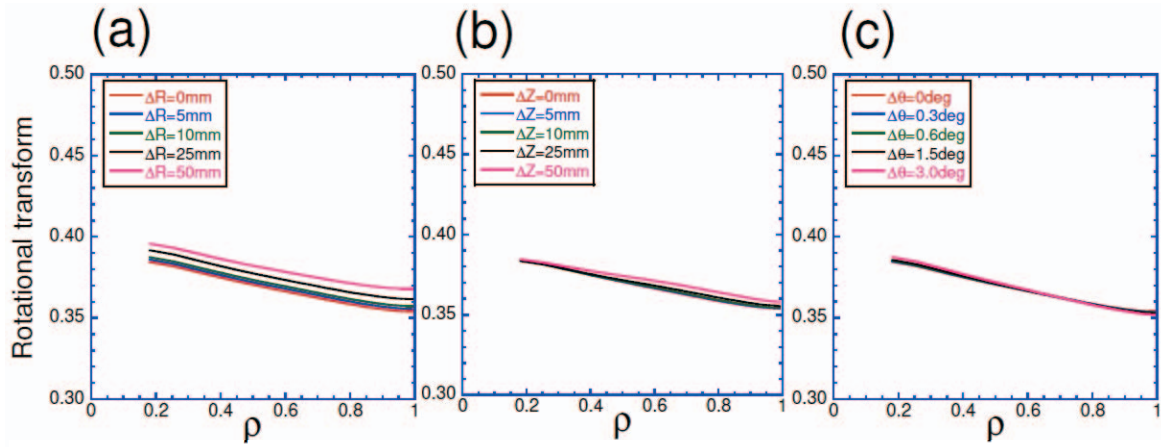


Fig. 3 Radial profile of rotational transform, with horizontal axis as the normalized minor radius. (a) change in the rotational transform for Case A, (b) Case B, and (c) Case C.

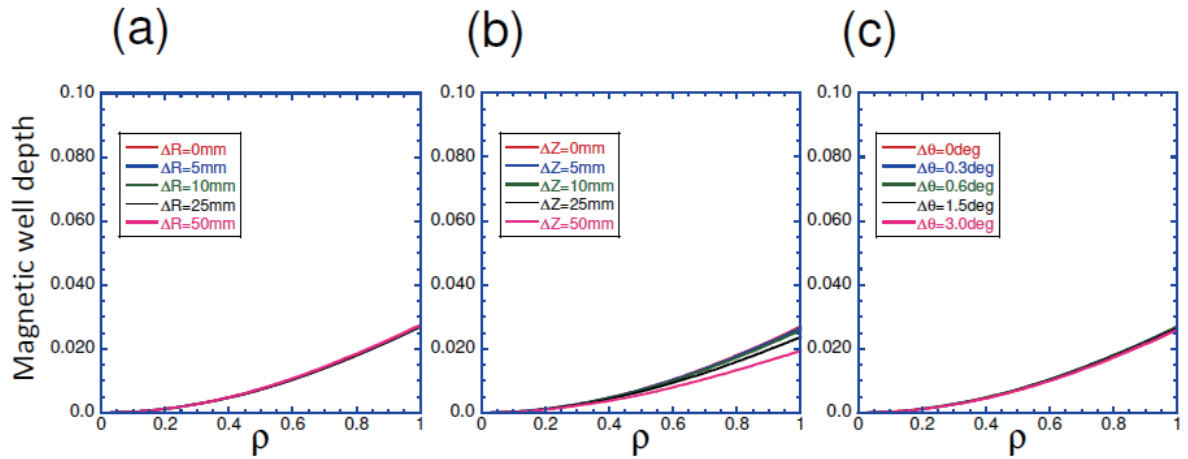


Fig. 4 Radial profile of magnetic well depth. (a) change in magnetic well depth for Case A, (b) Case B, and (c) Case C.

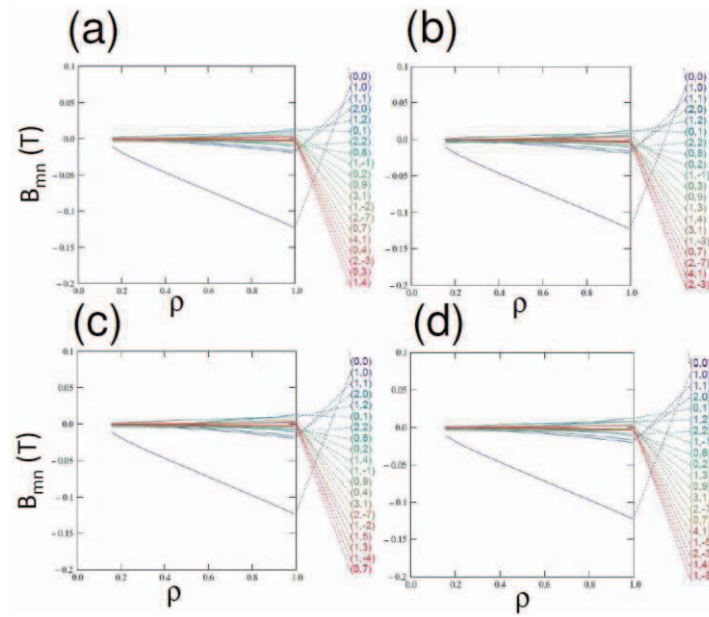


Fig. 5 B_{mn} as a function of normalized major radius, ρ , (a) with no displacement, (b) with $\Delta R = 10$ mm in Case A, (c) $\Delta Z = 10$ mm in Case B, and (d) $\Delta\theta = 0.6$ degree in Case C.

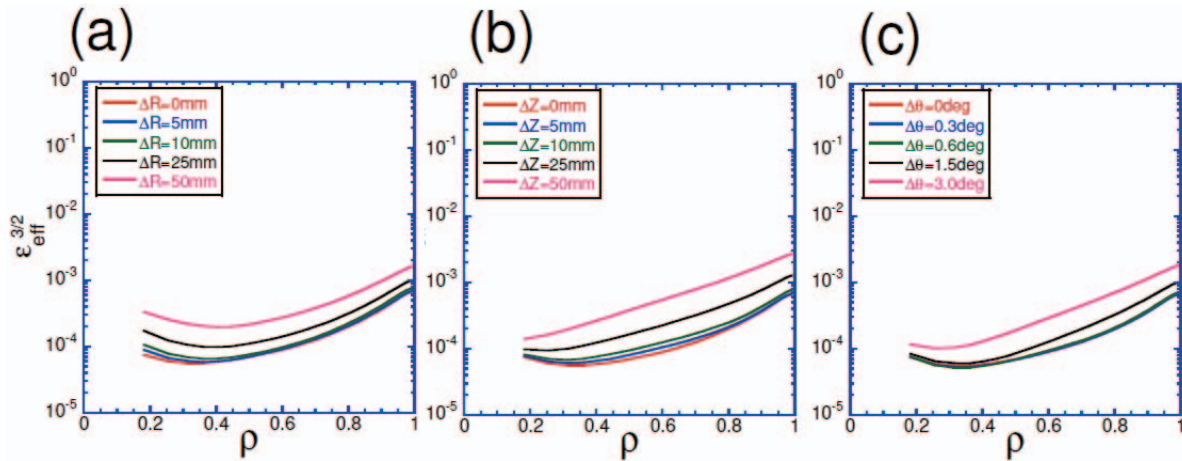


Fig. 6 Radial profile of effective helical ripple, $\varepsilon_{eff}^{3/2}$ (a) change in effective helical ripple for displacement in Case A, (b) Case B, and (c) Case C.

non-axisymmetric terms except $B_{2,0}$. The largest 19 components are presented in these figures. These Fourier components are important for the neoclassical transport property; however, it is difficult to understand those effects directly from B_{mn} . The effective helical ripple, ε_{eff} , is employed because the neoclassical diffusion coefficient in the $1/\nu$ regime, D_{NEO} , is proportional to $\nu_d \varepsilon_{eff}^{3/2} / \nu$. Here, ν_d is the drift velocity, and ν is the collision frequency. Figure 6 shows the radial profiles of the $\varepsilon_{eff}^{3/2}$ calculated from NEO code [11] for the displacement in Case A (Fig. 6 (a)), B (Fig. 6 (b)), and C (Fig. 6 (c)). The quantitative estimation of effects of the displacement of coils on neoclassical transport becomes directly possible from these figures.

4. Discussion

If the displacement of modular coils is less than 10 mm, the physical properties such as magnetic surfaces, the profile of rotational transform, and magnetic well depth are not significantly changed according to the calculation results. For the neoclassical diffusion coefficient estimated from ε_{eff} , the magnitude does not change. Meanwhile, if the displacement reaches 25 mm, a few factors of D_{neo} will increase. Therefore, if the displacement of coils is less than 10 mm, main physical properties such as the rotational transport, magnetic well, and quasi-axisymmetric property do not change significantly. This conclusion is limited to the case where the displacement structure has stellarator symmetry (and toroidal periodic number is two). However, these results are very helpful to consider and de-

termine the tolerance in the coil assembly and design of supporting structures. This robustness of the magnetic surface is considered a common feature in modular coil devices, because in W7-X, good magnetic surfaces are also maintained when a large deformation (~ 20 mm) of modular coils is caused by the electromagnetic force during operation [8]. However, this robustness is considered to be seen only in the case of stellarator symmetric deformation. For a more general conclusion, the effect of non-symmetric deformation should be investigated.

Another analysis required in the future is the effect of the misalignment on the confinement of the high energy particle, because this transport is not similar to the neo-classical diffusion process, and collisionless stochastic orbit behavior becomes important. Small ripples produced by the misalignment of coils may affect this property. Another factor is the effect of non-stellarator symmetric displacement on physical properties, although the calculation in this case will become complicated.

5. Summary

To estimate the effect of misalignment of modular coils on the physical properties in the CFQS, simple assumptions are made regarding the displacement structure of coils, and their effects on various physical properties are calculated. Although the displacement structure is a limited case, i.e., the only structure with stellarator symmetry, the effects are calculated quantitatively, and if the displacement is less than 10 mm, changes in physical proper-

ties (e.g., magnetic surfaces, rotational transport, magnetic well, and neoclassical diffusion coefficient) are small.

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